

# Aluminum Alloy Castings

Properties, Processes, and Applications

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# Preface

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This book is intended to provide a comprehensive summary of the physical and mechanical properties of most types of aluminum alloy castings. It includes discussion of the factors that affect those properties, including composition, casting process, microstructure, soundness, heat treatment, and densification. Extensive previously unpublished technical data including aging response, growth, fatigue, and high- and low-temperature performance have been consolidated with existing and updated materials property characterizations to provide a single authoritative source for most performance evaluation and design needs.

The consideration of casting process technologies is intentionally limited to typical capabilities and to their influence on property performance. Many excellent references are available for more detailed information and guidance on production methods and on important aspects of melting, melt processing, solidification, and structure control. Interested readers are referred to the publications of the American Foundry Society (AFS), the North American Die Casting Association (NADCA), and the Non-Ferrous Founders' Society (NFFS). Many of these publications are included in the reference lists at the end of each chapter.

It is also beyond the scope of this book to provide more than generalized economics of aluminum casting production.

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generously provided extensive previously unpublished production and property data from their archives, adding significantly to the industry's shared knowledge base. We wish, especially, to thank R.R. Sawtell and R.J. Bucci of Alcoa for their cooperation in arranging the release of this material. We are pleased that the American Foundry Society has been credited as co-publisher of this book. The AFS Aluminum Division Review Committee provided substantive and constructive suggestions; the members of the committee are listed in these pages. In addition, Laura Moreno and Joseph S. Santner of AFS provided content from AFS publications and arranged for the necessary permissions to reproduce information as needed. We would also like to thank Joseph C. Benedyk of the Illinois Institute of Technology for his helpful comments, and John C. Hebeisen of Bodycote for his assistance in providing the results of recent studies in hot isostatic processing. The North American Die Casting Association and the Non-Ferrous Founders' Society also gave us permission to cite, with appropriate references, information from their publications. We also acknowledge the support and assistance of the Aluminum Association, Inc., notably, permission to include information from their publications covering aluminum casting alloys.

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## About the Authors

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**J.G. (Gil) Kaufman** has a background of almost fifty years in the aluminum and materials information industries and remains an active consultant in both areas. In 1997, he retired as vice president, technology, for the Aluminum Association, Inc., headquartered in Washington, D.C., and is currently president of his consulting company, Kaufman Associates. Earlier in his career, he spent twenty-six years with the Aluminum Company of America and five with ARCO Metals, where he was vice president, R&D. He also served as president and CEO of the National Materials Property Data Network, establishing a worldwide online network of more than twenty-five materials databases. Mr. Kaufman is a Fellow and Honorary Member of ASTM, and a Fellow and Life Member of ASM International. He has published more than 125 articles, including four books, on aluminum alloys and materials data systems.

**Elwin Rooy** retired after thirty-five years with the Aluminum Company of America, where he was corporate manager of metallurgy and quality assurance, to form a consulting firm specializing in aluminum process and product technologies, quality systems, and industry relations. He has been active in committees of the Aluminum Association, American Foundry Society, American Die Casting Institute, The Institute of Scrap Recycling Industries, Society of Die Casting Engineers, ASM International, and TMS. He has served as chairman of the TMS Aluminum Committee, chairman of the AFS Light and Reactive Metals Division, director and chairman of the Northeast Ohio chapter of AFS, regional director of the Foundry Education Foundation, and charter member of the Drexel/WPI Advanced Casting Research Laboratory. Mr. Rooy's honors include the AFS award for Scientific Merit, The TMS/AIME Distinguished Service Award, the M.C. Flemings Award for contributions in the field of solidification, and the Arthur Vining Davis Award for technical achievement. He has served on the editorial boards of the *Journal of Metals* and *Advanced Materials & Processes*, published more than thirty articles and papers, edited *Light Metals 1991*, and authored or coauthored articles in the *ASM Handbook* series.



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# Contents

|                                                                  |          |                                                                  |           |
|------------------------------------------------------------------|----------|------------------------------------------------------------------|-----------|
| <b>Chapter 1: Introduction .....</b>                             | <b>1</b> |                                                                  |           |
| 1.1 Background and Scope .....                                   | 1        | 2.5.20 Tin .....                                                 | 16        |
| 1.2 History .....                                                | 1        | 2.5.21 Titanium .....                                            | 16        |
| 1.3 Advantages and Limitations of Aluminum Castings .....        | 2        | 2.5.22 Zinc .....                                                | 17        |
| 1.4 Major Trends Influencing Increased Use of Aluminum           |          | 2.6 Alloy Groupings by Application or Major Characteristic ..... | 17        |
| Castings .....                                                   | 3        | 2.6.1 General-Purpose Alloys .....                               | 17        |
| 1.4.1 Technology .....                                           | 3        | 2.6.2 Elevated-Temperature Alloys .....                          | 19        |
| 1.4.2 Recycling .....                                            | 5        | 2.6.3 Wear-Resistant Alloys .....                                | 19        |
| 1.5 Selecting the Right Aluminum Alloy and Casting Process ..... | 5        | 2.6.4 Moderate-Strength Alloys with Low Residual Stresses ..     | 19        |
|                                                                  |          | 2.6.5 Bearings .....                                             | 20        |
|                                                                  |          | 2.6.6 High-Strength Alloys .....                                 | 20        |
| <b>Chapter 2: Aluminum Casting Alloys .....</b>                  | <b>7</b> |                                                                  |           |
| 2.1 General .....                                                | 7        | <b>Chapter 3: Aluminum Casting Processes .....</b>               | <b>21</b> |
| 2.2 Specifications .....                                         | 7        | 3.1 History .....                                                | 21        |
| 2.3 Alloy Designations .....                                     | 8        | 3.2 Casting Process Selection .....                              | 21        |
| 2.3.1 The Aluminum Association (AA) Casting Alloy                |          | 3.2.1 Casting Design .....                                       | 21        |
| Designation System .....                                         | 8        | 3.2.2 Specification Requirements .....                           | 21        |
| 2.3.2 Aluminum Association Casting Temper Designation            |          | 3.2.3 Volume of Production .....                                 | 22        |
| System .....                                                     | 9        | 3.2.4 Costs .....                                                | 22        |
| 2.3.3 Evolution of Designation System; Cross-Reference to        |          | 3.2.5 Quality .....                                              | 22        |
| Older Designations .....                                         | 9        | 3.3 Casting Process Technology .....                             | 22        |
| 2.3.4 The UNS Alloy Designation System .....                     | 9        | 3.3.1 Expendable and Nonexpendable Mold Processes .....          | 22        |
| 2.3.5 International Casting Alloy Designations .....             | 9        | 3.3.2 Pressure versus Gravity .....                              | 22        |
| 2.3.6 Nomenclature System for Aluminum Metal-Matrix              |          | 3.3.3 Gating and Riserless .....                                 | 22        |
| Composites .....                                                 | 9        | 3.4 Expendable Mold Gravity-Feed Casting Process and             |           |
| 2.4 Composition Groupings .....                                  | 13       | Its Variations .....                                             | 23        |
| 2.4.1 Aluminum-Copper .....                                      | 13       | 3.4.1 Sand Casting .....                                         | 23        |
| 2.4.2 Aluminum-Silicon-Copper .....                              | 13       | 3.4.2 Evaporative (Lost-Foam) Pattern Casting (EPC) .....        | 24        |
| 2.4.3 Aluminum-Silicon .....                                     | 13       | 3.4.3 Shell Mold Casting .....                                   | 25        |
| 2.4.4 Aluminum-Silicon-Magnesium .....                           | 14       | 3.4.4 Plastic Casting .....                                      | 25        |
| 2.4.5 Aluminum-Magnesium .....                                   | 14       | 3.4.5 Investment Casting .....                                   | 25        |
| 2.4.6 Aluminum-Zinc-Magnesium .....                              | 14       | 3.4.6 Vacuum Mold (V-Mold) Casting .....                         | 26        |
| 2.4.7 Aluminum-Tin .....                                         | 14       | 3.5 Nonexpendable (Permanent) Mold Gravity Feed Casting          |           |
| 2.5 Effects of Alloying Elements .....                           | 14       | Process and Its Variations .....                                 | 26        |
| 2.5.1 Antimony .....                                             | 14       | 3.5.1 Permanent Mold Casting .....                               | 26        |
| 2.5.2 Beryllium .....                                            | 15       | 3.5.2 Low-Pressure Die Casting (LP), Pressure Riserless          |           |
| 2.5.3 Bismuth .....                                              | 15       | Casting (PRC) .....                                              | 27        |
| 2.5.4 Boron .....                                                | 15       | 3.5.3 Vacuum Riserless Casting (VRC) .....                       | 28        |
| 2.5.5 Cadmium .....                                              | 15       | 3.5.4 Centrifugal Casting .....                                  | 28        |
| 2.5.6 Calcium .....                                              | 15       | 3.5.5 Squeeze Casting .....                                      | 29        |
| 2.5.7 Chromium .....                                             | 15       | 3.5.6 Semisolid Forming .....                                    | 29        |
| 2.5.8 Copper .....                                               | 15       | 3.6 Pressure Die Casting and Its Variations .....                | 29        |
| 2.5.9 Iron .....                                                 | 15       | 3.6.1 Acurad Die Casting Process .....                           | 31        |
| 2.5.10 Lead .....                                                | 15       | 3.6.2 High-Integrity Pressure Die Casting .....                  | 31        |
| 2.5.11 Magnesium .....                                           | 15       | 3.6.3 Pore-Free Pressure Die Casting .....                       | 31        |
| 2.5.12 Manganese .....                                           | 15       | 3.6.4 Vacuum Die Casting .....                                   | 31        |
| 2.5.13 Mercury .....                                             | 16       | 3.6.5 Rotor Casting .....                                        | 31        |
| 2.5.14 Nickel .....                                              | 16       | 3.7 Premium Engineered Castings .....                            | 31        |
| 2.5.15 Phosphorus .....                                          | 16       | 3.7.1 Melt Processing .....                                      | 32        |
| 2.5.16 Silicon .....                                             | 16       | 3.7.2 Melt Quality Assessment .....                              | 32        |
| 2.5.17 Silver .....                                              | 16       | 3.7.3 Solidification .....                                       | 32        |
| 2.5.18 Sodium .....                                              | 16       | 3.7.4 Solidification Rate .....                                  | 32        |
| 2.5.19 Strontium .....                                           | 16       | 3.7.5 Mold Materials .....                                       | 32        |

|                                                                                                   |                                                                           |    |                                                                                                                                  |                                                                                                 |     |
|---------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|----|----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----|
| 3.7.6                                                                                             | Alloys.....                                                               | 32 | 8.3.2                                                                                                                            | Published Minimum and Design Mechanical Properties .....                                        | 71  |
| 3.7.7                                                                                             | Aluminum-Silicon Eutectic Modification and Grain Refinement .....         | 34 | 8.3.3                                                                                                                            | Effects of Subzero and Elevated Temperatures on Mechanical Properties .....                     | 71  |
| 3.7.8                                                                                             | Mold Filling.....                                                         | 34 | 8.3.4                                                                                                                            | Influence of Premium Practices and Emerging Casting Technologies on Mechanical Properties ..... | 84  |
| 3.7.9                                                                                             | Quality Assurance.....                                                    | 35 | 8.4                                                                                                                              | Fatigue Properties of Aluminum Casting Alloys .....                                             | 92  |
| 3.7.10                                                                                            | Relevance of Premium Casting Engineering.....                             | 35 | 8.4.1                                                                                                                            | Influence of Casting Quality on Fatigue Strength.....                                           | 97  |
| 3.8                                                                                               | Other Process Technologies .....                                          | 35 | 8.4.2                                                                                                                            | Influence of Stress Raisers on Fatigue Strength of Aluminum Castings .....                      | 101 |
| 3.8.1                                                                                             | Metallurgical Bonding.....                                                | 35 | 8.4.3                                                                                                                            | Fatigue Strengths of Welded Aluminum Castings .....                                             | 102 |
| 3.8.2                                                                                             | Cast Aluminum-Matrix Composites.....                                      | 36 | 8.4.4                                                                                                                            | Design Fatigue Strengths for Aluminum Castings.....                                             | 103 |
| 3.8.3                                                                                             | Hot Isostatic Pressing (HIP).....                                         | 37 | 8.5                                                                                                                              | Fracture Resistance of Aluminum Alloys.....                                                     | 103 |
| <b>Chapter 4: The Effects of Microstructure on Properties.....</b>                                | <b>39</b>                                                                 |    | 8.5.1                                                                                                                            | Notch Toughness and Notch Sensitivity .....                                                     | 103 |
| 4.1                                                                                               | Intermetallic Phases.....                                                 | 39 | 8.5.2                                                                                                                            | Tear Resistance .....                                                                           | 110 |
| 4.2                                                                                               | Dendrite Arm Spacing.....                                                 | 39 | 8.5.3                                                                                                                            | Fracture Toughness .....                                                                        | 112 |
| 4.3                                                                                               | Grain Refinement .....                                                    | 40 | 8.5.4                                                                                                                            | Interrelation of Measures of Fracture Resistance.....                                           | 114 |
| 4.4                                                                                               | Aluminum-Silicon Eutectic Modification.....                               | 40 | 8.6                                                                                                                              | Subcritical Crack Growth.....                                                                   | 114 |
| 4.5                                                                                               | Refinement of Hypereutectic Aluminum-Silicon Alloys .....                 | 45 | 8.6.1                                                                                                                            | Fatigue Crack Growth .....                                                                      | 115 |
| <b>Chapter 5: The Influence and Control of Porosity and Inclusions in Aluminum Castings .....</b> | <b>47</b>                                                                 |    | 8.6.2                                                                                                                            | Creep Crack Growth.....                                                                         | 116 |
| 5.1                                                                                               | Hydrogen Porosity.....                                                    | 47 | 8.6.3                                                                                                                            | Stress-Corrosion Crack Growth .....                                                             | 116 |
| 5.2                                                                                               | Shrinkage Porosity .....                                                  | 49 | 8.7                                                                                                                              | Corrosion Resistance .....                                                                      | 116 |
| 5.3                                                                                               | Inclusions.....                                                           | 50 | 8.7.1                                                                                                                            | Aluminum-Copper Casting Alloys (2xx.x).....                                                     | 116 |
| 5.4                                                                                               | Combined Effects of Hydrogen, Shrinkage, and Inclusions..                 | 51 | 8.7.2                                                                                                                            | Al-Si-Cu and/or Mg Casting Alloys (3xx.x) .....                                                 | 120 |
| 5.5                                                                                               | Radiographic Inspection.....                                              | 53 | 8.7.3                                                                                                                            | Aluminum-Silicon Casting Alloys (4xx.x) .....                                                   | 120 |
| <b>Chapter 6: Hot Isostatic Pressing .....</b>                                                    | <b>55</b>                                                                 |    | 8.7.4                                                                                                                            | Aluminum-Magnesium Casting Alloys (5xx.x).....                                                  | 120 |
| 6.1                                                                                               | The HIP Process.....                                                      | 55 | 8.7.5                                                                                                                            | Aluminum-Zinc Casting Alloys (7xx.x) .....                                                      | 120 |
| 6.2                                                                                               | The Effect of HIP on Tensile Properties .....                             | 56 | 8.7.6                                                                                                                            | Aluminum-Tin Casting Alloys (8xx.x) .....                                                       | 122 |
| 6.3                                                                                               | The Effect of HIP on Fatigue Performance .....                            | 56 | 8.8                                                                                                                              | Properties of Cast Aluminum Matrix Composites .....                                             | 122 |
| 6.4                                                                                               | Radiographic Inspection of HIPped Castings .....                          | 56 | <b>Data Set 1: Aging Response Curves .....</b>                                                                                   | <b>133</b>                                                                                      |     |
| <b>Chapter 7: Heat Treatment of Aluminum Castings.....</b>                                        | <b>61</b>                                                                 |    | <b>Data Set 2: Growth Curves .....</b>                                                                                           | <b>175</b>                                                                                      |     |
| 7.1                                                                                               | Solution Heat Treatment .....                                             | 62 | <b>Data Set 3: Stress-Strain Curves.....</b>                                                                                     | <b>193</b>                                                                                      |     |
| 7.2                                                                                               | Quenching.....                                                            | 62 | <b>Data Set 4: Tensile Properties at High and Low Temperatures and at Room Temperature after High-Temperature Exposure .....</b> | <b>211</b>                                                                                      |     |
| 7.3                                                                                               | Precipitation Heat Treating/Aging .....                                   | 64 | <b>Data Set 5: Creep-Rupture Properties .....</b>                                                                                | <b>243</b>                                                                                      |     |
| 7.3.1                                                                                             | Aluminum-Copper .....                                                     | 65 | <b>Data Set 6: Rotating-Beam Reversed-Bending Fatigue Curves..</b>                                                               | <b>253</b>                                                                                      |     |
| 7.3.2                                                                                             | Aluminum-Copper Magnesium.....                                            | 65 | <b>Appendix 1: Glossary of Terms.....</b>                                                                                        | <b>293</b>                                                                                      |     |
| 7.3.3                                                                                             | Aluminum-Silicon-Magnesium .....                                          | 65 | <b>Appendix 2: Abbreviations and Symbols.....</b>                                                                                | <b>299</b>                                                                                      |     |
| 7.3.4                                                                                             | Aluminum-Zinc-Magnesium .....                                             | 65 | <b>Appendix 3: Test Specimen Drawings .....</b>                                                                                  | <b>301</b>                                                                                      |     |
| 7.4                                                                                               | Annealing.....                                                            | 66 | <b>Alloy Index.....</b>                                                                                                          | <b>305</b>                                                                                      |     |
| 7.5                                                                                               | Stability.....                                                            | 66 | <b>Subject Index.....</b>                                                                                                        | <b>325</b>                                                                                      |     |
| 7.6                                                                                               | Residual Stresses.....                                                    | 66 |                                                                                                                                  |                                                                                                 |     |
| 7.7                                                                                               | Troubleshooting Heat Treatment Problems .....                             | 66 |                                                                                                                                  |                                                                                                 |     |
| 7.7.1                                                                                             | Acceptance Criteria .....                                                 | 66 |                                                                                                                                  |                                                                                                 |     |
| 7.7.2                                                                                             | Diagnosis.....                                                            | 67 |                                                                                                                                  |                                                                                                 |     |
| <b>Chapter 8: Properties and Performance of Aluminum Castings .....</b>                           | <b>69</b>                                                                 |    |                                                                                                                                  |                                                                                                 |     |
| 8.1                                                                                               | Compositions and Influence of Composition on Characteristics .....        | 69 |                                                                                                                                  |                                                                                                 |     |
| 8.2                                                                                               | Physical Properties of Aluminum Casting Alloys.....                       | 69 |                                                                                                                                  |                                                                                                 |     |
| 8.3                                                                                               | Typical and Minimum Mechanical Properties of Aluminum Alloy Castings..... | 71 |                                                                                                                                  |                                                                                                 |     |
| 8.3.1                                                                                             | Published Typical Mechanical Properties.....                              | 71 |                                                                                                                                  |                                                                                                 |     |

## CHAPTER 1

# Introduction

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### 1.1 Background and Scope

It is the objective of this book to comprehensively summarize material properties and engineering data for aluminum alloy castings and to address the need for a single reference that covers production, quality assurance, properties, and applications of aluminum alloy castings.

Unlike most sources, the content addresses not only conventional sand and permanent mold castings, but also pressure die castings and many of the variations of all three that have developed over the years.

The physical and mechanical properties of aluminum castings may be altered through:

- *Alloying composition:* The composition of alloys determines the potential for achieving specific physical and mechanical properties. Alloy content is designed to produce characteristics that include castability as well as desired performance capabilities. The interaction of alloying elements is recognized in promoting desired microstructural phases and solid-solution effects for the development of these properties.
- *Cooling rate during and after solidification:* The conditions under which solidification takes place determine the structural features that affect the physical and mechanical properties of an alloy.
- *Casting process:* There are a large number of casting processes, and each imposes different rates of heat extraction, solidification rates, and means of compensating for solidification-related microstructural and macrostructural tendencies.
- *Solidification:* Engineered castings are susceptible to internal and superficial defects. The complex geometries of shaped castings, fluid dynamics, and solidification mechanics combine to present unique and difficult challenges to the objective of dense, discontinuity-free parts. Internal porosity can result from shrinkage and hydrogen porosity, as well as from visually detectable defects such as misruns, cracks, moisture reactions, folds, and tears. Nonmetallic inclusions affect mechanical properties and nucleate hydrogen pore formation. Pore volume fraction and the geometry and distribution of internal voids reduce tensile properties, fatigue strength, toughness, and ductility, while surface defects strongly influence mechanical and fatigue performance.
- *Heat treatment:* Mechanical properties can be altered by post-solidification thermal treatment, including annealing, solution heat treatment, and precipitation aging.
- *Postsolidification densification:* Hot isostatic processing (HIP) of castings can result in improved levels of internal soundness, higher tensile properties, ductility, and fatigue performance.

These factors and their effects are considered in Chapters 2 through 7, and a comprehensive summary of the mechanical and physical properties of aluminum alloy castings is provided in Chapter 8.

### 1.2 History

Castings were the first important market for aluminum, following the commercialization of the Hall-Heroult electrolytic reduction process. At first, applications were limited to curiosities such as house numbers, hand mirrors, combs, brushes, tie clasps, cuff links, hat pins, and decorative lamp housings that emphasized the light weight, silvery finish, and novelty of the new metal. Cast aluminum cookware was a welcome alternative to cast iron and brass pots, pans, and kettles. The cost of aluminum steadily declined, and by the end of the 19th century important engineering applications became economically viable.

Aluminum in cast as well as wrought forms was a metal for its time. Three emerging markets coincided with the appearance of aluminum as a material alternative:

- Electrification demanded not only low-density, corrosion-resistant, high-conductivity wire and cable for which aluminum was well-suited, but also transmission towers and cast installation hardware.
- Automotive pioneers sought innovative materials and product forms to differentiate the performance and appearance of their products.
- When the Wright Brothers succeeded in powered flight, engine and other parts in cast aluminum represented the beginning of a close collaboration with what would become the aviation and aerospace industries.

The large number of applications for which aluminum competed in these and other markets required the development of specialized compositions and material conditions to satisfy specific engineering requirements. The characterization of physical and mechanical properties and the results of performance testing were the basis for continuous new alloy developments and refinements in composition control. The development of permanent mold and pressure die casting as alternatives to sand casting encouraged the development of new alloys suited not just to application requirements but also to the

casting process. Continuing technological improvements in alloy, casting, and recycling technology have improved the competitiveness and enhanced the growth of aluminum castings markets.

1.3 Advantages and Limitations of Aluminum Castings

Aluminum castings are produced in a range of alloys demonstrating wide versatility in the characteristics than can be achieved. More than 100 compositions are registered with the Aluminum Association, and more than 300 alloys are in international use. Properties displayed by these alloys, without considering the expanded capabilities of metal-matrix and other composite structures, include:

|                                                                                      |                                                                    |
|--------------------------------------------------------------------------------------|--------------------------------------------------------------------|
| Tensile strength, ksi (MPa)                                                          | 10–72 (70–505)                                                     |
| Yield strength, ksi (MPa)                                                            | 3–65 (20–455)                                                      |
| Elongation, %                                                                        | <1–30                                                              |
| Hardness, HB                                                                         | 30–150                                                             |
| Electrical conductivity, %IACS                                                       | 18–60                                                              |
| Thermal conductivity, Btu · in./h · ft <sup>2</sup> · °F at 77 °F (W/m · K at 25 °C) | 660–1155 (85–175)                                                  |
| Fatigue limit, ksi (MPa)                                                             | 8–21 (55–145)                                                      |
| Coefficient of linear thermal expansion at 68–212 °F (20–100 °C)                     | 9.8–13.7 × 10 <sup>−6</sup> /°F (17.6–24.7) × 10 <sup>−6</sup> /°C |
| Shear strength, ksi (MPa)                                                            | 6–46 (42–325)                                                      |
| Modulus of elasticity, 10 <sup>6</sup> psi (GPa)                                     | 9.5–11.2 (65–80)                                                   |
| Specific gravity                                                                     | 2.57–2.95                                                          |

An ability to produce near-net-shape parts with dimensional accuracy, controlled surface finish, complex geometries including internal passages, and properties consistent with specified engineering requirements represents significant manufacturing advantages (Fig. 1.1, 1.2):

- In many cases, multicomponent welded or joined assemblies can be replaced with a single cast part.
- Machining requirements are reduced.
- Aluminum castings display controlled variations in as-cast finish.
- Contrasts between as-cast and machined finishes can be highlighted to create pleasing cosmetic effects.
- Capital requirements are typically less than for wrought products.
- Tooling can range from simple patterns to complex tool steel dies depending on product requirements and production volume.
- Metallurgically or mechanically bonded bimetal parts can be routinely cast.
- Aluminum parts are routinely cast by every known process, offering a broad range of volume, productivity, quality, mechanization, and specialized capabilities.
- Most aluminum casting alloys display solidification characteristics compatible with foundry requirements for the production of quality parts.



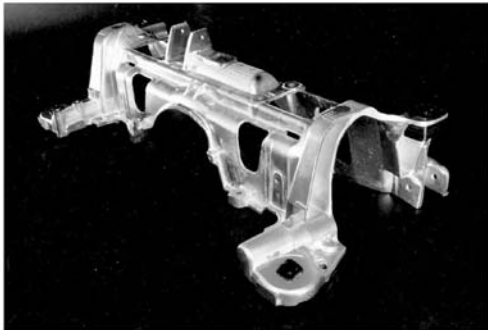
(a)



(b)



(c)



(d)



(e)

**Fig. 1.1** Casting applications include innovative and complex designs serving the needs of diverse industries. (a) Aircraft stabilizer. (b) Golf irons. (c) Crankcase for small engine. (d) Cross member for a minivan. (e) Cellular phone casing. Source: Ref 1



- Many aluminum casting alloys display excellent fluidity for casting thin sections and fine detail.
- Aluminum casting alloys melt at relatively low temperatures.
- Aluminum casting processes can be highly automated.

Many limitations do apply. Very thin sections may not be castable. There are practical limitations in size for specific casting processes. The solidification behavior of some alloys precludes casting in difficult engineered configurations or in specific casting processes. The casting process is simpler and less capital intense than processes for producing forgings, extrusions, and rolled products. However, solidification in complex geometrical shapes, as with other fabrication options, can result in surface discontinuities and internal microstructure features with varying degrees of quality that affect properties and performance.

Aluminum alloy castings can display the tensile properties of most forgings, extrusions, and rolled plate. Because wrought products are normally characterized by finely recrystallized grain structures with specific anisotropy and highly textured microstructural features, ductility in longitudinal directions is typically greater than in castings that contain coarser grain structures. Conversely, the typically uniaxial grain structure and absence of anisotropy in cast structures do not present design engineers with the challenges associated with transverse property limitations.

## 1.4 Major Trends Influencing Increased Use of Aluminum Castings

### 1.4.1 Technology

The importance of improved energy efficiency in recent decades reflects the effects of increased gasoline and oil costs to the consumer and graduated government-mandated fuel-efficiency standards for automobile and truck manufacturers. Environmental concerns, global competitiveness, and raw-material concerns reinforce

the incentives to reduce fuel consumption while preserving product performance and cost objectives.

The most cost-effective means of addressing these challenges has been the substitution of lightweight materials in existing and projected automotive designs. The U.S. automotive industry in collaboration with suppliers and the U.S. Department of Energy formed coalitions, including USAMP, which focused on materials characterization, and USCAR, which focused on materials development and process capabilities. Their objective has been to facilitate the transition to lighter-weight materials and more fuel-efficient performance without sacrifice in safety and with minimal impact on cost.

The emphasis placed on improved efficiency in energy-consuming applications has resulted in a steady increase in the production and use of aluminum castings. The recent pattern of growth in aluminum casting shipments in the United States, including projections through the year 2005 is (Ref 2):

| Year | Casting shipments in the United States |                    |
|------|----------------------------------------|--------------------|
|      | 10 <sup>6</sup> lb                     | 10 <sup>6</sup> kg |
| 1994 | 2880                                   | 1306               |
| 1995 | 2990                                   | 1356               |
| 1996 | 3260                                   | 1479               |
| 1997 | 3380                                   | 1533               |
| 1998 | 3490                                   | 1583               |
| 1999 | 3550                                   | 1610               |
| 2000 | 3640                                   | 1651               |
| 2001 | 3800                                   | 1724               |
| 2202 | 4100                                   | 1860               |
| 2003 | 4500                                   | 2041               |
| 2004 | 4900                                   | 2223               |
| 2005 | 5160                                   | 2341               |

Cast aluminum has been used or demonstrated successfully for many decades in power-train applications including engine blocks, cylinder heads, pistons, transmission cases, and oil pans. In the first wave of light-weighting, aluminum was extensively adopted for these parts. For maximum impact on fuel efficiency, this expansion in the role of cast aluminum necessitated substitutions in more critical structural parts requiring the qualification of new component designs, materials, and production methods. These applications include traditionally cast iron, malleable iron, nodular iron and steel cross members, suspension and control arms, brackets, brake valves, rotors, and calipers. The commercialization of aluminum-intensive automobile designs can result in 20 lb less engine emissions over the life of an automobile for each pound of iron or steel replaced by lower-density aluminum with correspondingly significant reductions in fuel consumption (Ref 3). New aluminum-intensive automotive construction concepts include cast fittings or nodes for extruded stringers in monocoque assemblies and the development of energy-absorbing thin-wall cast space frames. Figures 1.3 through 1.6 summarize the results of a study performed for the Aluminum Association showing the growth in cast aluminum as well as total aluminum products in North American light vehicle production.

The most significant barrier to the acceptance of cast aluminum in these and many other structural applications has been its reputation for variability. Overcoming this barrier required the demonstration of integrity and reliability derived from the evolu-

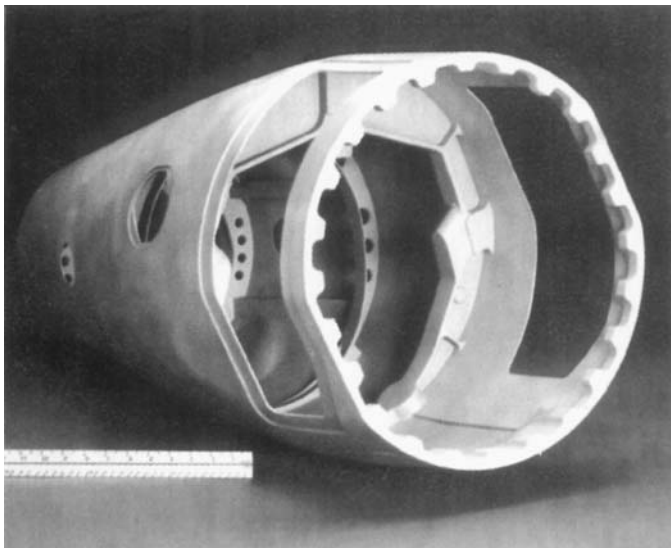


**Fig. 1.2** One-piece cast missile tail cone. A cost-effective and reliable alternative to what had been a multicomponent assembly

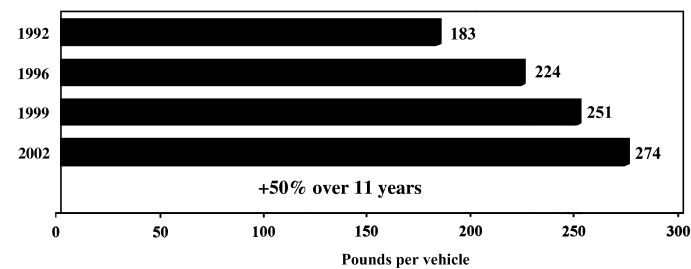
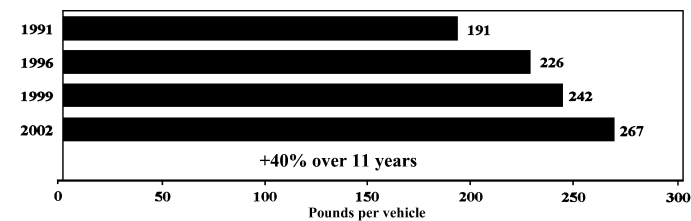
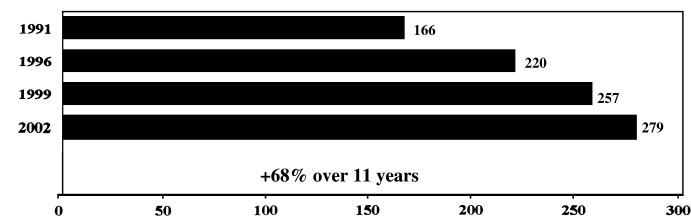


Fig. 1.3 North American light vehicle change in aluminum content, 1991 to 2002



(a)



(b)

Fig. 1.4 North American light vehicle change in aluminum content, 1991 to 2002. (a) Passenger cars. (b) Trucks

tion of manufacturing processes and effective process controls. To be economic, casting results must be consistent and predictable without reliance on extensive inspection and nondestructive evaluation.

Each step in these developments has been the product of close collaboration between aluminum casting suppliers and the automotive industry. Not only are specific engineering criteria to be met for each new component, process designs and controls must reliably demonstrate capability and consistent product quality in the high volumes that are required. New casting processes, alloys, composite compositions, thermal treatments, process control methodologies, and the sensors and controls they require have contributed to an accelerated evolution of technologies that has been facilitated by research and development programs, many of which were sponsored by USCAR and USAMP in cooperation with national laboratories, colleges, and universities and with supplier industries.

Aluminum castings will play an important future role when inevitable electric, hybrid, or fuel-cell technologies are developed to combine materials, design, and construction methods for maximum efficiency.

Technological progress achieved in automotive programs affects all phases of aluminum foundry operations and all casting applications. Technology is also being broadly advanced by the activities of the U.S. Department of Energy that has identified metal casting as one of nine important “Industries of the Future.” Benefits have been the development of a technology roadmap (Ref 4) that includes many of the challenges and technical barriers facing the aluminum castings industry and the funding of research and development programs in casting, aluminum, sensors, automation, and industrial materials of the future to meet or overcome them.

The product of these efforts has been greater versatility and improved capability in consistently and economically meeting even the most severe engineering challenges in automotive and other industries. Understanding the material and process changes that are

| Aluminum product form                            | 1999 lb/vehicle | Percent of total | 2002 lb/vehicle | Percent of total | Percent change 1999 vs 2002 |
|--------------------------------------------------|-----------------|------------------|-----------------|------------------|-----------------------------|
| Die castings                                     | 95.76           | 38.2%            | 101.42          | 37.1%            | + 5.9% or 5.66 lb           |
| Permanent mold castings                          | 92.43           | 36.9%            | 100.58          | 36.8%            | + 8.8% or 8.15 lb           |
| Flat rolled products                             | 27.24           | 10.9%            | 29.39           | 10.7%            | + 7.9% or 2.15 lb           |
| Extruded and drawn products                      | 16.83           | 6.7%             | 18.49           | 6.8%             | + 9.9% or 1.66 lb           |
| Forgings and impacts                             | 6.34            | 2.5%             | 6.10            | 2.2%             | - 3.8% or -0.24 lb          |
| Sand, lost foam, squeeze, and semisolid castings | 11.94           | 4.8%             | 17.52           | 6.4%             | + 46.7% or 5.58 lb          |
| Total                                            | 250.54          | 100%             | 273.50          | 100%             | + 9.2% or 22.96 lb          |

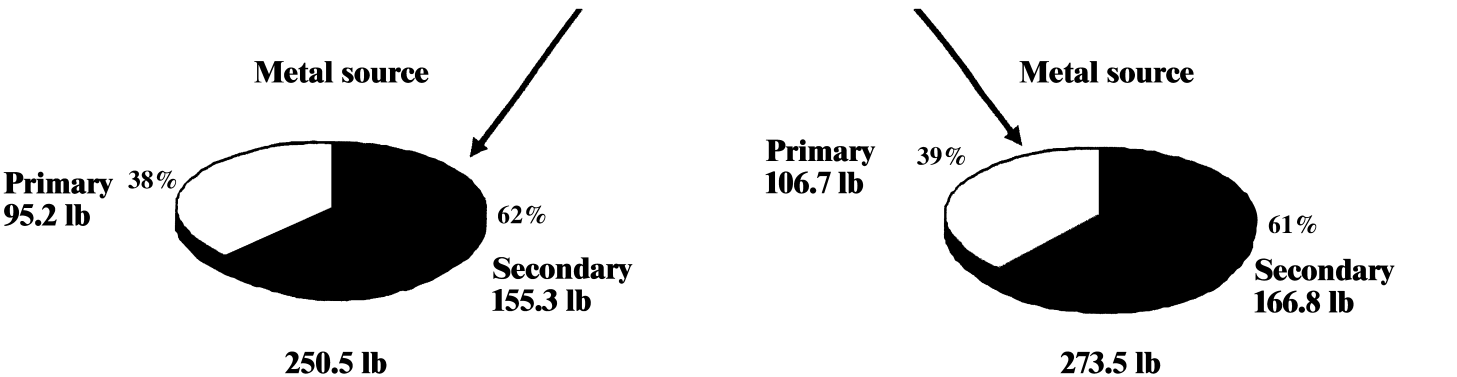


Fig. 1.5 North American light vehicle change in aluminum content by product form and metal source, 1999 to 2002

taking place to further increase the comfort of design engineers in the use of aluminum castings is essential for defining material advantages for any new application.

### 1.4.2 Recycling

Recycling and its impact in life-cycle studies are increasingly important considerations in materials selection (Ref 5). The manner in which energy efficiency can be directly and indirectly affected is important, but so are environmental and competitive considerations. While the production of aluminum is energy-intensive, it can be efficiently recovered from scrap at 5% of the energy required for reduction. Corrosion resistance preserves metal value, and new technologies are being developed for the segregation of scrap streams by alloy and product form for essentially closed-loop recycling.

Virtually all aluminum forms classified as old scrap (end of cycle) and new scrap (turnings, borings, gates and risers, rejections) are recyclable. With appropriate recycling processes, recoveries typically exceed 90%.

Many casting compositions are compatible with the alloy content of even mixed scrap. The cost of ingot produced from scrap is typically less than that of primary metal. As a consequence, most aluminum alloy castings are produced from recycled metal.

The use of aluminum in energy-consuming applications provides efficiencies with calculable benefits for prolonging product life, conserving raw materials, reducing energy consumption in manufacturing and service, reducing levels of environmental pollution and the costs of environmental control, and lowering material cost through recycling. When factored into cost comparisons

with competing materials, the advantage of aluminum in life-cycle analysis can be significant.

## 1.5 Selecting the Right Aluminum Alloy and Casting Process

The succeeding chapters review the substantial portfolio of aluminum casting alloys available; Chapter 2 illustrates the characteristics that have made certain alloys the first choice for specific applications. Chapters 3 through 7 focus on the process and thermal treatment variables that influence the metallurgical structure of aluminum alloys and, in turn, how the combination of process variables and metallurgical structure influence their properties and performance. Finally, Chapter 8 provides a broad range of physical and mechanical property data, a substantial amount of which has never been published before, certainly not all in a single resource.

This wide range of information contained herein is provided as a reference for aluminum alloy casting producers, heat treaters, designers, and users with the intent of aiding them in the selection of the right alloy, temper, and processing needed to achieve the performance required of cast components. The authors believe it is clear that, as suggested above, aluminum casting alloys provide a broad range of capabilities including—when appropriate, process-optimization and quality-control procedures are applied—components suitable for challenging applications where soundness, strength, and toughness are critical. The authors hope it will also be clear that there are great advantages for designers and casting suppliers working closely with their customers on the selection of alloys, tempers, and casting processes capable of meeting manu-

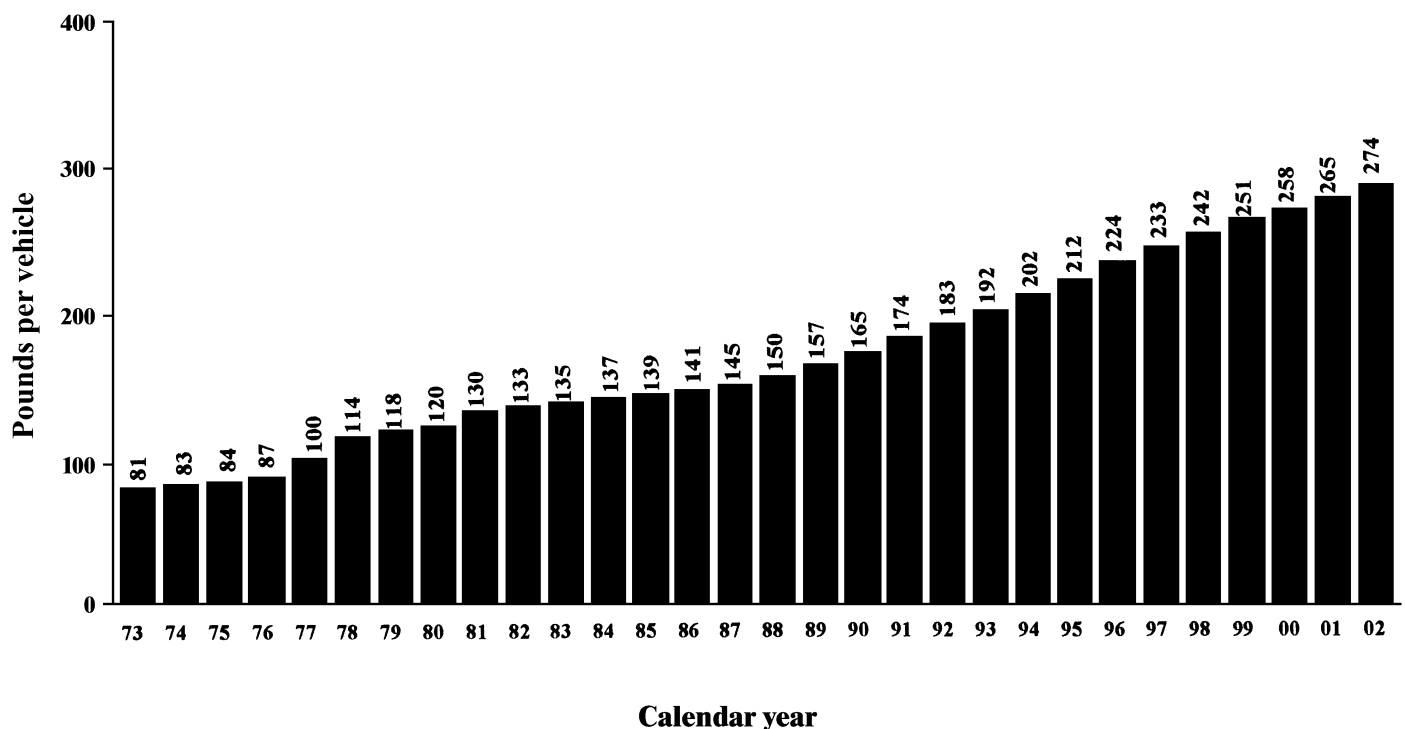


Fig. 1.6 North American light vehicle change in aluminum content, 1973 to 2002



facturing objectives, component performance criteria, and economic targets.

This reference volume is not intended as a guide to producing aluminum alloy castings; for example, it does not cover the details of how to design and build molds, inject the molten alloys, and sequence the finishing process. For more information on such matters, the reader is referred to the excellent aluminum casting industry publications of the American Foundry Society and similar organizations (Ref 1, 6–9) plus those of the Aluminum Association (Ref 10–12). For those interested in a broader overview of the entire aluminum industry, D.G. Altenpohl's volume (Ref 13) is recommended.

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## CHAPTER 2

# Aluminum Casting Alloys

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### 2.1 General

Aluminum casting alloy compositions parallel wrought alloy compositions in many respects. Hardening and desired properties are achieved through the addition of alloying elements and through heat treatment. Since work hardening plays no significant role in the development of casting properties, the use and purposes of some alloying elements differ in casting and wrought alloys.

The most important consideration in differentiating wrought and casting alloy compositions is castability. While wrought products are typically produced in simple round and rectangular cross sections by casting processes that minimize the depth and maximize the uniformity of the solidification front, solidification in engineered castings with complex shapes and variable rates of solidification present different demands on alloy solidification behavior. Cracking during and after solidification and internal shrinkage dictate alloys for shape casting that minimize these tendencies.

The term *castability* is not precisely defined. It is used to estimate the suitability of a composition for solidification in a specific process to produce defect-free, sound castings. For gravity casting, the components of castability are generally considered to be fluidity as the measure of mold-filling capability, resistance to hot cracking during and after solidification, and feeding characteristics that promote the flow of metal during solidification to avoid or minimize the formation of shrinkage voids. For pressure die castings, the criteria of castability are resistance to hot cracking, fluidity, die soldering and surface finish.

Fluidity is a complex function that can be quantified and mathematically defined. Fluidity is most strongly affected by temperature above the liquidus or degree of superheat. More fluid compositions at conventional pouring temperatures are those of eutectic or near-eutectic composition.

Improved feeding characteristics are usually associated with narrow solidus-liquidus ranges and in greater percent liquid at the eutectic temperature.

The tendency for solidification and postsolidification cracking is dominated by element effects on elevated-temperature strength and on solidification rate.

Die soldering is most strongly influenced by metal chemistry, but die condition and other process parameters are also important.

The most commonly used castability ratings were developed by consensus estimates based on practical experience. Castability ratings from A to F or from 1 to 10 imply excellent to poor casting

characteristics, respectively. Castability and other fabricating and finishing ratings are summarized in Table 8.1 in Chapter 8.

The casting alloys used in the greatest volumes contain silicon in excess of that of most wrought alloys. Solidification results in shaped casting are improved by fluidity, elevated-temperature resistance to cracking, and feeding characteristics that sufficient amounts of silicon impart.

The optimal concentration of silicon depends in part on the casting process. Processes characterized by higher heat flux use alloys with higher silicon contents since fluidity is improved. Feeding, the compensation for internal shrinkage, also varies as a result of gradients in the solidification zone that are process controlled. In general, castability, is associated with alloys of reduced solidification range.

There are nevertheless many common foundry alloys that do not rely on silicon for casting performance.

The recyclability of aluminum is a principal material advantage, and a number of casting alloys have been developed specifically for production from remelted scrap. These “secondary” compositions specify broader impurity ranges and include additional elements as impurities to reflect variations in raw materials. By contrast, primary alloys that are produced from smelted aluminum, metallurgical metals, and master alloys display more restrictive and more limited, element-specific impurity limits.

### 2.2 Specifications

Aluminum castings are the subject of numerous specifications and standards. Within the United States, alloy chemistry and thermal practices are registered with the Aluminum Association (see Section 2.3.1 of this chapter). Procurement specifications and standards are developed and maintained by, among others, ASTM and Military and Federal agencies. Procedural methods and standards are often referenced. These pertain to radiographic and penetrant inspection, test procedures for determination of chemical, mechanical, and physical properties, and other required procedures. In many cases, specifications are written for specific parts or classes of parts by the purchaser. All specifications are subject to negotiation and exceptions to be agreed upon by the casting producer and the customer as part of the purchasing process.

Specifications for aluminum alloy chemistries include the effects of major, minor, and impurity elements:

## 8 / Aluminum Alloy Castings: Properties, Processes, and Applications

- *Major alloying elements* define the ranges of elements that control castability and property development.
- *Minor alloying elements* control solidification behavior, modify eutectic structure, refine primary phases, refine grain size and form, promote or suppress phase formation, and reduce oxidation.
- *Impurity elements* influence castability and the form of insoluble phases that at times limit or promote desired properties.

Preferred major, minor, and impurity element concentrations and relationships may not be defined by alloy specifications. Optimal results are not implied by nominal chemistries. The addition of structure-controlling elements or combinations of elements can be contained within chemistry limits when not otherwise specified under “Other Elements Each.”

Stoichiometric ratios for favored phase formation can be specified, but also may not be controlled or defined.

Concentration limits allow biasing of composition for castability and property development. For maximum strength, the concentration of elements that form hardening phases can be maximized. Improved ductility results from finer structures, restricting insoluble-element concentrations, and by controlling the concentrations of impurities in ratios that favor the formation of the least detrimental intermetallic constituents. Composition biasing can be specified in ingot procurement or can result from alloying adjustments in the foundry.

### 2.3 Alloy Designations

Designation systems and alloy nomenclature for aluminum casting alloys are not internationally standardized. Many nations have developed and published their own standards. Individual firms have also promoted alloys by proprietary designations. In North America, the most commonly used system is that developed and maintained by the Aluminum Association. General procurement specifications issued through government agencies and technical associations and societies typically reference this nomenclature.

#### 2.3.1 The Aluminum Association (AA) Casting Alloy Designation System

The most widely used casting alloy designation system in the United States is the Aluminum Association (AA) alloy and temper systems (Ref 1), which are described below. Regrettably, the AA system is not universally used, and some of its earlier modifications are still widely quoted. Therefore, subsequent sections discuss the earlier variations as well as other rather widely used designations.

In the AA alloy designation, there are four numeric digits, with a period between the third and fourth. The meanings of the four digits are:

- *First digit:* Principal alloying constituent(s)
- *Second and third digits:* Specific alloy designation (number has no significance but is unique)
- *Fourth digit:* Casting (0) or ingot (1, 2) designation

Variations in the composition limits that are too small to require a change in numeric designation are indicated by a preceding letter (A, B, C, etc). The first version of an alloy, say 356.0, contains no letter prefix; the first variation has an A, e.g., A356.0, the second a B, for example, B356.0, and so forth.

The first digit defines the major alloying constituent or constituents, with the following categories being defined:

- 1xx.x, pure aluminum (99.00% or greater)
- 2xx.x, aluminum-copper alloys
- 3xx.x, aluminum-silicon + copper and/or magnesium
- 4xx.x, aluminum-silicon
- 5xx.x, aluminum-magnesium
- 7xx.x, aluminum-zinc
- 8xx.x, aluminum-tin
- 9xx.x, aluminum + other elements
- 6xx.x, unused series

In designations of the 1xx.x type, the second and third digits indicate minimum aluminum content (99.00% or greater); these digits are the same as the two to the right of the decimal point in the minimum aluminum percentage expressed to the nearest 0.01%. For example, alloy 170.0 contains a minimum of 99.70% Al.

In 2xx.x through 8xx.x designations for aluminum alloys, the second and third digits have no numerical significance, but only arbitrarily identify individual alloys in the group.

In all casting alloy designations, the fourth digit, that to the right of the decimal point, indicates product form:

- 0 denotes castings
- 1 denotes standard ingot
- 2 denotes ingot having composition ranges narrower than but within those of standard ingot

Designations in the form xxx.1 and xxx.2 include the composition of specific alloys in remelt ingot form suitable for foundry use. Designations in the form xxx.0 in all cases define composition limits applicable to castings. Further variations in specified compositions are denoted by prefix letters used primarily to define differences in impurity limits. Accordingly, one of the most common gravity cast alloys, 356, has variations A356, B356, and C356; each of these alloys has identical major alloy contents, but has decreasing specification limits applicable to impurities, especially iron content.

Alloying-element and impurity limits for ingot are usually the same as those for castings of the same alloy. When the ingot is remelted, iron and silicon contents tend to increase and magnesium content decreases. For these reasons, ingot chemistry for some alloys may be somewhat different from those specified for castings.

Despite the broad acceptance of the AA casting alloy designation system, including recognition by the American National Standards Institute (ANSI), it remains relatively common to see the alloys listed with only the first three digits of the alloy designation, for example, for 356.0, one may see simply 356 (see Section 2.3.3 in this chapter). Technically, this is obsolete usage of the designation system, and for cast components the “.0” should always be utilized.

The nominal compositions and composition limits of aluminum alloys in commercial use today are presented in Table 2.1.

### 2.3.2 Aluminum Association Casting Temper Designation System

The Aluminum Association Casting Temper Designation System (Ref 1) uses letters and numbers to indicate the major types of thermal treatments applicable to engineered castings:

- F, as-cast
- O, annealed
- T4, solution treated and aged
- T5, precipitation hardened
- T6, solution heat treated, quenched, and precipitation hardened
- T7, solution heat treated, quenched, and overaged

Temper designation is presented immediately following the alloy designation. Thus, for a 356.0 alloy casting that has been solution heat treated, quenched, and artificially aged, the full alloy and temper designation would be shown as 356.0-T6. Examples of registered temper variations are A357.0-T61, 242.0-T571, and 355.0-T71.

Other variations of temper designations are permitted by the Aluminum Association Temper Designation System (Ref 1), the most common being the use of “P” added to a standard temper designation (e.g., T6P) indicating a producer variation of the standard processing treatment. There is further discussion of temper designations in Chapter 7, “Heat Treatment of Aluminum Castings.”

### 2.3.3 Evolution of Designation System; Cross-Reference to Older Designations

As noted previously, over the years there have been several evolutionary steps in the development of the Aluminum Association casting alloy designation system, with the result that it is not uncommon to find variations of the current designations appearing on drawings and in publications from not too many years ago, and in some cases even in current publications. To assist in dealing with such variations, Table 2.2 illustrates a number of the variations in casting alloy designations over the past 50 years.

The overall most common variation is clearly the omission of the decimal point and the fourth digit, always a .0 for a foundry product. While inconsistent with current Aluminum Association standards, this variation is not usually a problem resulting in confusion, as for example it is relatively clear that an alloy designated 354 may safely be assumed to be 354.0 by today’s standard system.

While the most common variation is the omission of the decimal point and the fourth digit in the designation, there are two other types of variations reflected in Table 2.2 that are also seen frequently and can be more confusing. One variation is simply a proprietary designation that has become rather widely known in the past, for example, Hiduminium, Frontier 40E, Precedent 71, and Almag 35. These designations originated before the alloy compositions were registered with the Aluminum Association and had no

formal basis. They cause confusion because there is no obvious link to the current system if one does not have a conversion guide such as Table 2.2.

The other fairly often seen variation is the result of the significant revision of the Aluminum Association system in around 1990, when the guidelines for registering the alloys including copper and magnesium were changed. The result was that some alloys shifted classification; for example, alloy 195.0 became 295.0 and alloy 214.0 became 514.0.

### 2.3.4 The UNS Alloy Designation System

Another rather widely known alloy classification system is the Unified Numbering System (UNS) (Ref 2). The UNS system has the advantage of covering all metallic alloy systems.

For aluminum alloys, as illustrated in Table 2.2, this system is essentially an adaptation of the Aluminum Association alloy designation system to fit the UNS format. UNS numbers are obtained by taking the three digits to the left of the decimal point in the Aluminum Association system and adding A9 (meaning aluminum alloys) and a digit reflecting the letter prefix to the alloy designation. For alloys with no letter prefix, the next numeric digit after A9 is a 0; for those with A, the next digit is 1, for B, it is 2, and so forth.

Thus, in the UNS system, 356.0 becomes A90356, A356.0 becomes A91356, C356.0 becomes A93356; and so forth.

The UNS system is not as widely used for aluminum alloys as for certain other classes of alloys. An example would be copper alloys, for which the UNS designations have been selected as the U.S. standards.

### 2.3.5 International Casting Alloy Designations

Unlike the case for wrought aluminum alloys, there is no international accord on casting alloy designations, and other systems are rather universally used overseas (Ref 3). Most systems employ some system based on identifying the major alloying elements, but regrettably there are many variations of these.

One of the mostly widely used international systems is the Euronorm designation, and so, where applicable, designations of that type have been included in Table 2.2. There are no comparable Euronorm designations for about half of the alloys registered in the United States, nor is there any simple guide to generate them.

### 2.3.6 Nomenclature System for Aluminum Metal-Matrix Composites

Aluminum casting alloys are now regularly used as the matrix material in metal-matrix composites (MMC). The Aluminum Association, Inc, and ANSI H35.5 (Ref 4) have published a standard nomenclature system for such composites that builds on the standard casting alloy designation system as outlined below. Although this standard nomenclature has been established, some MMC suppliers have preferred their own designations. One reason is that matrix alloys may not coincide exactly with Aluminum Association ranges.



## 10 / Aluminum Alloy Castings: Properties, Processes, and Applications

**Table 2.1 Nominal composition and composition limits of aluminum alloy castings**

Based on industry handbooks, notably *Aluminum Association Standards for Sand and Permanent Mold Castings*, and the *Aluminum Association Registration Sheets for Alloys in the Form of Castings and Ingot*

| Alloy     | Type(a)   | Composition, wt% |         |          |           |           |           |          |         |           |      | Others  |          |     |
|-----------|-----------|------------------|---------|----------|-----------|-----------|-----------|----------|---------|-----------|------|---------|----------|-----|
|           |           | Si               | Fe      | Cu       | Mn        | Mg        | Cr        | Ni       | Zn      | Ti        | Sn   | Each(b) | Total(b) | Al  |
|           |           |                  |         |          |           |           |           |          |         |           |      |         |          |     |
| 100.1     | Nominal   | ...              | 0.7     | ...      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 0.15             | 0.6–0.8 | 0.10     | (c)       | ...       | (c)       | ...      | 0.05    | (c)       | ...  | 0.03    | 0.10     | bal |
| 150.1     | Nominal   | ...              | ...     | ...      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | (d)              | (d)     | 0.05     | (c)       | ...       | (c)       | ...      | 0.05    | (c)       | ...  | 0.03    | 0.10     | bal |
| 170.1     | Nominal   | ...              | ...     | ...      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | (e)              | (e)     | ...      | (c)       | ...       | (c)       | ...      | 0.05    | (c)       | ...  | 0.03    | 0.10     | bal |
| 201.0(f)  | Nominal   | ...              | ...     | ...      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 0.10             | 0.15    | 4.0–5.2  | 0.20–0.50 | 0.15–0.55 | ...       | ...      | ...     | 0.15–0.35 | ...  | 0.05    | 0.10     | bal |
| 203.0     | Nominal   | ...              | ...     | 5.0      | 0.25      | ...       | ...       | 1.5      | ...     | 0.20      | ...  | ...     | ...      | ... |
|           | Limits(g) | 0.30             | 0.50    | 4.5–5.5  | 0.20–0.30 | 0.10      | ...       | 1.3–1.7  | 0.10    | 0.15–0.25 | ...  | 0.05    | 0.20     | bal |
| 204.0     | Nominal   | ...              | ...     | ...      | ...       | 0.25      | ...       | ...      | ...     | 0.22      | ...  | ...     | ...      | ... |
|           | Limits    | 0.20             | 0.35    | 4.2–5.0  | 0.10      | 0.15      | ...       | 0.05     | 0.10    | 0.15–0.30 | 0.05 | 0.05    | 0.15     | bal |
| A206.0    | Nominal   | ...              | ...     | 4.6      | 0.35      | 0.25      | ...       | ...      | ...     | 0.22      | ...  | ...     | ...      | ... |
|           | Limits    | 0.05             | 0.10    | 4.2–5.0  | 0.20–0.50 | 0.15–0.35 | ...       | 0.05     | 0.10    | 0.15–0.30 | 0.05 | 0.05    | 0.15     | bal |
| 208.0(h)  | Nominal   | 3.0              | ...     | 4.0      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 2.5–3.5          | 1.2     | 3.5–4.5  | 0.50      | 0.10      | ...       | 0.35     | 1.0     | 0.25      | ...  | ...     | 0.50     | bal |
| 222.0(h)  | Nominal   | ...              | ...     | 10.0     | ...       | 0.25      | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 2.0              | 1.5     | 9.2–10.7 | 0.50      | 0.15–0.35 | ...       | 0.50     | 0.8     | 0.25      | ...  | ...     | 0.35     | bal |
| 224.0(h)  | Nominal   | ...              | ...     | 5.0      | 0.35      | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits(i) | 0.06             | 0.10    | 4.5–5.5  | 0.20–0.50 | ...       | ...       | ...      | ...     | 0.35      | ...  | 0.03    | 0.10     | bal |
| 240.0     | Nominal   | ...              | ...     | 8.0      | 0.5       | 6.0       | ...       | 0.5      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 0.50             | 0.50    | 7.0–9.0  | 0.30–0.7  | 5.5–6.5   | ...       | 0.30–0.7 | 0.10    | 0.20      | ...  | 0.05    | 0.15     | bal |
| 242.0     | Nominal   | ...              | ...     | 4.0      | ...       | 1.5       | ...       | 2.0      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 0.7              | 1.0     | 3.5–4.5  | 0.35      | 1.2–1.8   | 0.25      | 1.7–2.3  | 0.35    | 0.25      | ...  | 0.05    | 0.15     | bal |
| A242.0    | Nominal   | ...              | ...     | 4.1      | ...       | 1.4       | 0.20      | 2.0      | ...     | 0.14      | ...  | ...     | ...      | ... |
|           | Limits    | 0.6              | 0.8     | 3.7–4.5  | 0.10      | 1.2–1.7   | 0.15–0.25 | 1.8–2.3  | 0.10    | 0.07–0.20 | ...  | 0.05    | 0.15     | bal |
| 249.0(h)  | Nominal   | ...              | ...     | 4.2      | 0.38      | 0.38      | ...       | ...      | 3.0     | 0.18      | ...  | ...     | ...      | ... |
|           | Limits    | 0.05             | 0.10    | 3.8–4.6  | 0.25–0.50 | 0.25–0.50 | ...       | ...      | 2.5–3.5 | 0.02–0.35 | ...  | 0.03    | 0.10     | bal |
| 295.0     | Nominal   | 1.1              | ...     | 4.5      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 0.7–1.5          | 1.0     | 4.0–5.0  | 0.35      | 0.03      | ...       | ...      | 0.35    | 0.25      | ...  | 0.05    | 0.15     | bal |
| 308.0     | Nominal   | 5.5              | ...     | 4.5      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 5.0–6.0          | 1.0     | 4.0–5.0  | 0.50      | 0.10      | ...       | ...      | 1.0     | 0.25      | ...  | ...     | 0.50     | bal |
| 319.0     | Nominal   | 6.0              | ...     | 3.5      | ...       | ...       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 5.5–6.5          | 1.0     | 3.0–4.0  | 0.50      | 0.10      | ...       | 0.35     | 1.0     | 0.25      | ...  | ...     | 0.50     | bal |
| 328.0(h)  | Nominal   | 8.0              | ...     | 1.5      | 0.40      | 0.40      | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 7.5–8.5          | 1.0     | 1.0–2.0  | 0.20–0.6  | 0.20–0.6  | 0.35      | 0.25     | 1.5     | 0.25      | ...  | ...     | 0.50     | bal |
| 332.0     | Nominal   | 9.5              | ...     | 3.0      | ...       | 1.0       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 8.5–10.5         | 1.2     | 2.0–4.0  | 0.50      | 0.50–1.5  | ...       | 0.50     | 1.0     | 0.25      | ...  | ...     | 0.50     | bal |
| 333.0     | Nominal   | 9.0              | ...     | 3.5      | ...       | 0.28      | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 8.0–10.0         | 1.0     | 3.0–4.0  | 0.50      | 0.05–0.50 | ...       | 0.50     | 1.0     | 0.25      | ...  | ...     | 0.50     | bal |
| 336.0     | Nominal   | 12.0             | ...     | 1.0      | ...       | 1.0       | ...       | 2.5      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 11.0–13.0        | 1.2     | 0.50–1.5 | 0.35      | 0.7–1.3   | ...       | 2.0–3.0  | 0.35    | 0.25      | ...  | 0.05    | ...      | bal |
| 354.0     | Nominal   | 9.0              | ...     | 1.8      | ...       | 0.5       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 8.6–9.4          | 0.20    | 1.6–2.0  | 0.10      | 0.40–0.6  | ...       | ...      | 0.10    | 0.20      | ...  | 0.05    | 0.15     | bal |
| 355.0     | Nominal   | 5.0              | ...     | 1.25     | ...       | 0.5       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 4.5–5.5          | 0.6     | 1.0–1.5  | 0.50      | 0.40–0.6  | 0.25      | ...      | 0.35    | 0.25      | ...  | 0.05    | 0.15     | bal |
| C355.0    | Nominal   | 5.0              | ...     | 1.25     | ...       | 0.5       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 4.5–5.5          | 0.20    | 1.0–1.5  | 0.10      | 0.40–0.6  | ...       | ...      | 0.10    | 0.20      | ...  | 0.05    | 0.15     | bal |
| 356.0     | Nominal   | 7.0              | ...     | ...      | ...       | 0.32      | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 6.5–7.5          | 0.6     | 0.25     | 0.35      | 0.20–0.45 | ...       | ...      | 0.35    | 0.25      | ...  | 0.05    | 0.15     | bal |
| A356.0    | Nominal   | 7.0              | ...     | ...      | ...       | 0.35      | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 6.5–7.5          | 0.20    | 0.20     | 0.10      | 0.25–0.45 | ...       | ...      | 0.10    | 0.20      | ...  | 0.05    | 0.15     | bal |
| 357.0     | Nominal   | 7.0              | ...     | ...      | ...       | 0.52      | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 6.5–7.5          | 0.15    | 0.05     | 0.03      | 0.45–0.6  | ...       | ...      | 0.05    | 0.20      | ...  | 0.05    | 0.15     | bal |
| A357.0(j) | Nominal   | 7.0              | ...     | ...      | ...       | 0.55      | ...       | ...      | ...     | 0.12      | ...  | ...     | ...      | ... |
|           | Limits    | 6.5–7.5          | 0.20    | 0.20     | 0.10      | 0.40–0.7  | ...       | ...      | 0.10    | 0.04–0.20 | ...  | 0.05    | 0.15     | bal |
| D357.0(j) | Nominal   | 7.0              | ...     | ...      | ...       | 0.58      | ...       | ...      | ...     | 0.15      | ...  | ...     | ...      | ... |
|           | Limits    | 6.5–7.5          | 0.20    | ...      | 0.10      | 0.55–0.6  | ...       | ...      | ...     | 0.10–0.20 | ...  | 0.05    | 0.15     | bal |
| 359.0     | Nominal   | 9.0              | ...     | ...      | ...       | 0.6       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 8.5–9.5          | 0.20    | 0.20     | 0.10      | 0.50–0.7  | ...       | ...      | 0.10    | 0.20      | ...  | 0.05    | 0.15     | bal |
| 360.0     | Nominal   | 9.5              | ...     | ...      | ...       | 0.5       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 9.0–10.0         | 2.0     | 0.6      | 0.35      | 0.40–0.6  | ...       | 0.50     | 0.50    | ...       | 0.15 | ...     | 0.25     | bal |
| A360.0    | Nominal   | 9.5              | ...     | ...      | ...       | 0.5       | ...       | ...      | ...     | ...       | ...  | ...     | ...      | ... |
|           | Limits    | 9.0–10.0         | 1.3     | 0.6      | 0.35      | 0.40–0.6  | ...       | 0.50     | 0.50    | ...       | 0.15 | ...     | 0.25     | bal |

(continued)

(a) Both nominal compositions and composition limits are shown. Nominal values are midrange of limits for elements for which a composition range is specified. Limits are maximum unless a range is shown. (b) Maximum for “each” and “total” of elements not shown and present at 0.010% or more each, when expressed to the second decimal. (c) Ingot; 0.025% max Mn + Cr + Ti + V. (d) Ingot; 2.0 min Fe/Si ratio. (e) Ingot; 1.5 min Fe/Si ratio. (f) Also contains 0.40–1.0% (0.7% nominal) Ag. (g) Also contains 0.20–0.30% Sb (0.25% nominal), 0.20–0.30% Co (0.25% nominal), and 0.10–0.30% Zr. Ti + Zr contents = 0.50% max. (h) Alloy has been designated “Inactive” by the Aluminum Association, but still occurs in some publications. (i) Also contains 0.05–0.15 V and 0.10–0.25 Zr. (j) Also contains 0.04–0.07% (0.055% nominal) Be. (k) Also contains 0.03–0.015 (0.010% nominal) Sr and a maximum 0.001% P. (l) If iron exceeds 0.45%, manganese content shall not be less than one-half iron content. (m) Also contains 0.0003–0.007% (0.005% nominal) Be and 0.005% maximum B.

Table 2.1 (continued)

| Alloy    | Type(a)   | Composition, wt% |         |           |           |           |           |          |         |           |         | Others  |          | Al  |
|----------|-----------|------------------|---------|-----------|-----------|-----------|-----------|----------|---------|-----------|---------|---------|----------|-----|
|          |           | Si               | Fe      | Cu        | Mn        | Mg        | Cr        | Ni       | Zn      | Ti        | Sn      | Each(b) | Total(b) |     |
| 365.0    | Nominal   | ...              | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits(k) | 9.5–11.5         | 0.15    | 0.03      | 0.50–0.8  | 0.10–0.50 | ...       | ...      | 0.07    | 0.04–0.15 | 0.03    | 0.03    | 0.10     | bal |
| 380.0    | Nominal   | 8.5              | ...     | 3.5       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 7.5–9.5          | 2.0     | 3.0–4.0   | 0.50      | 0.10      | ...       | 0.50     | 3.0     | ...       | 0.35    | ...     | 0.50     | bal |
| A380.0   | Nominal   | 8.5              | ...     | 3.5       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 7.5–9.5          | 1.3     | 3.0–4.0   | 0.50      | 0.10      | ...       | 0.50     | 3.0     | ...       | 0.35    | ...     | 0.50     | bal |
| 383.0    | Nominal   | 10.5             | ...     | 2.5       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 9.5–11.5         | 1.3     | 2.0–3.0   | 0.50      | 0.10      | ...       | 0.30     | 3.0     | ...       | 0.15    | ...     | 0.50     | bal |
| 384.0    | Nominal   | 11.2             | ...     | 3.8       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 10.5–12.0        | 1.3     | 3.0–4.5   | 0.50      | 0.10      | ...       | 0.50     | 3.0     | ...       | 0.35    | ...     | 0.50     | bal |
| B390.0   | Nominal   | 17.0             | ...     | 4.5       | ...       | 0.55      | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 16.0–18.0        | 1.3     | 4.0–5.0   | 0.50      | 0.45–0.65 | ...       | 0.10     | 1.5     | 0.20      | ...     | 0.10    | 0.20     | bal |
| 391.0    | Nominal   | 19.0             | ...     | ...       | ...       | 0.58      | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 18.0–20.0        | 1.2     | 0.20      | 0.30      | 0.45–0.7  | ...       | ...      | 0.10    | 0.20      | ...     | 0.10    | 0.20     | bal |
| A391.0   | Nominal   | 19.0             | ...     | ...       | ...       | 0.58      | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits(l) | 18.0–20.0        | 0.6     | 0.20      | 0.30      | 0.45–0.7  | ...       | ...      | 0.10    | 0.20      | ...     | 0.10    | 0.20     | bal |
| B391.0   | Nominal   | 19.0             | ...     | ...       | ...       | 0.58      | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 18.0–20.0        | 0.15    | 0.20      | 0.30      | 0.45–0.7  | ...       | ...      | 0.10    | 0.20      | ...     | 0.10    | 0.20     | bal |
| 413.0    | Nominal   | 12.0             | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 11.0–13.0        | 2.0     | 1.0       | 0.35      | 0.10      | ...       | 0.50     | 0.50    | ...       | 0.15    | ...     | 0.25     | bal |
| A413.0   | Nominal   | 12.0             | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 11.0–13.0        | 1.3     | 1.0       | 0.35      | 0.10      | ...       | 0.50     | 0.50    | ...       | 0.15    | ...     | 0.25     | bal |
| 443.0    | Nominal   | 5.2              | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 4.5–6.0          | 0.8     | 0.6       | 0.50      | 0.05      | 0.25      | ...      | 0.50    | 0.25      | ...     | ...     | 0.35     | bal |
| B443.0   | Nominal   | 5.2              | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 4.5–6.0          | 0.8     | 0.15      | 0.35      | 0.05      | ...       | ...      | 0.35    | 0.25      | ...     | 0.05    | 0.15     | bal |
| C443.0   | Nominal   | 5.2              | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 4.5–6.0          | 2.0     | 0.6       | 0.35      | 0.10      | ...       | 0.50     | 0.50    | ...       | 0.15    | ...     | 0.25     | bal |
| A444.0   | Nominal   | 7.0              | ...     | ...       | ...       | ...       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 6.5–7.5          | 0.20    | 0.10      | 0.10      | 0.05      | ...       | ...      | 0.10    | 0.20      | ...     | 0.05    | 0.15     | bal |
| 512.0    | Nominal   | 1.8              | ...     | ...       | ...       | 4.0       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 1.4–2.2          | 0.6     | 0.35      | 0.8       | 3.5–4.5   | 0.25      | ...      | 0.35    | 0.25      | ...     | 0.05    | 0.15     | bal |
| 513.0    | Nominal   | ...              | ...     | ...       | ...       | 4.0       | ...       | ...      | 1.8     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.30             | 0.40    | 0.10      | 0.30      | 3.5–4.5   | ...       | ...      | 1.4–2.2 | 0.20      | ...     | 0.05    | 0.15     | bal |
| 514.0    | Nominal   | ...              | ...     | ...       | ...       | 4.0       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.35             | 0.50    | 0.15      | 0.35      | 3.5–4.5   | ...       | ...      | 0.15    | 0.25      | ...     | 0.05    | 0.15     | bal |
| 518.0    | Nominal   | ...              | ...     | ...       | ...       | 8.0       | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.35             | 1.8     | 0.25      | 0.35      | 7.5–8.5   | ...       | 0.15     | 0.15    | ...       | 0.15    | ...     | 0.25     | bal |
| 520.0    | Nominal   | ...              | ...     | ...       | ...       | 10.0      | ...       | ...      | ...     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.25             | 0.30    | 0.25      | 0.15      | 9.5–10.6  | ...       | ...      | 0.15    | 0.25      | ...     | 0.05    | 0.15     | bal |
| 535.0(m) | Nominal   | ...              | ...     | ...       | 0.18      | 6.8       | ...       | ...      | ...     | 0.18      | ...     | ...     | ...      | ... |
|          | Limits    | 0.15             | 0.15    | 0.05      | 0.10–0.25 | 6.2–7.5   | ...       | ...      | ...     | 0.10–0.25 | ...     | 0.05    | 0.15     | bal |
| 705.0    | Nominal   | ...              | ...     | ...       | 0.5       | 1.6       | 0.30      | ...      | 3.0     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.20             | 0.8     | 0.20      | 0.40–0.6  | 1.4–1.8   | 0.20–0.40 | ...      | 2.7–3.3 | 0.25      | ...     | 0.05    | 0.15     | bal |
| 707.0    | Nominal   | ...              | ...     | ...       | 0.50      | 2.1       | 0.30      | ...      | 4.2     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.20             | 0.8     | 0.20      | 0.40–0.6  | 1.8–2.4   | 0.20–0.40 | ...      | 4.0–4.5 | 0.25      | ...     | 0.05    | 0.15     | bal |
| 710.0    | Nominal   | ...              | ...     | 0.50      | ...       | 0.7       | ...       | ...      | 6.5     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.15             | 0.50    | 0.35–0.65 | 0.05      | 0.6–0.8   | ...       | ...      | 6.0–7.0 | 0.25      | ...     | 0.05    | 0.15     | bal |
| 711.0    | Nominal   | ...              | 1.0     | 0.50      | ...       | 0.35      | ...       | ...      | 6.5     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.30             | 0.7–1.4 | 0.35–0.65 | 0.05      | 0.25–0.45 | ...       | ...      | 6.0–7.0 | 0.20      | ...     | 0.05    | 0.15     | bal |
| 712.0    | Nominal   | ...              | ...     | ...       | ...       | 0.58      | 0.50      | ...      | 6.0     | 0.20      | ...     | ...     | ...      | ... |
|          | Limits    | 0.30             | 0.50    | 0.25      | 0.10      | 0.50–0.65 | 0.40–0.6  | ...      | 5.0–6.5 | 0.15–0.25 | ...     | 0.05    | 0.20     | bal |
| 713.0    | Nominal   | ...              | ...     | 0.7       | ...       | 0.35      | ...       | ...      | 7.5     | ...       | ...     | ...     | ...      | ... |
|          | Limits    | 0.25             | 1.1     | 0.40–1.0  | 0.6       | 0.20–0.50 | 0.35      | 0.15     | 7.0–8.0 | 0.25      | ...     | 0.10    | 0.25     | bal |
| 771.0    | Nominal   | ...              | ...     | ...       | ...       | 0.9       | 0.40      | ...      | 7.0     | 0.15      | ...     | ...     | ...      | ... |
|          | Limits    | 0.15             | 0.15    | 0.10      | 0.10      | 0.8–1.0   | 0.06–0.20 | ...      | 6.5–7.5 | 0.10–0.20 | ...     | 0.05    | 0.15     | bal |
| 850.0    | Nominal   | ...              | ...     | 1.0       | ...       | ...       | ...       | 1.0      | ...     | ...       | 6.2     | ...     | ...      | ... |
|          | Limits    | 0.7              | 0.7     | 0.7–1.3   | 0.10      | 0.10      | ...       | 0.7–1.3  | ...     | 0.20      | 5.5–7.0 | ...     | 0.30     | bal |
| 851.0    | Nominal   | 2.5              | ...     | 1.0       | ...       | ...       | ...       | 0.50     | ...     | ...       | 6.2     | ...     | ...      | ... |
|          | Limits    | 2.0–3.0          | 0.7     | 0.7–1.3   | 0.10      | 0.10      | ...       | 0.30–0.7 | ...     | 0.20      | 5.5–7.0 | ...     | 0.30     | bal |
| 852.0    | Nominal   | ...              | ...     | 2.0       | ...       | 0.75      | ...       | 1.2      | ...     | ...       | 6.2     | ...     | ...      | ... |
|          | Limits    | 0.40             | 0.7     | 1.7–2.3   | 0.10      | 0.6–0.9   | ...       | 0.9–1.5  | ...     | 0.20      | 5.5–7.0 | ...     | 0.30     | bal |

(a) Both nominal compositions and composition limits are shown. Nominal values are midrange of limits for elements for which a composition range is specified. Limits are maximum unless a range is shown. (b) Maximum for “each” and “total” of elements not shown and present at 0.010% or more each, when expressed to the second decimal. (c) Ingot; 0.025% max Mn + Cr + Ti + V. (d) Ingot; 2.0 min Fe/Si ratio. (e) Ingot; 1.5 min Fe/Si ratio. (f) Also contains 0.40–1.0% (0.7% nominal) Ag. (g) Also contains 0.20–0.30% Sb (0.25% nominal), 0.20–0.30% Co (0.25% nominal), and 0.10–0.30% Zr, Ti + Zr contents = 0.50% max. (h) Alloy has been designated “Inactive” by the Aluminum Association, but still occurs in some publications. (i) Also contains 0.05–0.15 V and 0.10–0.25 Zr. (j) Also contains 0.04–0.07% (0.055% nominal) Be. (k) Also contains 0.03–0.015 (0.010% nominal) Sr and a maximum 0.001% P. (l) If iron exceeds 0.45%, manganese content shall not be less than one-half iron content. (m) Also contains 0.0003–0.007% (0.005% nominal) Be and 0.005% maximum B.



Table 2.2 Cross reference for older casting alloy designations and frequently used specifications

| Current Aluminum Association designation | Former Aluminum Association designation | Former proprietary company names | Unified Numbering System (UNS) designation | Former Federal specification designation | Former ASTM specification designation | Former SAE specification designation | Former military specification designation | Current ISO specification designation | Current Euronorm specification designation |
|------------------------------------------|-----------------------------------------|----------------------------------|--------------------------------------------|------------------------------------------|---------------------------------------|--------------------------------------|-------------------------------------------|---------------------------------------|--------------------------------------------|
| 150.0                                    | 150                                     | ...                              | A01500                                     | ...                                      | ...                                   | ...                                  | ...                                       | Al-99.5                               | ...                                        |
| 201.0                                    | 201                                     | K01                              | A02010                                     | ...                                      | CQ51A                                 | 382                                  | ...                                       | ...                                   | ...                                        |
| 203.0                                    | 203                                     | Hiduminium 350                   | A02030                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 204.0                                    | 204                                     | A-U5GT                           | A02040                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 208.0                                    | 108                                     | ...                              | A02080                                     | 108                                      | CS43A                                 | ...                                  | ...                                       | ...                                   | ...                                        |
| 213.0                                    | C113                                    | ...                              | A02130                                     | 113                                      | CS74A                                 | 33                                   | ...                                       | ...                                   | ...                                        |
| 222.0                                    | 122                                     | ...                              | A02130                                     | 122                                      | CG100A                                | 34                                   | ...                                       | Al-Cu10Si2Mg                          | ...                                        |
| 224.0                                    | 224                                     | ...                              | A02240                                     | 224                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 240.0                                    | A140, A240                              | ...                              | A02400                                     | 140                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 242.0                                    | 142                                     | ...                              | A02220                                     | 142                                      | CN42A                                 | 39                                   | 4222                                      | ...                                   | ...                                        |
| 249.0                                    | 149                                     | ...                              | A02490                                     | 149                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 295.0                                    | 195                                     | ...                              | A02950                                     | 195                                      | C4A                                   | 38                                   | 4231                                      | ...                                   | ...                                        |
| 296.0                                    | B295                                    | ...                              | A02960                                     | B195                                     | ...                                   | 380                                  | ...                                       | ...                                   | ...                                        |
| 308.0                                    | A108                                    | ...                              | A03080                                     | A108                                     | ...                                   | ...                                  | ...                                       | Al-Si6Cu4                             | 45000                                      |
| 319.0                                    | 319                                     | Allcast                          | A03190                                     | 319                                      | SC64D                                 | 326                                  | ...                                       | Al-Si5Cu3                             | 45200                                      |
| 328.0                                    | 328                                     | Red X-8                          | A03280                                     | ...                                      | SC82A                                 | 327                                  | ...                                       | ...                                   | ...                                        |
| 332.0                                    | F332                                    | ...                              | A03320                                     | F132                                     | SC103A                                | 332                                  | ...                                       | Al-Si9Cu3Mg                           | ...                                        |
| 333.0                                    | 333                                     | ...                              | A03330                                     | 333                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 336.0                                    | A332                                    | ...                              | A03360                                     | A132                                     | SN122A                                | 321                                  | ...                                       | Al-Si12Cu                             | 48000                                      |
| 354.0                                    | 354                                     | ...                              | A03540                                     | ...                                      | ...                                   | ...                                  | C354                                      | ...                                   | ...                                        |
| 355.0                                    | 355                                     | ...                              | A03550                                     | 355                                      | SC51A                                 | 322                                  | 4210                                      | Al-Si5Cu1Mg                           | 45300                                      |
| C355.0                                   | C355                                    | ...                              | A33550                                     | C355                                     | SC51B                                 | 355                                  | C355                                      | ...                                   | ...                                        |
| 356.0                                    | 356                                     | ...                              | A03560                                     | 356                                      | SG70A                                 | 323                                  | 356                                       | ...                                   | ...                                        |
| A356.0                                   | A356                                    | ...                              | A33560                                     | A356                                     | SG70B                                 | 336                                  | A356                                      | Al-Si7Mg                              | 42000                                      |
| 357.0                                    | 357                                     | ...                              | A03570                                     | 357                                      | ...                                   | ...                                  | 4241                                      | ...                                   | ...                                        |
| A357.0                                   | A357                                    | ...                              | A33570                                     | ...                                      | ...                                   | ...                                  | A357                                      | ...                                   | ...                                        |
| 358.0                                    | B358                                    | Tens-50                          | A03580                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 359.0                                    | 359                                     | ...                              | A03590                                     | ...                                      | ...                                   | ...                                  | 359                                       | ...                                   | ...                                        |
| 360.0                                    | 360                                     | ...                              | A03600                                     | ...                                      | SG100B                                | ...                                  | ...                                       | ...                                   | ...                                        |
| A360.0                                   | A360                                    | ...                              | A13600                                     | ...                                      | SG100A                                | 309                                  | ...                                       | Al-Si10Mg                             | 43100                                      |
| 365.0                                    | ...                                     | Silafont-36                      | A03650                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 380.0                                    | 380                                     | ...                              | A03800                                     | ...                                      | SC84B                                 | 308                                  | ...                                       | ...                                   | ...                                        |
| A380                                     | A380                                    | ...                              | A13800                                     | ...                                      | SC84A                                 | 306                                  | ...                                       | Al-Si8Cu3Fe                           | 46500                                      |
| 383.0                                    | 383                                     | ...                              | A03830                                     | ...                                      | SC102                                 | 383                                  | ...                                       | ...                                   | ...                                        |
| 384.0                                    | 384                                     | ...                              | A03840                                     | ...                                      | SC114A                                | 303                                  | ...                                       | Al-Si10Cu2Fe                          | 46100                                      |
| A384.0                                   | A384                                    | ...                              | A143840                                    | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 390.0                                    | 390                                     | ...                              | A03080                                     | ...                                      | SC174B                                | ...                                  | ...                                       | Al-Si17Cu4Mg                          | ...                                        |
| A390.0                                   | ...                                     | ...                              | A13900                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| B390.0                                   | ...                                     | ...                              | A23900                                     | ...                                      | SC174B                                | ...                                  | ...                                       | ...                                   | ...                                        |
| 391.0                                    | ...                                     | Mercosil                         | A03910                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| A391.0                                   | ...                                     | Mercosil                         | A13910                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| B391.0                                   | ...                                     | Mercosil                         | A23910                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 393.0                                    | 393                                     | Vanasil                          | A03930                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 413.0                                    | 13                                      | ...                              | A04130                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| A413.0                                   | A13                                     | ...                              | A14130                                     | ...                                      | ...                                   | 305                                  | ...                                       | Al-Si12Cu                             | 44100                                      |
| B443.0                                   | 43 (high purity)                        | ...                              | A24430                                     | 43                                       | S5A                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| C443.0                                   | 43                                      | ...                              | A34430                                     | 43                                       | S5C                                   | 304                                  | ...                                       | ...                                   | ...                                        |
| A444.0                                   | A344                                    | ...                              | A14440                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 511.0                                    | F514                                    | ...                              | A05110                                     | F214                                     | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 512.0                                    | B514                                    | ...                              | A25120                                     | B214                                     | GS42A                                 | ...                                  | ...                                       | ...                                   | ...                                        |
| 513.0                                    | A514                                    | ...                              | A05130                                     | A214                                     | GZ42A                                 | ...                                  | ...                                       | ...                                   | ...                                        |
| 514.0                                    | 214                                     | ...                              | A05140                                     | 214                                      | G4A                                   | 320                                  | ...                                       | Al-Mg5Si1                             | 51300                                      |
| 518.0                                    | 218                                     | ...                              | A05180                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 520.0                                    | 220                                     | ...                              | A05200                                     | 220                                      | G10A                                  | 324                                  | 4240                                      | ...                                   | ...                                        |
| 535.0                                    | 535                                     | Almag 35                         | A05350                                     | Almag 35                                 | GM70B                                 | ...                                  | 4238                                      | ...                                   | ...                                        |
| A535.0                                   | A218                                    | ...                              | A15350                                     | A218                                     | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 705.0                                    | 603                                     | Ternalloy 5                      | A07050                                     | Ternalloy 5                              | ZG32A                                 | 311                                  | ...                                       | ...                                   | ...                                        |
| 707.0                                    | 607                                     | Ternalloy 7                      | A07070                                     | Ternalloy 7                              | ZG42A                                 | 312                                  | ...                                       | ...                                   | ...                                        |
| 710.0                                    | A712                                    | ...                              | A07100                                     | A612                                     | ZG61B                                 | 313                                  | ...                                       | ...                                   | ...                                        |
| 711.0                                    | C712                                    | ...                              | A07110                                     | ...                                      | ZC60A                                 | 314                                  | ...                                       | ...                                   | ...                                        |
| 712.0                                    | D712                                    | Frontier 40E                     | A07120                                     | 40E                                      | ZG61A                                 | 310                                  | ...                                       | Al-Zn5Mg                              | 71000                                      |
| A712.0                                   | A712                                    | ...                              | A17120                                     | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| C712.0                                   | C612                                    | ...                              | ...                                        | ...                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 713.0                                    | 613                                     | Tenzaloy                         | A07130                                     | Tenzaloy                                 | ZC81A                                 | 315                                  | ...                                       | ...                                   | ...                                        |
| 771.0                                    | ...                                     | Precedent 71A                    | A07710                                     | Precedent 71A                            | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 772.0                                    | B771                                    | Precedent 71B                    | A07720                                     | Precedent 71B                            | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 850.0                                    | 750                                     | ...                              | A08500                                     | 750                                      | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 851.0                                    | A850                                    | ...                              | A08510                                     | A750                                     | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |
| 852.0                                    | B850                                    | ...                              | A08520                                     | B750                                     | ...                                   | ...                                  | ...                                       | ...                                   | ...                                        |

The designation system for aluminum metal-matrix composites consists of four parts:

- The matrix alloy designation employs the Aluminum Association alloy designation as described in Section 2.1 in this chapter. It is immediately followed by a slash that separates it from the rest of the composite designation.
- The composition of the reinforcement is shown immediately after the slash, using the appropriate chemical designation, with the exception that no subscripts or superscripts are used. Some common examples cited in the standard are: C for graphite, SiC for silicon carbide, and Al<sub>2</sub>O<sub>3</sub> for aluminum oxide (alumina). This reinforcement designation is also followed without space by a slash.
- The volume percent of the reinforcement is shown immediately after the second slash. It is always presented as two digits, for example, 05 for 5%, 10 for 10%, 20 for 20%, and so forth.
- Immediately following the percentage is a single lower-case letter for the type of reinforcement: c for cut or chopped fibers, filaments, or monofilaments; f for continuous fibers, filaments, or monofilaments; p for particles (particulate); and w for whiskers.

Some common illustrations of cast aluminum metal-matrix composite designations are:

- A356.0/Al<sub>2</sub>O<sub>3</sub>/05f: Alloy A356.0 reinforced with 5% aluminum filaments
- 360.0/C/20c: Alloy 360.0 reinforced with 20% chopped fibers
- 380.0/SiC/10p: Alloy 380.0 reinforcement 10% silicon carbide particulate

## 2.4 Composition Groupings

Although a large number of aluminum casting alloys have been developed, there are seven basic families:

- Aluminum-copper (2xx)
- Aluminum-silicon-copper (3xx)
- Aluminum-silicon (4xx)
- Aluminum-silicon-magnesium (3xx)
- Aluminum-magnesium (5xx)
- Aluminum-zinc-magnesium (7xx)
- Aluminum-tin (8xx)

### 2.4.1 Aluminum-Copper

Aluminum-copper alloys have been used extensively in cast and wrought form where strength and toughness are required. These alloys exhibit high strength and hardness at room and elevated temperatures.

The first significant aluminum casting alloys contained copper at concentrations up to 10%. With no understanding of heat treatment, these alloys displayed significantly improved strengths and hardnesses in the as-cast state.

Many alloys containing 4 to 5% Cu have been developed, usually with varying amounts of magnesium. Silver accelerates aging response and reduces the risk of stress corrosion. These heat treatable compositions represent the highest-strength capabilities of any commercial casting alloys. With controlled impurities, excellent ductilities are also achieved. The combination of tensile properties and ductility provide exceptional toughness.

Alloys of this type are susceptible to solidification cracking and to interdendritic shrinkage. Exacting foundry techniques are required to avoid these conditions. In permanent mold or other rigid mold casting methods, excellent grain refinement and selective chilling are essential.

Copper-containing aluminum alloys are less resistant to corrosion, and certain compositions and material conditions may be susceptible to stress corrosion.

Copper is typically the alloy basis for improved mechanical properties at elevated temperature, often with nickel additions.

### 2.4.2 Aluminum-Silicon-Copper

Among the most widely used aluminum casting alloys are those that contain silicon and copper. The amounts of both additions vary widely, so that copper predominates in some alloys and silicon in others. Copper contributes to strengthening and machinability, and silicon improves castability and reduces hot shortness. Alloys containing higher hypoeutectic concentrations of silicon are normally better suited for more complex castings and for permanent mold and die casting processes.

Aluminum-silicon-copper alloys with less than 5.6% Cu are heat treatable, but the more important alloys of this family are those also containing magnesium. Heat treatment response is enhanced, leading to a very attractive range of properties including premium-strength capabilities.

Many hypereutectic silicon alloys (12 to 30% Si) also contain copper. The primary silicon phase imparts excellent wear resistance, and copper contributes to matrix hardening and elevated-temperature strength.

### 2.4.3 Aluminum-Silicon

Binary aluminum-silicon alloys exhibit excellent fluidity, castability, and corrosion resistance. These alloys display low strength and poor machinability. Ductility, which can be exceptional, is a function of low impurity concentrations and microstructural features. The strength, ductility, and castability of hypoeutectic aluminum-silicon alloys can be further improved by modification of the aluminum-silicon eutectic. Modification is particularly advantageous in sand castings and can be effectively achieved through the controlled addition of sodium and/or strontium. Calcium is a weak eutectic modifier and a more lamellar eutectic can be achieved with antimony. Higher solidification rates also promote a finer unmodified eutectic microstructure.

Aluminum-silicon alloys exhibit low specific gravity and coefficients of thermal expansion.

In hypereutectic aluminum-silicon alloys, refinement of the proeutectic silicon phase by phosphorus additions is essential for casting and product performance.

#### 2.4.4 Aluminum-Silicon-Magnesium

The addition of magnesium to aluminum-silicon alloys forms the basis for an extremely important and useful family of compositions that combines outstanding casting characteristics with excellent properties after heat treatment. Corrosion resistance is also excellent, and a low level of thermal expansion is retained.

While not as strong as high-strength Al-Cu and Al-Si-Cu alloys, the mechanical properties of several Al-Si-Mg alloys provide mechanical properties in the premium-strength range. Beryllium additions improve strength and ductility by affecting the morphology and chemistry of the iron-containing intermetallic.

Eutectic modification remains important as a means of improving strength, substantially increasing elongation, and improving casting results.

#### 2.4.5 Aluminum-Magnesium

These are essentially single-phase binary alloys with moderate to high strength and toughness. Their most important characteristic is corrosion resistance, including exposure to seawater and marine atmospheres. This characteristic is also the basis for extensive use in food and beverage processing. Aluminum-magnesium alloys offer excellent weldability and are often used in architectural and other decorative applications. Aluminum-magnesium alloys have good machinability, weldability, and an attractive appearance whether as-cast, machined, polished, or anodized.

In comparison with aluminum-silicon alloys, all aluminum-magnesium alloys require more care in gating, larger risers, and greater control of temperature gradients.

Magnesium in aluminum alloys increases oxidation rates. In the molten state, magnesium losses can be significant and oxides of aluminum and magnesium can affect casting quality. Spinel of aluminum and magnesium oxides form with unprotected exposure at high molten metal temperatures. The potential for inclusions is especially important because many applications involve polishing and/or fine surface finishing.

Alloys containing >7.0% Mg are heat treatable, although thermal treatments are more typically used to stabilize properties that could otherwise change, in some compositions, over long periods of time.

#### 2.4.6 Aluminum-Zinc-Magnesium

Many alloys of this type naturally age, achieving full strength within 20 to 30 days at room temperature after casting. Solution heat treatment is not typically necessary for property development. Rapid solidification in these alloys can result in microsegregation of magnesium-zinc phases that reduces hardening potential. Conventional solution heat treatments can be used when adequate property development does not occur through natural aging.

Since high-temperature solution heat treatment and quench are not normally required, the cost of heat treatment, high residual stress levels and distortion are avoided.

Artificial aging treatments can be used to accelerate the hardening process, and annealing treatments accomplish the same purpose with improved dimensional and structural stability.

These alloys typically display moderate to good tensile properties in the as-cast condition. The melting temperatures of alloys of this group are high, an advantage in castings that are to be brazed.

Machinability and resistance to general corrosion is usually good. The chemistry of most alloys is controlled to minimize stress-corrosion susceptibility.

The castability of Al-Zn-Mg alloys is poor, and good foundry practices are required to minimize hot tearing and shrinkage defects.

#### 2.4.7 Aluminum-Tin

Tin is the major alloying element in compositions developed for bearing applications. It has also been employed with bismuth, lead, and cadmium at lower concentrations to provide free-machining properties. The 850-series alloys can often be substituted for 660 or similar bronzes. Their light weight minimizes loads in reciprocating applications, and heat dissipation improves bearing life.

Alloys containing 5.0 to 7.0% Sn are broadly used in bearings and bushings in which low friction, compressive strength, fatigue strength, and resistance to corrosion are important criteria. Additions of copper, nickel, and magnesium contribute to hardness and strength, and silicon is added to improve castability, reduce hot shortness, and increase compressive yield strength.

Most bearings are produced by the permanent mold process. Higher-solidification rates promote the finer, more uniform dispersion of tin. Larger, special-design, and low-volume bearings are nevertheless cast successfully in sand molds. Because most bearings are simple hollow or solid cylinders, the direct chill (DC) casting process has also been used for production.

Aluminum-tin alloys are unique among significant compositions. Aluminum and tin are essentially immiscible. Before and after solidification, tin is present in dispersed form. Mechanical agitation is required initially to achieve suspension of tin, and, because of density differences, gravity segregation may occur over time in the molten state.

Aluminum-tin alloys containing copper are conventionally precipitation hardened and may be fully heat treated. Because most bearings are cast in simple solid or hollow cylindrical shapes, parts may be plastically cold worked to improve compressive yield strength. Solidification and thermal stresses are also relieved by axial compression resulting in 4% permanent deformation.

### 2.5 Effects of Alloying Elements

#### 2.5.1 Antimony

At concentration levels equal to or greater than ~0.10%, antimony refines the aluminum-silicon eutectic. The effect is essentially that of modification, but a distinctly lamellar eutectic rather than a fine fibrous form results. The effectiveness of antimony in altering the eutectic structure depends on an absence of phosphorus and on an adequately rapid rate of solidification. Antimony also reacts with either sodium or strontium to form coarse intermetallics with adverse effects on castability and metallurgical structure.

Antimony is classified as a heavy metal with potential toxicity and hygiene implications, especially associated with stibine gas ( $\text{SbH}_3$ ) formation and the effects of human exposure to other antimony compounds.

### 2.5.2 Beryllium

Additions of a few parts per million beryllium can be effective in reducing oxidation losses and associated inclusions in magnesium-containing compositions.

At higher concentrations (>0.04%), beryllium affects the form and composition of iron-containing intermetallics, markedly improving strength and ductility. In addition to changing the morphology of the insoluble phase from script or plate to nodular form, beryllium changes its composition, rejecting magnesium from the Al-Fe-Si complex and thus permitting its full use for hardening purposes.

Beryllium-containing compounds are, however, known carcinogens that require specific precautions in melting, molten metal handling, gross handling, gross disposition, and welding.

### 2.5.3 Bismuth

Bismuth additions improve the machinability of cast aluminum alloys at concentrations greater than 0.1%.

### 2.5.4 Boron

Boron combines with other metals to form borides, such as  $\text{AlB}_2$  and  $\text{TiB}_2$ . Titanium boride forms stable nucleation sites that interact with active grain-refining phases such as  $\text{TiAl}_3$  for grain refinement.

Metallic borides reduce tool life in machining operations and form coarse or agglomerated inclusions with detrimental effects on mechanical properties and ductility. Borides also contribute to sludging, the precipitation of intermetallics from liquid solution in furnaces and troughing.

Boron treatment of aluminum-containing peritectic elements such as titanium, zirconium, and vanadium is practiced to improve purity and conductivity in electrical applications. Rotor alloys may specify boron to exceed titanium and vanadium contents to ensure either the complexing or precipitation of these elements for improved electrical performance.

### 2.5.5 Cadmium

In concentrations exceeding 0.1%, cadmium improves machinability. Precautions that acknowledge volatilization of cadmium at 1413 °F (767 °C) are essential.

### 2.5.6 Calcium

Calcium is a weak aluminum-silicon eutectic modifier. It increases hydrogen solubility and is often responsible for casting porosity at trace concentration levels. Calcium greater than approximately 0.005% also adversely affects ductility in aluminum-magnesium alloys.

### 2.5.7 Chromium

Additions of chromium are commonly made in low concentrations to room-temperature aging and thermally unstable compositions in which germination and grain growth are known to occur. Chromium typically forms the compound  $\text{CrAl}_7$ , which displays extremely limited solid-state solubility and is therefore useful in suppressing grain-growth tendencies. Sludge that contains iron, manganese, and chromium is sometimes encountered in die casting

compositions, but it is rarely encountered in gravity casting alloys. Chromium improves corrosion resistance in certain alloys and increases quench sensitivity at higher concentrations.

### 2.5.8 Copper

Copper substantially improves strength and hardness in the as-cast and heat treated conditions. Alloys containing 4 to 5.5% Cu respond most strongly to thermal treatment and display relatively improved casting properties. Copper generally reduces resistance to general corrosion and in specific compositions and material conditions increases stress-corrosion susceptibility. Conversely, low concentrations of copper in aluminum-zinc alloys inhibit stress corrosion.

Copper reduces hot tear resistance and increases the potential for interdendritic shrinkage.

### 2.5.9 Iron

Iron improves hot-tear resistance and decreases the tendency for die sticking or soldering in die casting. Increases in iron content are accompanied by substantially decreased ductility. Iron reacts to form a number of intermetallic phases, the most common of which are  $\text{FeAl}_3$ ,  $\text{FeMnAl}_6$ , and  $\alpha\text{AlFeSi}$ . These essentially insoluble phases are responsible for improvements in strength, especially at elevated temperature, but also the embrittlement of the microstructure. As the fraction of insoluble phases increases with increased iron content, casting considerations such as feeding characteristics are adversely affected. Iron participates in the formation of sludging phases with manganese, chromium, and other elements.

### 2.5.10 Lead

Lead is used at concentrations greater than 0.1% to improve machinability.

### 2.5.11 Magnesium

Magnesium is the basis for strength and hardness development in heat treated aluminum-silicon alloys and is commonly used in more complex aluminum-silicon alloys containing copper, nickel, and other elements for the same purpose. The hardening-phase  $\text{Mg}_2\text{Si}$  displays a useful solubility limit corresponding to approximately 0.70% Mg, beyond which either no further strengthening occurs or matrix softening takes place. Common high-strength aluminum-silicon compositions specify magnesium in the range of 0.40 to 0.070%.

Binary aluminum-magnesium alloys are widely used in applications requiring a bright surface finish, excellent response to chemical finishing, corrosion resistance, and attractive combinations of strength and ductility. Common compositions range from 4 to 10% Mg, and compositions containing more than 7% Mg are heat treatable. Instability and long-term room-temperature aging at higher magnesium concentrations can be avoided by heat treatment.

### 2.5.12 Manganese

Normally considered an impurity in casting compositions, manganese is controlled to low levels in most gravity cast compositions. Manganese is an important element in work-hardened



wrought alloys through which secondary foundry compositions may contain higher manganese levels. In the absence of work hardening, manganese offers no significant benefits in cast aluminum alloys. Some evidence exists, however, that a high-volume fraction of  $\text{MnAl}_6$  in alloys containing more than 0.5% Mn may beneficially influence internal soundness (Ref 5). Manganese can also be employed to alter response in chemical finishing and anodizing. Iron and manganese may be considered isomorphous, and alloy chemistry may reflect stoichiometries favoring the least detrimental insoluble Al-Fe-Mn phases.

### **2.5.13 Mercury**

Compositions containing mercury were developed as sacrificial anodes for cathodic protection systems, especially in marine environments. The use of these optimally electronegative alloys, which do not passivate in seawater, was severely restricted for environmental reasons.

### **2.5.14 Nickel**

Nickel is commonly used with copper to enhance elevated-temperature properties. It also reduces coefficient of thermal expansion.

### **2.5.15 Phosphorus**

As  $\text{AlP}_3$ , phosphorus nucleates and refines primary silicon-phase formation in hypereutectic aluminum-silicon alloys. At parts per million concentrations, phosphorus coarsens the eutectic structure in hypoeutectic aluminum-silicon alloys and diminishes the effectiveness of common eutectic modifiers, sodium and strontium.

### **2.5.16 Silicon**

The outstanding effect of silicon in aluminum alloys is the improvement of casting characteristics. Additions of silicon dramatically improve fluidity, hot tear resistance, and feeding characteristics. The most prominently used compositions in all aluminum casting processes are those in which silicon plays a major role. Commercial alloys span the hypoeutectic and hypereutectic ranges up to about 30% Si.

Increasing silicon content improves fluidity for filling thin walls and for reproducing more intricate designs and details. Aluminum-silicon alloys are typically more resistant to solidification cracking and display excellent castability and feeding characteristics.

Percent liquid in the solidification range is dictated by the initial composition and by the degree of nonequilibrium cooling. For higher-solidification-rate processes such as pressure die and permanent mold casting and for thinner sections in which more rapid solidification takes place, shrinkage porosity is strongly affected by the temperature at which mass feeding from liquid to partially solidified structures no longer occurs. Feeding to minimize shrinkage porosity improves as the volume fraction solidified is increased at the temperature at which mass feeding ceases. For this reason, the most desirable silicon content of aluminum-silicon alloys corresponds to the characteristic process solidification rate. For slow cooling rate processes such as plaster, investment, and sand, the preferred range is 5 to 7%, for permanent mold 7 to 9%, and for die casting 8 to 12%. The bases for these recommendations are the

relationship between cooling rate and fluidity and the effect of percentage of eutectic on feeding as solidification progresses.

Silicon combines with magnesium to form  $\text{Mg}_2\text{Si}$  in heat treatable alloys. It combines with iron and other elements to form complex insoluble phases.

Silicon also reduces specific gravity and coefficient of thermal expansion.

### **2.5.17 Silver**

Used in only a limited range of aluminum-copper premium-strength alloys at concentrations of 0.5 to 1.0%. Silver contributes to precipitation hardening and stress-corrosion resistance.

### **2.5.18 Sodium**

Sodium modifies the aluminum-silicon eutectic. In the absence of phosphorus, recovered concentrations of 0.01% are effective. Sodium interacts with phosphorus to reduce its effectiveness in modifying the eutectic and that of phosphorus in the refinement of the primary silicon phase.

Sodium at less than 0.005% is embrittling in aluminum-magnesium alloys.

Sodium is rapidly lost in molten aluminum through its high vapor pressure so that modifying effects are transient. Periodic additions are required to maintain modification levels.

Sodium increases surface tension and through addition methods can increase hydrogen content. Overmodification increases misrun tendencies in gravity casting.

Unlike some other modifiers, sodium provides effective aluminum-silicon eutectic modification under all solidification conditions.

### **2.5.19 Strontium**

Strontium modifies the aluminum-silicon eutectic. Effective modification can be achieved at very low addition levels, but a range of recovered strontium of 0.008 to 0.04% is commonly used. Lower concentrations are effective with higher solidification rates. Higher addition levels are associated with casting porosity. Degassing efficiency may also be adversely affected at higher strontium levels.

Strontium has been regarded as ineffective as a modifier at slow solidification rates, but some investigators report beneficial effects in AFS Level 4 and 5 structures in 319.0 and 356.0 alloys when >200 ppm Sr is present.

### **2.5.20 Tin**

Tin is effective in improving antifriction characteristics and is therefore useful in bearing applications. Casting alloys may contain up to 25% Sn. Additions of tin also improve machinability.

### **2.5.21 Titanium**

Titanium is extensively used to refine the grain structure of aluminum casting alloys, often in combination with smaller amounts of boron. The operable phase is  $\text{TiAl}_3$  with lattice spacing closely matched to that of aluminum. Titanium in excess of the



stoichiometry of  $TiB_2$  is necessary for effective grain refinement. Titanium is often employed at concentrations greater than those required for grain refinement to reduce cracking tendencies in hot-short compositions.

### 2.5.22 Zinc

Zinc offers no significant benefits in aluminum casting. Accompanied by the addition of copper and/or magnesium, however, zinc results in attractive heat treatable or naturally aging compositions. A number of such compositions are in common use. Zinc is also commonly found in secondary gravity and die casting compositions. In these alloys, tolerance for up to 3% Zn allows the use of lower-grade and wrought alloy scrap.

## 2.6 Alloy Groupings by Application or Major Characteristic

### 2.6.1 General-Purpose Alloys

Alloys with silicon as the major alloying constituent are the most important commercial casting alloys, primarily because of their superior casting characteristics. The large number of alloys of this type that have been developed displays a broad range of properties.

Binary aluminum-silicon alloys (443.0, 444.0, 413.0, and A413.0) are low-density, weldable, and resistant to corrosion. Although castings of these alloys are somewhat difficult to machine, good results are obtained with cutting fluids, sintered carbide tools, and chip breakers.

Alloy 443.0 is used with all casting processes for parts in which strength is less important than ductility, resistance to corrosion, and pressure tightness.

Permanent mold alloys 444.0 and A444.0 display high ductility and are used where impact resistance is a primary consideration.

Alloys 413.0 and A413.0 are close to the eutectic composition and, as a result, have very high fluidity. They are useful in die casting and where large-area, thin-walled parts with cast-in lettering or other high-definition details are required.

Representative applications for these alloys are:

- Architectural panels and spandrels
- Outdoor lamp housings
- Lawn mower decks
- Outdoor grills
- Marine components
- Cooking utensils
- Parts used in food, dairy, and beverage processing
- Medical and dental equipment
- Electronic cabinet frames and components
- Tire molds
- Escalator and moving sidewalk tread plates and parts
- Highway railing posts (Fig. 2.1); alloy A444.0 being the standard for this application

Aluminum-silicon-copper alloys such as 308.0, 319.0, 360.0, 380.0, and 384.0 offer good casting characteristics, higher strength and hardness, and improved machinability with reduced ductility

and lower resistance to corrosion. These and similar general-purpose alloys are often produced in the as-cast condition. Artificial aging can improve hardness, stability, and machinability. Typical applications include:

- Machinery
- Transmission cases (Fig. 2.2)
- Engine blocks
- Gas meters and regulators
- Gear blocks
- Gear cases
- Fuel pumps
- Impellers
- Instrument cases
- Lawnmower decks
- Intake manifolds
- Cylinder heads
- Clutch housings
- Oil pans
- Outboard motor propellers, motor parts and housings



**Fig. 2.1** Example of one of the many highway railing post designs utilizing aluminum castings that have been developed. The alloy is A444.0-T4 with minimum elongation in permanent mold castings of 20% in front flanges for maximum energy absorption during impact.

## 18 / Aluminum Alloy Castings: Properties, Processes, and Applications

Aluminum-silicon-magnesium alloys including 356.0 and A356.0 have excellent casting characteristics and resistance to corrosion. Heat treatment provides combinations of tensile and physical properties that make them attractive for many applications including machinery, automotive, military, and aerospace parts. Higher tensile properties are obtained with 357.0, A357.0, 358.0, and 359.0 alloys. The high properties of these alloys, attained by heat treatment to the fully hardened condition, are of special interest in structural applications. Developments in high-integrity die casting have resulted in low-iron, manganese-containing Al-Si-Mg alloys such as 365.0 and AlMg3Mn. Some typical uses include:

- Automotive space frames
- Automotive wheels
- Truck wheels
- Axle and differential housings (Fig. 2.3)
- Pump bodies
- Meter bodies
- Compressor bodies
- Intake manifolds
- Cylinder heads
- Dies for plastic injection molding
- Machine parts
- Truck and bus frames and chassis components
- Suspension saddles (Fig. 2.4)
- Aircraft pylons, canopies, flaps, speed-brakes hatch covers, and other fittings
- Impellers
- Wave guides
- Electronic cases
- Fuel pumps
- Missile bodies, fins, and other structural parts

- Industrial beam heads
- Brake cylinders
- Automobile cross members and suspension components

Aluminum-silicon-copper-magnesium alloys such as 328.0, 333.0, 354.0, 355.0, and C355.0 offer excellent strength and hardness with some sacrifice in ductility and corrosion resistance. Casting characteristics are good, but inferior to those displayed by copper-free aluminum-silicon alloys. Properties in the as-cast condition can be acceptable for some applications, but these alloys are typically heat treated for optimal properties. Alloy C355.0 with low iron is a higher-strength version of 355.0. When premium-strength casting processes are used, even higher tensile properties can be obtained with heat treated Alloy 354.0. Alloys of this type are routinely cast in sand and permanent mold.

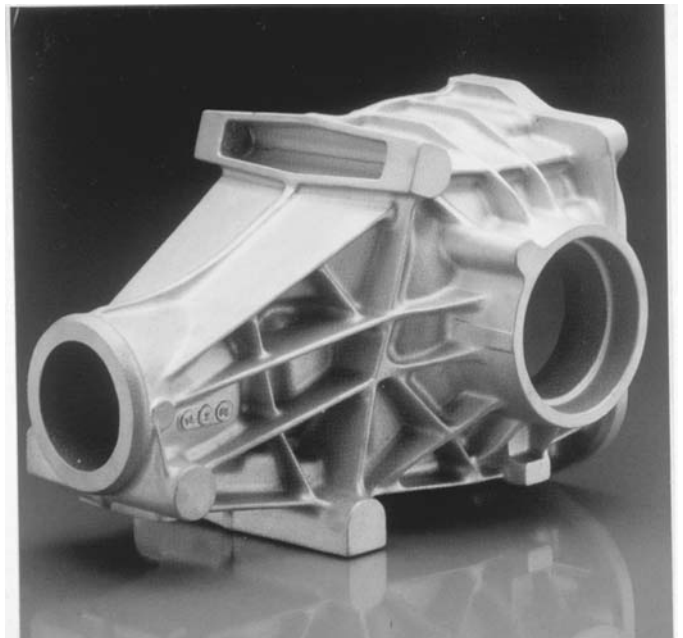


**Fig. 2.3** Die cast alloy 380.0 rear axle housing

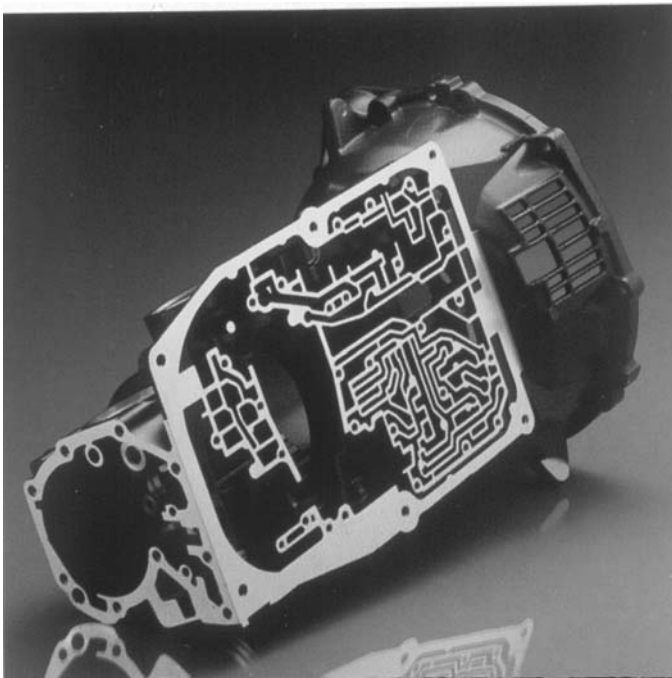


**Fig. 2.2** Die cast alloy 380.0 transmission case

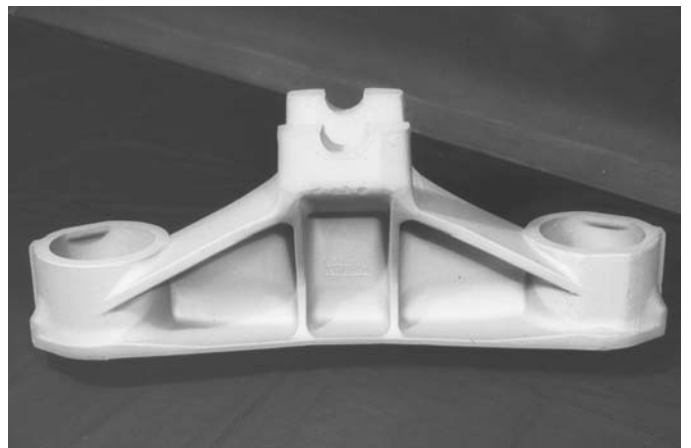


**Fig. 2.4** Alloy A356.0 trailer suspension saddle

Applications include:

- Engine cooling fans
- Clutch housings
- Crankcases
- High-speed rotating parts such as fans and impellers
- Structural aerospace components
- Air compressor pistons
- Fuel pumps (Fig. 2.5)
- Compressor cases
- Rocker arms
- Timing gears
- Machine parts

### 2.6.2 Elevated-Temperature Alloys

Many aluminum alloys have been developed to provide strength, wear resistance, and hardness at elevated temperatures. The retention of these properties as temperature increases is an advantage in many applications.

Cast aluminum alloy pistons featuring low specific gravity, low thermal expansion, elevated-temperature strength, wear resistance, and high thermal conductivity are the international standard for internal combustion engines. Lower inertial forces permit higher engine speeds, reduced bearing requirements, and lighter, simpler crankshaft designs.

Aluminum pistons are usually permanent mold castings. Wrist pin bore struts and compression ring-groove inserts can be cast-in; in large diesel engine pistons, integral cooling passages can be incorporated through copper coils or coring methods.

The alloy most commonly used for pistons in passenger cars, sports-utility vehicles, and light trucks, 332.0-T5, demonstrates a desirable combination of foundry, mechanical, and physical characteristics, including low thermal expansion. Precipitation hardening from air or water quenching from the mold improves hardness for improved machinability and eliminates or reduces changes in dimensions from residual growth at operating temperatures.

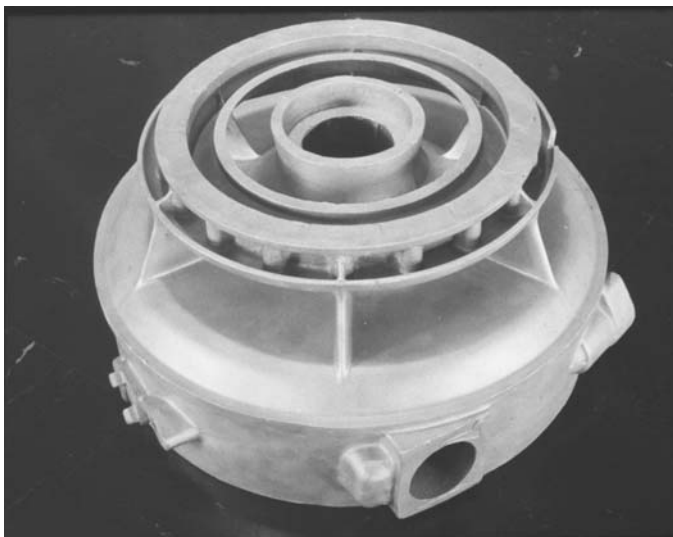


**Fig. 2.5** Alloy C355.0 fuel pump housing

More complex aluminum-silicon alloys have been developed to meet the demands of high specific output, fuel-efficient engines that operate at higher temperatures. Some of these alloys retain yield strengths over 10 ksi (70 MPa) at temperatures exceeding 500 °F (260 °C).

Piston alloys for heavy-duty and diesel engines include low-expansion alloys 332.0-T5 and 336.0-T551. Alloy 242.0-T571 offers higher thermal conductivity and superior properties at elevated temperatures.

Other applications of aluminum alloys for elevated-temperature use include air-cooled cylinder heads for aircraft and motorcycles. Alloy 220.0-T61 was once used extensively for this purpose, but has been largely replaced by more castable 242.0 and 243.0 alloys with superior elevated-temperature properties.

Alloys 295.0, 355.0, and C355.0 have been extensively used in applications requiring strength and hardness at temperatures up to 350 °F (175 °C). They include aircraft motor and gear housings. Alloy A201.0 and 204.0/206.0 type alloys have also been used in this temperature range when the combination of high strength at room temperatures and elevated temperatures is required.

Applications include:

- Cylinder heads
- Motorcycle engine parts
- Gear housings
- Pistons
- Structural parts exposed to elevated temperatures

### 2.6.3 Wear Resistant Alloys

Alloys containing greater-than-eutectic silicon concentrations display low specific gravity and elevated-temperature strength and are often used in applications requiring a high degree of wear resistance. While wear resistance is usually associated with surface hardness resulting from matrix properties or anodized coatings, wear resistance in these alloys results from the presence of a large volume fraction of hard primary silicon particles in the microstructure. Growth in the popularity of these alloys has accelerated in recent years. Alloys include 390.0, 392.0, and 393.0.

Hypereutectic aluminum-silicon alloys are relatively more difficult to cast and machine, but are used in all casting processes.

Matrix-hardening alloys also provide improved wear resistance. Alloys of the 2xx.0 and 355.0 family are considered wear resistant.

Applications include:

- Brake rotors
- Cylinder blocks
- Cylinder liners
- Marine engines
- Pistons

### 2.6.4 Moderate-Strength Alloys with Low Residual Stresses

A number of casting compositions have been developed to provide strength and hardness without heat treatment through natural aging. These alloys offer dimensional stability that reduces distortion during machining and simplifies straightening to close tol-

erances. The cost of heat treatment is avoided or reduced and postweld heat treatment is typically not required.

In many cases, properties in the as-cast condition approach those of higher-strength heat treated alloys. Castability is distinctly inferior, and full properties may not be realized for days, weeks, or longer periods of room-temperature hardening. Stability can be an issue addressed by artificial aging or heat treatment without quenching.

Alloys of this type include selected Al-Mg, Al-Zn-Mg, and Al-Zn-Mg-Cu alloys such as 535.0, 712.0, 771.0, and 772.0.

Typical applications include:

- Tooling plate
- Complex thin-walled shapes such as impellers and cooling fans
- Explosion-proof enclosures
- Electrical fittings
- Brazed parts
- Machinery
- Instrument cases
- Marine components
- Pistol frames
- Food and beverage processing
- Decorative parts
- Reflectors
- Optical systems

### 2.6.5 Bearings

Aluminum-tin alloys 850.0, 851.0, 852.0, and 853.0 are specialized compositions displaying excellent bearing characteristics under moderate loads and with effective lubrication. Castability, hardness, compressive yield strength, and other properties are influenced by alloy variations involving silicon and copper additions.

The principal applications for these alloys are bushings and bearings.

### 2.6.6 High-Strength Alloys

High-strength alloys include compositions designed to provide high strength and ductility and in the case of premium engineered castings also imply high levels of internal soundness and microstructural refinement. Alloys considered premium strength by definition and specification (AMS-A-21180) are A201.0, A206.0, 224.0, 249.0, 354.0, A through D356.0, A through D357.0, 358.0, and 359.0. Other alloys displaying high strength are 204.0, 206.0, C355.0, and metal-matrix composite compositions.

Applications include:

- Missile bodies
- Missile fins
- Aircraft pylons
- Aircraft canopies
- Wing flaps
- Speed brakes
- Hatch covers
- Hydraulic pumps

- Automotive suspension systems and cross-members
- Fuel pumps
- Brake valves
- Armored cupolas
- Aerospace structural parts

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## CHAPTER 3

# Aluminum Casting Processes

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### 3.1 History

Aluminum alloy castings were first produced using processes that had been in historical use for other metals. It is generally believed that the art of metal casting was first practiced more than 5500 years ago, when shaped cavities were carved or impressed into molds of soft minerals and clay. Naturally occurring copper, silver, and gold were melted and solidified in these cavities. Brass, bronze, tin and zinc artifacts, weapons, and tools were cast as extractive metallurgy developed, and more complex molds of sand and clay mixtures evolved. These methods were duplicated later for other metals including iron and steel.

The relatively attractive engineering properties of aluminum—low melting point and castability—quickly led to the adoption of existing casting processes and to developments that broadened the means by which engineered shapes could be produced from molten metal.

Iron or steel dies had been used in casting print type in lead-base alloys in the 17th century. Iron molds were also used in colonial times to cast pewter. Intensive efforts to employ iron and steel molds in the casting of aluminum resulted in commercial “permanent mold” operations by the first decade of the 20th century.

Pressure die casting came into existence in the early 1820s in response to the expanding need for large volumes of cast print type. The injection of metal under pressure into metallic dies was at first purely mechanical, using hand cranks. Later, pneumatic and hydraulic systems were used as applications grew to include bicycle, phonograph, and consumer durable parts. By 1870, jobbing die casters were producing lead and other low-temperature metals with a surprising degree of automation. Progress in die casting aluminum was limited until the development of the cold chamber process in the 1920s.

Aluminum can be cast by essentially all existing processes including pressure die casting, permanent mold, clay/water bonded sand, chemically bonded sand, plaster mold, and investment casting. Important variations include molding and pattern distinctions such as lost-foam (evaporative pattern), shell and V-mold, and process derivatives such as squeeze casting, low-pressure permanent mold, vacuum riserless casting, and semisolid forming based on rheocasting/thixocasting principles.

### 3.2 Casting Process Selection

Many factors influence the selection of a casting process for producing a specific part. Process selection is strongly influenced by part requirements that are often the basis for defining alloy candidates that in turn influence the range of process choices. The most important process selection criteria are:

- Casting process considerations: requirements for fluidity, resistance to hot tearing, minimization of shrinkage tendencies
- Casting design considerations: draft, wall thickness, internal passages
- Mechanical property requirements: strength and ductility, hardness, fatigue strength, toughness, impact strength, specification limits
- Physical property requirements: electrical and thermal conductivity, specific gravity, expansion characteristics
- Process requirements: machinability, brazability, weldability, impregnation, and chemical finishing
- Service requirements: pressure tightness, corrosion resistance, wear resistance, elevated-temperature strength, dimensional and thermal stability
- Economics: volume, productivity, process yield, material costs, tooling costs, cost of machining, welding, and heat treatment

Many aluminum alloy castings can be produced by any of the available methods. In most cases, dimensions, design features, and material property requirements limit the range of candidate processes. Compromises in specified criteria are made to facilitate the use of the most cost-effective process.

#### 3.2.1 Casting Design

Design considerations include size, shape, complexity, wall thicknesses, and required dimensional accuracy. Parts with undercuts and complex internal passageways can usually be made by sand, plaster, or investment casting, but may be impractical or impossible to produce in permanent mold or pressure die casting.

#### 3.2.2 Specification Requirements

Conformance to specification requirements including mechanical and physical properties may limit process choice. Metallurgical



characteristics also vary as a function of cooling rates and solidification conditions imposed by differing casting processes. An alloy selection imposed by specified requirements and metallurgical considerations often dictates the casting process.

### 3.2.3 Volume of Production

The number of castings that are estimated to be required is a major factor in the choice of casting method. Loose or simple patterns may be used for sand cast prototypes or when only one or a few parts are required. When production is limited, tooling cost dominates. For larger production volumes, tooling costs, though significant, become less important. As volume requirements increase, the trend is toward automated molding processes, permanent molds, and die casting. For extended production in die and permanent mold operations, more expensive, difficult-to-machine tool steels provide improved life. Recent developments for reducing tooling costs include near-net-shape forming of dies, composite die materials, the deposition of hard, wear-resistant die surfaces, and in situ bonding of dissimilar materials by laser and high-intensity infrared technologies.

### 3.2.4 Costs

Costs are strongly influenced by process choice. Tooling costs associated with die and permanent mold casting are justified by higher levels of production and product reproducibility. The use of high-speed molding machines in volume sand casting improves production rates with increased capital and maintenance costs. Low-volume investment castings require precise patterns, hand mold assembly, and pouring practices that are justified by the extreme detail, accuracy, and finish of the final product. Premium engineered castings are typically low volume and high cost. When two or more casting processes are capable of satisfying part requirements, selection is dictated by unit cost.

### 3.2.5 Quality

Quality factors are also important in the selection of the casting process. Quality refers to the degree of internal soundness and to the mechanical properties and performance characteristics that are a reflection of alloy chemistry, molten-metal quality, solidification conditions, microstructural features, and soundness. The casting process dictates solidification conditions and, to a large extent, variations in microstructural features and soundness. The selected casting process must be competent to deliver the required level of quality.

## 3.3 Casting Process Technology

### 3.3.1 Expendable and Nonexpendable Mold Processes

Casting processes for aluminum may be categorized as involving expendable or nonexpendable molds. In sand casting, for example, the mold is destroyed when the casting is produced. Similarly, plaster and investment castings are made in molds that cannot be reused. Permanent molds and dies are reused, although each has finite life based on the number of castings that can be produced

before wear, heat checking caused by thermal fatigue, or other conditions that affect their acceptability for continued production.

Sections 3.4 and 3.5 describe casting technologies under expendable and nonexpendable mold processes.

### 3.3.2 Pressure versus Gravity

A second important factor in categorization of aluminum casting processes is whether molten metal flows by gravity into the die or mold cavity or is forced under pressure. Casting by injection under pressure requires nonexpendable dies and is commonly referred to as pressure die casting. Countergravity processes that employ low-pressure differentials such as low pressure, displacement, or pumped systems for mold filling are considered variations of either expendable or gravity permanent mold processes.

### 3.3.3 Gating and Riser

There is a commonality in practices and terminologies for gravity casting in both expendable and nonexpendable molds. Molten metal is normally introduced to the mold cavity in an arrangement referred to as the gating system (Fig. 3.1, 3.2). It consists of a pouring basin leading to a downsprue through which molten metal is delivered to the parting plane of the mold. From the base of the downsprue, metal is conveyed along the casting periphery in runners that supply metal to in-gates from which metal enters the casting cavity. Risers—volumes of heat and pressure-differentiated

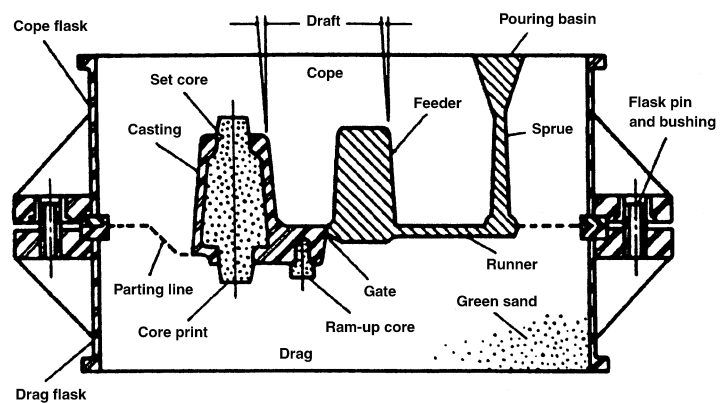


Fig. 3.1 Typical sand mold gating. Source: Ref 1

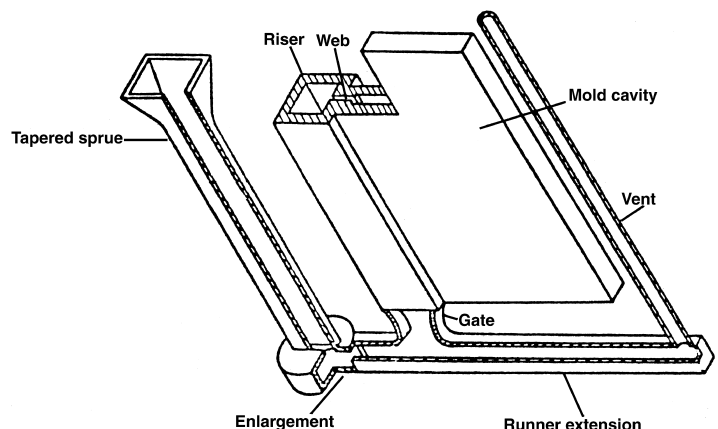


Fig. 3.2 Typical permanent mold gating. Source: Ref 2

molten metal—are strategically located external to the mold cavity to compensate for volumetric shrinkage as solidification of the casting progresses. The gating system is comprehensively designed to minimize turbulence and prevent aspiration.

Pressure die castings are filled through runners and in-gates, but risers are not normally used because solidification rate limits their effectiveness (Fig. 3.3). Instead, internal soundness is promoted by die design features, elaborate mold cooling, and pressure intensification during the shot cycle.

Most sand castings are produced in molds with a horizontal parting plane, while the parting plane in most permanent mold casting is vertically oriented. Pressure die castings are produced with both horizontal and vertical parting-plane orientation. In horizontally parted molds, the upper mold half is referred to as the cope, and the lower, the drag.

### 3.4 Expendable Mold Gravity-Feed Casting Process and Its Variations

#### 3.4.1 Sand Casting

**Green and Dry Sand.** Sand casting involves the forming of a geometrically dimensioned impression in sand. The process includes green sand and dry sand casting. Green sand refers to the use of uncured bonding systems, usually a blended mixture of sand, clay, and water. In the dry sand process, resins, oil, or other chemical binding agents are used to precoat the molding sand. The dry sand mold is then thermally or chemically cured. Another dry sand method reacts carbon dioxide ( $\text{CO}_2$ ) gas with sodium silicate in the sand blend to form a silica gel bond.

The important parameters of molding sand are compressive strength and permeability. Tests for each are routinely performed

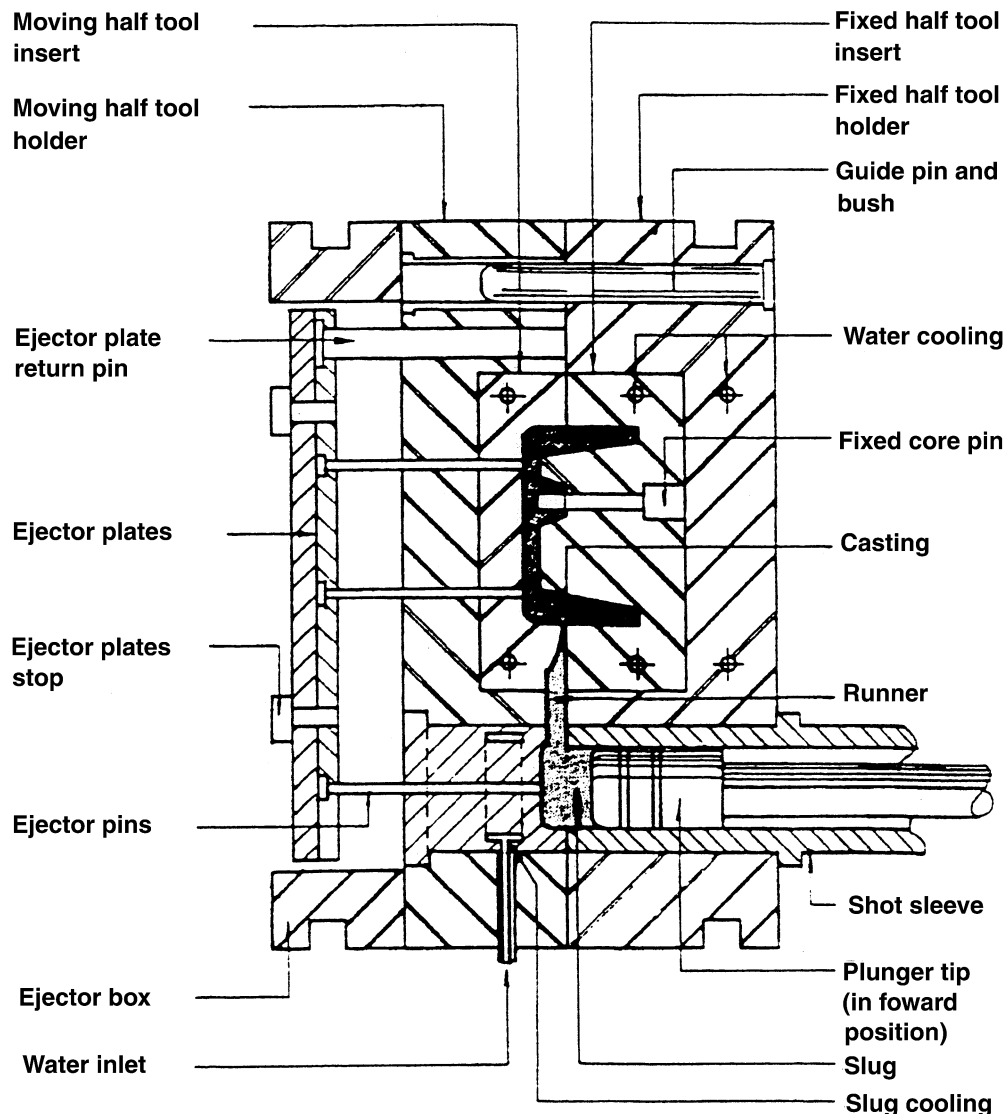


Fig. 3.3 Typical die casting gating. Source: Ref 3

for quality assurance. The mold must have sufficient strength to maintain its shape through the casting process and sufficient permeability to permit the air, and gases formed during pouring, to evacuate the mold cavity as the metal enters. Compressive strength and permeability in green sand are functions of sand particle size and shape, moisture and binder contents, and the degree of compaction applied in forming the mold.

The advantages of typical sand casting are versatility in a wide variety of alloys, shapes, and sizes. Alloys considered hot short because of cracking tendencies during solidification are more easily cast in green sand since molds offer reduced resistance to dimensional contraction during solidification. Lower mold strength is also advantageous for parts with widely varying section thicknesses and intricate designs. These advantages are diminished in chemically bonded molds, which display greater rigidity than green sand molds.

There are only practical limitations in the size of the parts that can be cast. Minimum wall thickness is normally 0.15 in. (4 mm), but thicknesses as little as 0.090 in. (2 mm) can be achieved.

Among disadvantages are relatively low dimensional accuracy and poor surface finish; basic linear tolerances of  $\pm 0.03$  in./in. ( $\pm 30$  mm/m) with a minimum tolerance of 0.020 in./in. (20 mm/m), and surface finishes of 250 to 500  $\mu$ in. (6 to 13  $\mu$ m) root mean square (rms). Chemically bonded sands offer improved surface finish and dimensional accuracy, and relatively unlimited shelf life, depending on the type of binder used. Achievable dimensional tolerances can be substantially improved using precision methods in the forming and assembly of dry sand mold components. Surface quality can be improved by using a finer grade of facing sand in the molding process.

Strength is typically lower as a result of slow solidification rates. Mechanical properties are improved by using sands such as zircon and olivine with higher heat capacity than silica and by the use of copper, iron, or steel chills at strategic locations in the mold.

Sand casting involves minimum tooling and equipment cost when smaller numbers of castings are to be produced.

**Sand Molding.** In both green and dry sand processes, the mold is formed by compacting the preconditioned sand over the pattern. In floor or hand molding, the sand is compacted using manual or pneumatic rams; for pattern plates (match plates), machines use jolt/squeeze mechanisms to ensure mold integrity. Automatic molding machines provide a high degree of uniformity and very high mold production rates.

Patterns may consist of wood, composite, or metal plates containing the casting impression or may consist of loose pieces assembled in the form to be cast. After compaction of the molding sand, the pattern is carefully removed, leaving a cavity in the shape of the casting to be made. A dusting of calcium carbonate or other parting compound on the pattern surface is helpful in facilitating the separation of the pattern from the mold. A small amount of vibration through transducers attached to the match plate also facilitates pattern removal.

The runners and in-gates are usually integral to the pattern, but may also be manually cut into the sand by the molder. A pattern of the sprue is separately placed on the pattern before sand is introduced.

If the casting contains internal passages or undercuts, dry sand cores may be used. In these cases, the mold includes locating points and additional impressions or prints for precisely positioning the cores after pattern removal and before final mold assembly. In rare cases, aluminum chaplets may be used to support the core position.

Molten metal is poured into the mold, and after it has solidified, the mold is physically removed from the casting. Removal is by physical means including vibration.

Casting quality is determined to a large extent by foundry technique. Proper molten metal processing, metal-handling and gating design and practices including the selective use of chills are necessary for obtaining sound castings. Complex castings with varying section thicknesses will be sound only if proper techniques are used.

While the principles of sand casting are relatively simple, a large number of process variations are in use that typically involve expendable pattern materials and molding methods.

### 3.4.2 Evaporative (Lost-Foam) Pattern Casting (EPC)

Lost foam is a sand casting process that uses an unbonded sand mold with an expendable polystyrene pattern. This process is somewhat similar to investment casting in that an expendable pattern is used to create the mold cavity. Unlike investment casting, the pattern vaporizes during the pouring of molten metal rather than before pouring.

The EPC process employs a foamed polystyrene pattern packed in unbonded sand. The polystyrene model is coated with a thin layer of ceramic or refractory wash that seals the pattern surface. The pattern is sequentially decomposed by the heat of the molten metal, thus replacing the foam pattern and duplicating the features of the pattern in the solidified casting. Use of the process has increased rapidly, especially in large-volume automotive foundries, and many casting facilities are now dedicated to the production of castings by this method (Fig. 3.4).

The major difference between sand castings and castings made by the EPC process is the extent of subsequent machining and cleaning operations required. Evaporative pattern castings are con-



**Fig. 3.4** Typical castings produced by the evaporative pattern casting (EPC) process



sistently poured at closer tolerances with less stock for grinding, machining, and finishing. Dimensional variability associated with core setting and the mating of cope and drag are eliminated. The use of untreated, unbonded sand simplifies sand processing, handling, and reclamation. Casting cleaning is also greatly reduced and can often be eliminated because of the absence of flash, sand adherence, and resin stains. Further benefits of the EPC process result from the freedom in part design offered by the process. Assembled patterns can be used to make castings that cannot be produced by any other high-production process.

### 3.4.3 Shell Mold Casting

In shell mold casting, molten metal is poured into a shell of resin-bonded sand only 0.4 to 0.8 in. (10 to 20 mm) thick. The mold is formed by introducing the chemically coated sand to a heated pattern that thermally cures the bond. By controlling the core mold temperature and cycle, the depth of cure can be controlled to the desired thickness. Cured mold sections are removed and assembled for pouring, usually backed by unbonded or green sand (Fig. 3.5). Shell mold castings surpass ordinary sand castings in surface finish



Fig. 3.5 Shell molds assembled before pouring. Source: Ref 1

and dimensional accuracy and cool at slightly higher rates; however, equipment and production costs are higher, and the size and complexity of castings that can be produced are limited.

### 3.4.4 Plaster Casting

In this method, either a permeable (aerated) or impermeable plaster is used for the mold. The plaster in slurry form is poured around a pattern. When the plaster has set, the pattern is removed and the plaster mold is baked to remove free water and reduce waters of hydration. The high insulating value of the plaster allows castings with thin walls to be poured. Minimum wall thickness of aluminum plaster casting is typically 0.060 in. (1.5 mm). Plaster molds have high reproducibility, permitting castings to be made with fine details and close tolerances; basic linear tolerances of  $\pm 0.005$  in./in. ( $\pm 5$  mm/m) are typical. The surface finish of plaster castings is excellent; aluminum castings attain finishes of 50 to 125  $\mu$ in. (1.3 to 3.2  $\mu$ m) rms.

For complex shapes, such as some precision impellers and electronic parts, mold patterns made of rubber are used because their flexibility makes them easier to withdraw from the molds than rigid patterns. Intricate plaster castings may also be produced using polystyrene or other expendable pattern materials such as those used in investment casting.

Mechanical properties and casting quality depend on alloy composition and foundry technique. Slow cooling due to the highly insulating nature of plaster molds magnifies solidification-related problems such as hydrogen pore formation and shrinkage voids and reduces strength and ductility.

For many plaster cast parts, there are only limited capabilities for improving internal soundness and properties through traditional gating and risering approaches. The configuration of impellers and other rotating parts subject to strict dimensional requirements as well as strengths compatible with high rotational stresses permits the use of extensive chilling of the shaft and base for purposes of improving internal soundness and mechanical property performance. These techniques are further enhanced when combined with nonturbulent mold filling by low-pressure or other counter-gravity methods. Figure 3.6 shows plaster cast alloy 224.0 impellers that were produced through a low-pressure method.

### 3.4.5 Investment Casting

Investment casting of aluminum most commonly employs ceramic molds and expendable patterns of wax, plastic, or other low-temperature melting materials. In the ceramic shell method, assembled patterns are invested in a ceramic slurry by repetitive immersion and air drying until the desired shell thickness has been formed. In the solid mold investment method, the assembled pattern is immersed in a container of sufficient size for ceramic slurry to encase and set around the pattern. In either case, the mold is placed in an autoclave to remove the pattern and then fired at high temperature to remove all free water and organic materials and to cure the binding system being used. Molds are typically preheated and poured under partial vacuum. Christmas-tree gating systems are employed to produce small multiple parts in one mold.

Aluminum investment castings can have walls as thin as 0.015 to 0.030 in. (0.40 to 0.75 mm), basic linear tolerances of  $\pm 5$  mils/in. ( $\pm 5$  mm/m) and surface finishes of 60 to 90  $\mu\text{in.}$  (1.5 to 2.3  $\mu\text{m}$ ).

Because of porosity and slow solidification, the mechanical properties of many aluminum investment castings are typically lower than those demonstrated by other casting processes. The interest of the aerospace and other industries in the combination of accurate dimensional control with controlled mechanical properties has resulted in the use of improved technologies to produce premium-quality castings by investment methods. Castings in the premium-

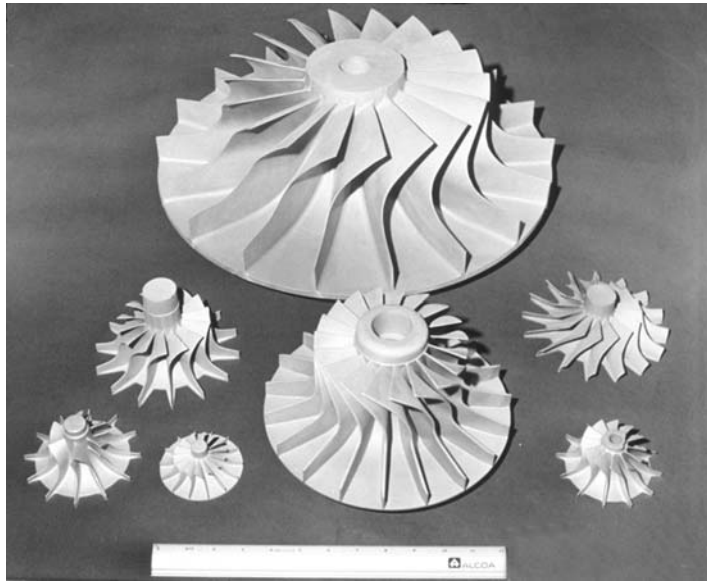


**Fig. 3.6** Alloy 224.0 impellers produced by low-pressure plaster casting



**Fig. 3.7** Vacuum molding unit. Source: Ref 1

strength range can be achieved with molten metal treatments, gating, and solidification conditions that are not typical for conventional investment castings.

Investment casting applications include: instrument parts, impellers, compressor vanes, gears, ratchets, pawls, scrolls, speed brakes, wing tips, and aircraft pylons.

### 3.4.6 Vacuum Mold (V-Mold) Casting

A heated plastic film is drawn over the pattern by vacuum. Unbonded sand is filled against the plastic-covered pattern within a vented flask and compacted by vibration. A vacuum is drawn through the flask after an unheated plastic film is placed over the back of the mold, creating a mold vacuum package. Pouring takes place with the vacuum retained or reapplied (Fig. 3.7).

Advantages are surface finish, minimum wall thickness, and reduced draft requirements. Disadvantages are tooling costs and size limitations imposed by maximum flask dimensions.

## 3.5 Nonexpendable (Permanent) Mold Gravity Feed Casting Process and Its Variations

### 3.5.1 Permanent Mold Casting

In principle, permanent mold casting is analogous to expendable mold casting processes. In this case the molds are machined cast, wrought or nodular iron, cast steel, or wrought steel and can be reused repetitively until damage, wear, or the effects of thermal fatigue necessitate repair or replacement (Fig. 3.8). The ability to form internal passages involves metallic or sand cores. Intricate details and undercuts can often be cast using segmented steel cores. Sand cores become necessary when the design prohibits drawing the core after the casting has solidified. When sand cores are used, the process is referred to as “semipermanent mold” casting.

Permanent mold tooling is typically more expensive than that required for sand casting and other expendable mold processes and is justified by the volume of production. The volume of production also dictates the extent of process automation. Molds can be manually operated or extensively automated. Production rates of automated multimold operations are high, and parts display consistent dimensional characteristics and properties.

While the principles and mechanics of gravity casting are similar, the metallurgical structure of permanent mold castings reflects the refinement of higher solidification rates. Typical and specified minimum mechanical properties including ductility are higher than those of expendable mold castings. The improved mechanical properties of permanent mold castings provide part of the justification for selecting this process over competing gravity casting options.

The same terminologies used in expendable mold gating apply. There is a downsprue into which molten metal is introduced from a pouring basin, from which the metal flows into runners, risers, in-feeds, and casting cavity. Directional solidification is promoted by selective chilling of mold sectors by air, mist, or water. An insulating coating is used to protect the mold from the molten aluminum and to facilitate removal of the casting from the mold after solidification is complete. Typical mold dressings or washes are suspensions of talc, various metal oxides such as zirconia,



chromia, iron oxide and titania, colloidal graphite and calcium carbonate in water, and sodium silicate. The thickness and thermal characteristics of these coatings are used to locally increase or decrease heat absorption during solidification. As a result of wear, these coatings must be periodically repaired or replaced to ensure consistent process performance and casting results. Mold surfaces are periodically blasted with dry ice or mild abrasives to remove coatings and scale after which new mold coatings are applied.

The permanent mold process is less alloy tolerant than most expendable mold processes. The most popular permanent mold alloys display superior castability such as those of the Al-Si, Al-Si-Mg, and Al-Si-Cu (Mg) families. Mold rigidity is a challenge in the casting of hot-short alloys in which liquidus-solidus range and elevated-temperature strength combine to increase the tendency for cracking during and after solidification. Determined efforts to cast even the most difficult foundry alloys such as low-iron aluminum-copper alloys have nevertheless been successful, and alloys with limited castability are routinely cast in permanent molds.

Permanent mold castings can be produced in sizes ranging from less than a pound to more than several hundred pounds. Surface finish typically varies 150 to 400  $\mu\text{in.}$  (3.8 to 10  $\mu\text{m}$ ). Basic linear tolerances of about  $\pm 0.01$  in./in. ( $\pm 10$  mm/m), and minimum wall thicknesses are about 0.100 in. (2.5 mm).



Fig. 3.8 Permanent mold machined from steel. Source: Ref 1

### 3.5.2 Low-Pressure Die Casting (LP), Pressure Riserless Casting (PRC)

In this process, permanent molds are mounted over a sealed furnace. A tube extends from the mold cavity into the molten metal below. By pressurizing the furnace, metal is forced through the tube into the mold cavity (Fig. 3.9). When the metal has solidified, the pressure is relieved, the mold is opened, and the casting is removed in preparation for repeating the cycle.

Most low-pressure casting has been confined to radially symmetrical designs, but a wide range of nonsymmetrical parts have also been produced. Nearly all automotive wheels are cast by this process (Fig. 3.10, 3.11).

Process parameters include (a) the rate at which pressure is applied, which regulates mold filling, (b) pressure, which is relatively unimportant once solidification begins, and (c) thermal gradients, which are essential for establishing directional solidification. As in conventional permanent mold, these gradients are established by the selection and controlled thicknesses of mold coatings and by selective chilling of mold sections. Since most low-pressure castings are produced using only one metal entry point and since risers normally necessary to avoid internal shrinkage voids are not typically used, the gross-to-net weight ratio is low and trimming and finishing operations associated with gating are minimized.

The low-pressure casting cycle is dictated by the solidification of metal at the junction of the fill-tube and mold cavity.

While countergravity metal flow into the mold cavity is quiescent, the process does present the risk of inclusion contamination. When the mold is opened and the casting is removed, the vacuum seal that existed at the liquid-solid interface is broken and molten metal remaining in the tube falls to the furnace metal level. The cycling of metal flow vertically in the fill tube can result in the buildup of oxides on the inner surfaces of the fill tube whether the

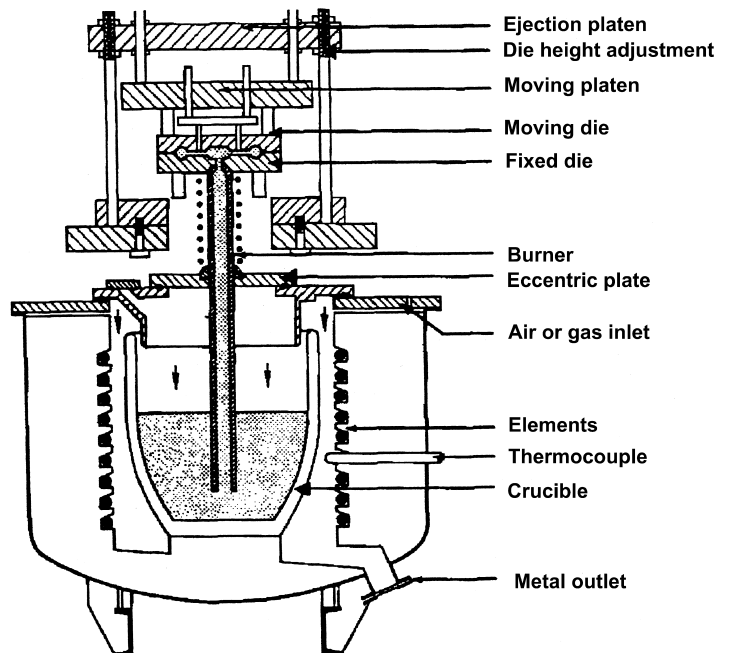


Fig. 3.9 Low-pressure permanent mold. Source: Ref 1

tube is ceramic or coated metal. To minimize this condition, back pressure can be maintained in the system so that molten metal is retained at an elevated level in the fill tube at all times. It is also possible to replenish metal in the furnace with each cycle by valving rather than periodically refilling when the metal in the furnace is nearly depleted. Filtration of metal at the point of entry into the mold is routinely used to prevent included matter from contami-

nating the casting. Filtration may consist of steel screens, ceramic strainers, or fused or foamed porous ceramics.

### 3.5.3 Vacuum Riserless Casting (VRC)

The use of vacuum rather than pressure to introduce molten metal into steel dies has significant advantages over low-pressure casting. The molten metal bath is open and accessible. Molten metal level can be maintained within a narrow range in close proximity to the mold entry point so that the vertical dimension between the metal surface and the mold cavity can be minimized.

Limitations are in the size and cost of molds that can be engineered to apply and retain vacuum pressures.

A high degree of mold chilling has been used to enhance metallurgical structures, improve mechanical properties, and shorten cycle times. The VRC process is ideally suited for automation and high production rates to produce castings with exceptional surface quality and metallurgical properties. Examples of VRC products are shown in Fig. 3.12.

### 3.5.4 Centrifugal Casting

Centrifugal force in aluminum casting involves rotating a mold or a number of molds filled with molten metal about an axis. Cylindrical or tubular shapes may be centrifugally formed in vertically or horizontally rotated drums, while conventional castings are produced by the rotation of one or more molds about a vertical axis. Metal may be introduced before or during rotation.

Baked sand, plaster, or graphite molds have been used, but iron and steel dies are most common. Centrifugal castings are generally, but not always, denser than conventionally poured castings and offer the advantage of greater detail.

Wheels, wheel hubs, motor rotors, and papermaking and printing rolls are examples of aluminum parts produced by centrifugal casting. Aluminum alloys suitable for permanent mold, sand, or plaster casting can be cast centrifugally.



**Fig. 3.10** Alloy A356.0 alloy automotive wheels produced by low-pressure casting



**Fig. 3.11** Variety of parts, including automotive pistons, metallurgically bonded diesel engine pistons, compressor pistons, cylindrical and journal bearings, anodes, and cookware, produced by the low-pressure casting process

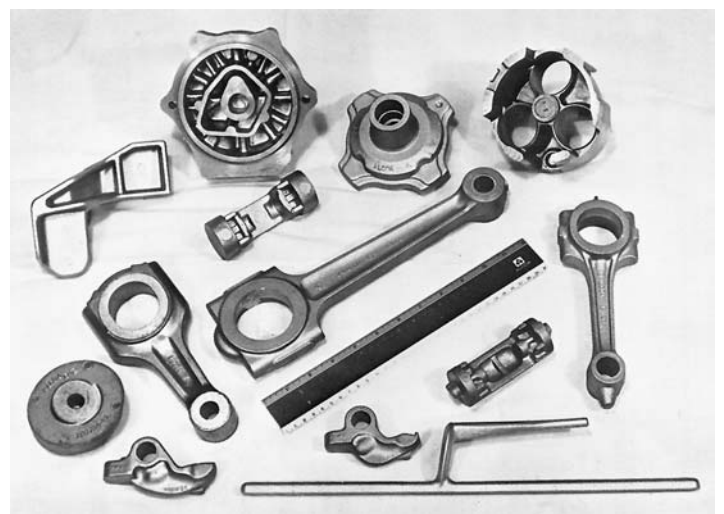


**Fig. 3.12** Examples of castings produced by the vacuum riserless casting (VRC) process include rocker arms, compressor pistons, connecting rods, trowel handles, valve components, and other parts



### 3.5.5 Squeeze Casting

Although a number of process developments have been referred to as squeeze casting, the process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic press is the only version of current commercial interest. The applied pressure and retained contact of the metal with the die surface improves heat transfer and inhibits hydrogen precipitation and shrinkage void formation. The result is a denser, fine-grained casting with excellent mechanical properties.

Squeeze casting has been successfully used for a variety of ferrous and nonferrous alloys in traditionally cast and wrought compositions. Applications of squeeze-cast aluminum alloys include reciprocating engine pistons, brake rotors, automotive and truck wheels, and structural automotive frame components (Fig. 3.13). Squeeze casting is simple and economical, is efficient in its use of raw material, and has excellent potential for automated operation at high rates of production.

### 3.5.6 Semisolid Forming

Semisolid forming incorporates elements of casting, forging, and extrusion. It involves the near-net-shape forming of metal parts from a semisolid raw material that incorporates a uniquely non-dendritic microstructure.

Mechanical or electromagnetic force is employed during billet solidification to fragment the solidifying structure. The result is a spherulitic structure that behaves thixotropically in the liquidus-solidus range. The billet retains its shape at closely controlled temperatures above the melting point at which the shear strength is low, even at relatively high percent fraction solid. When the billet has been reheated, it is forced into dies under pressure to form a casting that retains the characteristics of the starting billet microstructure. Just as important, the mold cavity is filled without the turbulence associated with gravity pouring or the injection of molten metal, and internal porosity formation is minimized by reducing the volume of liquid metal that solidifies from the semisolid condition (Fig. 3.14).



**Fig. 3.13** Automotive parts produced by the squeeze casting process. Courtesy of UBE Industries

A number of alternative approaches to the production of the semisolid raw material have been or are being developed. A process in which particle ingots are continuously fed and mechanically stirred to provide the required semisolid state and microstructure has been developed and used in magnesium alloy casting production. The incompatibility of materials of containment with sufficient strength for this process in molten aluminum remains to be overcome. Attempts to eliminate expensive thin-cast billet through slurry approaches in mold filling have also been undertaken.

Semisolid forming is more costly than conventional casting, but offers unique properties and consistently excellent quality. In addition, the viscous nature of semisolid alloys provides a natural environment for the incorporation of third-phase particles in the preparation of reinforced metal-matrix composites.

Specialized billets are commercially available, and semisolid-formed applications are broadening in the aerospace, automotive, military, and industrial sectors. The process represents an alternative to conventional forgings, permanent mold, investment and die castings, impact extrusions, machined extrusion profiles, and screw machine products. Applications include automotive wheels, master brake cylinders, antilock brake valves, disk brake calipers, power steering pump housings, power steering pinion valve housings, compressor housings, steering column parts, airbag containment housings, power brake proportioning valves, electrical connectors, and various covers and housings that require pressure tightness.

## 3.6 Pressure Die Casting and Its Variations

The production of aluminum alloy castings by the die casting process exceeds that of all other processes. It is ideally suited for high production rate and volume production of dimensionally accurate parts with excellent surface finish. One of the important

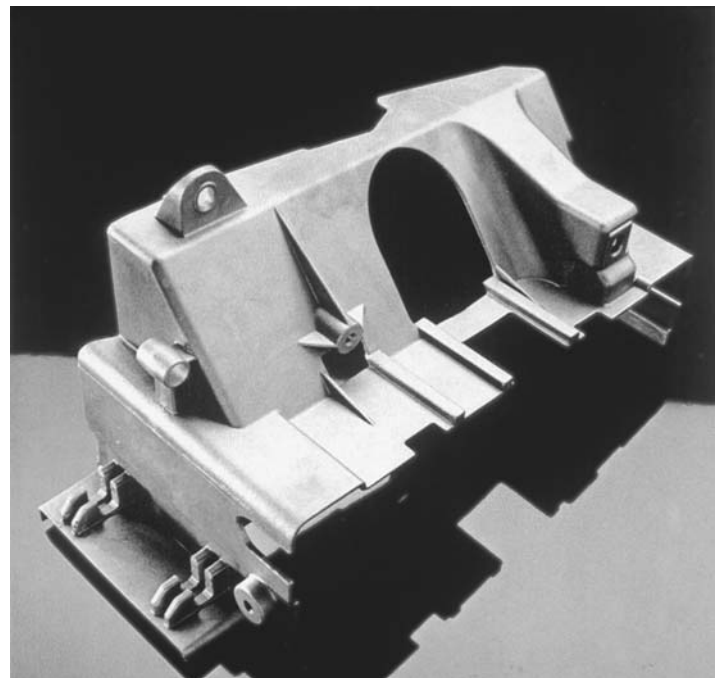


**Fig. 3.14** Semisolid formed alloy A357.0 landing gear component

reasons for the success of die castings has been the development of high-speed precision equipment. Another is the extension of die casting technologies to larger castings with heavier wall thicknesses.

In pressure die casting, molten metal is injected under pressure into water-cooled dies. Pressure is maintained until the part has solidified. Molten metal usually enters the mold by the action of a hydraulic ram in a containment chamber (shot chamber), resulting in rapid filling of the mold cavity. While lubrication is required to facilitate the separation of the casting from the die surface, the dies are otherwise uninsulated. Dies are usually machined from high-quality tool steels.

The die casting process has undergone significant changes through the evolution of machine design and instrumentation as well as process development and controls. The demand for larger, more complex castings with improved quality and lower cost has led to the development and promotion of specialized die casting machines capable of higher rates of production and improved performance.

Die casting machines vary in type, size, and capacity.

There are two basic concepts, hot and cold chamber operation. In the hot chamber process, the shot chamber and piston are immersed in molten metal. Metals such as magnesium and zinc that do not aggressively attack the materials of construction can be efficiently cast by this method with production rate advantages. Despite intensive efforts to develop hot chamber process designs and materials that could be used in aluminum casting, none have been commercially successful. Except in rare cases, all aluminum die casting is performed in cold chamber equipment in which the shot chamber is filled with each cycle, and the chamber and piston assembly are not continuously in contact with molten aluminum.

Die casting machine designs are also differentiated by parting plane orientation. In practice, the dies are mounted on platens that can operate in either vertical or horizontal directions. Early die casting was typically performed with vertical die movement. Today, with exceptions, vertical die casting is restricted to rotor production.

Locking pressure defines the capacity of the machine to contain the pressure generated during the injection cycle. The larger the plan area of the casting and the greater the hydraulic pressure applied, the greater the required locking pressure. Die casting machines are designed with locking pressures from as little as 25 tonnes to more than 4500 tonnes corresponding to injection pressures of up to 40 ksi (280 MPa).

The principles of directional solidification and gravity-based gating and risering are essentially inapplicable to die casting. Gates and runners are used to convey metal from the shot chamber to the die cavity. Geometrical considerations are observed to minimize turbulence, air entrapment, and fragmentation of the metal stream, but no effort other than the use of sustained pressure is used to promote internal soundness. Techniques are used to intensify pressure during the solidification phase to decrease the volume fraction of internal porosity. With metal velocities exceeding 100 ft/s (30 m/s) and solidification rates exceeding 1800 °F/s (1000 °C/s), the greatest quality concern is entrapped gases including combustion or volatilization components of the lubricant and turbulence-related inclusions.

Rapid filling of the mold (20 to 100  $\mu$ s) and rapid solidification under pressure combine to produce a consistently dense, fine-grained and highly refined surface structure with excellent properties including fatigue strength. Internal unsoundness affects bulk properties, the acceptability of machined surfaces, and pressure tightness. Impregnation is routine for die castings that must contain gases or liquids under substantial pressure. Internal unsoundness generally prevents full heat treatment and welding because of the risk of blister formation when die castings are exposed to elevated temperatures. Lower-temperature thermal treatments for stabilization or hardening are routinely used. In special cases and in restricted casting areas, limited welding can also be performed.

The die casting process is least alloy tolerant of important commercial casting processes. Solidification conditions require alloys of superior castability and that display good resistance to cracking at elevated temperatures. The highly castable alloys of the aluminum-silicon family are the most common. Of these, alloy 380.0 and its variations comprise about 85% of total die casting production. These compositions provide attractive combinations of cost, strength, hardness, and corrosion resistance in the as-cast state, with excellent fluidity and resistance to hot cracking. Aluminum-silicon alloys lower in copper, such as 360.0, 364.0, 413.0, and 443.0, offer improved corrosion resistance and excellent castability.

Hypereutectic aluminum-silicon alloys including 390.0 have become more important in wear-resistant applications.

Magnesium content is usually controlled at low levels to minimize oxidation and the generation of oxides in the casting process. Most commonly used die casting alloys specify restrictive magnesium limits. Nevertheless, aluminum-magnesium alloys can be die cast. Alloy 518.0, for example, is specified when the highest corrosion resistance and the brightest, most reflective finish are required.

Iron contents of 0.7% or greater are preferred to maximize elevated-temperature strength, to facilitate ejection, and to minimize soldering to the die face. Iron content is usually  $1 \pm 0.3\%$ , but greater concentrations are also used. Improved ductility through reduced iron content has been an incentive resulting in widespread efforts to develop a tolerance for iron as low as approximately 0.25%. These efforts focus on process refinements, design modifications, and improved die lubrication. At higher iron concentrations, there is a risk of exceeding solubility limits of coarse Al-Fe-Cr-Mn segregate at molten metal temperatures. Sludging or precipitation of segregate is prevented by chemistry controls related to metal temperature. A common rule is:

$$\text{Fe} + 2(\text{Mn}) + 3(\text{Cr}) \leq 1.7$$

where element values are expressed in weight percent.

Die casting is especially suited to production of large quantities of relatively small parts. Typical aluminum die castings weigh from a few ounces to more than 100 lb (50 kg).

Close tolerances and excellent surface finishes are characteristic. Aluminum alloys can be die cast to tolerances of  $\pm 4$  mils/in. ( $\pm 0.004$  in./in.) and commonly have finishes as fine as 50  $\mu$ m. (1.3  $\mu$ m). Parts are cast with walls as thin as 0.040 in. (1.0 mm). Cores,



which are made of metal, are restricted to simple shapes that permit drawing or removal after solidification is complete.

### 3.6.1 Acurad Die Casting Process

An acronym for accurate, rapid, and dense, the Acurad process claimed a degree of directional solidification from thermal analysis, die cooling and gating design, modulated lower metal injection velocities, and intensified injection pressures during solidification through the use of a secondary plunger. In effect, Acurad represents a compromise between die casting and permanent mold principles.

### 3.6.2 High-Integrity Pressure Die Casting

The combination of optimal die casting practices marries metallurgical and mechanical capabilities to provide quality levels exceeding those of conventional die casting. Solid-state lubricants are used in place of volatile die lubricants. Dies, lubricants, and ejector systems are designed to facilitate casting removal at reduced iron levels. The die cavity is evacuated before injection. Molten metal processing to reduce dissolved hydrogen and entrained nonmetallics approximates that used for gravity casting. Molten metal handling and the transfer of molten metal to the shot chamber are nonturbulent, and the injection sequence is adjusted to promote nonturbulent die filling. Large, thin-wall automotive structures and other high-quality die castings are being produced that display strength, ductility, and toughness that cannot be achieved in other die casting processes. With improved internal quality, high-integrity die castings can be welded and heat treated, although some limitations still apply.

### 3.6.3 Pore-Free Pressure Die Casting

In the “pore-free” process, the die cavity is purged with oxygen before metal injection. The oxygen reacts with molten aluminum to form oxides that influence fluid flow and by being chemically consumed reduces the tendency for entrapment as gas pores. The oxides are concentrated in the casting surface after solidification so that inclusion effects on properties are minimized.

### 3.6.4 Vacuum Die Casting

The application of a partial vacuum to the die cavity evacuates air and volatilized lubricant from the mold before and during metal injection. Vacuum die casting reduces the tendency for air entrapment resulting from rapid and turbulent die filling. The improvement in soundness results in degrees of acceptability for welding and heat treatment.

### 3.6.5 Rotor Casting

Most cast aluminum motor rotors are produced in specialized compositions by smaller vertical die casting machines. The objective is consistent electrical performance. Alloys 100.0, 150.0, and 170.0 (99.0, 99.5, and 99.7% Al, respectively) specify impurity limits and ratios for the formation of intermetallics least harmful to castability and limit the concentrations of peritectic elements most detrimental to electrical conductivity. Titanium and vanadium are precipitated or complexed by boron additions. Iron and silicon contents are controlled with the objective of promoting  $\alpha$ Al-Fe-Si formation that is less detrimental to castability. These impurity controls improve and minimize variations in conductivity and re-

duce the tendency for microshrinkage and cracking during solidification.

Because unalloyed aluminum can be purchased at lower cost than rotor alloys, there has been a trend for their substitution in rotor production. For example, P1020 unalloyed smelter ingot has the same purity as 170.2 but without impurity ratio controls and with uncontrolled titanium and vanadium content. Ignoring these differences results in variable electrical performance and poor castings.

Minimum and typical conductivities for each grade are:

| Alloy | Conductivity, %IACS |         |
|-------|---------------------|---------|
|       | Minimum             | Typical |
| 100.1 | 54                  | 56      |
| 150.1 | 57                  | 59      |
| 170.1 | 59                  | 60      |

Rotor alloy 100.0 with larger concentrations of iron and other impurities displays superior die casting characteristics. With higher iron content, crack resistance is improved and there is a lower tendency for internal shrinkage. This alloy is recommended when the maximum dimension of the part is greater than 5 in. (125 mm).

For the same reasons, alloy 150.0 offers castability advantages over alloy 170.0.

For rotors requiring high resistivity for higher starting torque, conventional die casting or other highly alloyed compositions are used. The most common are 443.2 and A380.2. By choosing alloys such as these, conductivities from 25 to 35% IACS can be obtained. Experimental rotor alloys have been developed with conductivities as low as 18% IACS.

Although gross casting defects may adversely affect electrical performance, the conductivity of alloys employed in rotor manufacture is almost exclusively controlled by composition. Simple calculation using these values accurately predicts total resistivity and its reciprocal, conductivity, for any composition. An easy-to-use formula for conductivity that offers sufficient accuracy for most purposes is:

$$\text{Conductivity, \%IACS} = 63.50 - 6.9(\text{Fe} + \text{Si}) - 83(\text{Ti} + \text{V} + \text{Mn} + \text{Cr})$$

where element values are expressed in weight percent.

More accurate calculations may be made from the elemental resistivities given in Table 8.4, in Chapter 8.

## 3.7 Premium Engineered Castings

A premium engineered casting is one that provides higher levels of quality and reliability than found in conventionally produced castings. Premium engineering includes intimately detailed design and control of each step in the manufacturing sequence. The results are minimally variable premium strength, ductility, soundness, dimensional control, and finish. Castings of this classification are notable primarily for mechanical property performance that reflects extreme soundness, fine dendrite-arm spacing, and well-refined grain structure.

Premium engineered casting objectives require the use of chemical compositions competent to display superior properties. Alloys

considered to be premium-strength compositions are listed in specification AMS-A-21180, which is extensively used in the United States for premium casting procurement. They include A201.0, A206.0, 224.0, 249.0, 354.0, C355.0, A356.0, A357.0, D357.0, 358.0, and 359.0.

Premium engineered aluminum castings represent the culmination of decades of research and development involving molten metal treatment, methods for the removal of included matter, measurement or assessment of dissolved hydrogen, gating development, microstructural modification and refinement, casting processes, mold materials, and the development of high-strength, ductile alloys. Each of these developments was necessary to advance casting capabilities to meet an increasingly challenging range of application requirements. The marriage of superior technologies in all phases of casting design and production was essential for meeting the most difficult of these challenges. The incentive was the cost-effective replacement of more expensive wrought product assemblies by competent monolithic cast structures.

### 3.7.1 Melt Processing

The principles of sparging for the removal of dissolved hydrogen had been developed in the late 1920s and 1930s. The use of active gases such as chlorine and the physicochemical separation of entrained oxides and other nonmetallics by fluxing became known in the 1930s. The use of diffusers for more efficient gas fluxing was developed later.

By 1950, particulate filtration and countercurrent fluxing using nitrogen, argon, chlorine, and combinations of these gases became common for wrought alloy production, and variations of these processes were being used in gravity casting foundries.

The later development of rotary degassing systems was quickly adapted to foundry use.

### 3.7.2 Melt Quality Assessment

To a large extent, melt quality has been assessed by variations of the Straube-Pfeiffer test in which the relationship of hydrogen solubility and pressure was qualitatively measured. The absence of entrained oxides was assessed by their influence on hydrogen precipitation under reduced pressure. A semiquantitative approach using sample densities was developed and used extensively as a process control tool (Ref 4). For greater sensitivity, controlled vibration during sample solidification at absolute pressures of 0.04 to 0.10 psi (2 to 5 mm Hg) was employed. Real-time measurement of dissolved hydrogen by partial pressure diffusion in molten metal supplemented vacuum test results. Validation of hydrogen assessments was provided by solid-state extraction techniques.

### 3.7.3 Solidification

Academics were largely responsible for improved mathematics-based understanding of solidification behavior. The parameters of metallurgical structure that were controlled in the solidification process were extensively studied. The relationships of dendrite arm spacing and grain size and type on physical and mechanical properties were established, and the influence of variations in soundness caused by hydrogen porosity, shrinkage, and inclusions on strength and ductility were broadly used in the development of new general

procurement and nondestructive evaluation specifications and standards.

Trial and error in alloy development gradually gave way to more systematic construction based on experience and the predictable interrelationship of elements in soluble and insoluble phase formation under differing solidification conditions.

The principles of directional solidification are easily grasped, but their translation to practice for complex cast parts remains problematic. There are nevertheless excellent simulation models and programs for predicting static and dynamic solidification patterns for specific part designs.

### 3.7.4 Solidification Rate

The relationship of properties and dendrite arm spacing has significantly influenced the premium engineered casting effort. Solidification rate not only improves tensile properties, but also dramatically improves ductility. Exploiting this relationship with appropriate alloys moved engineered aluminum castings away from the image of brittleness and damage intolerance that historically characterized design engineers' perceptions.

### 3.7.5 Mold Materials

Investment casting produced small parts in which dimensional accuracy and surface finish were important criteria. Plaster molds were used in the production of dimensionally accurate cast parts such as impellers and tire molds. There were corollary pattern, mold material, and mold processing developments. Differences in the molding and heat extraction characteristics of differing sands were measured, and at the same time supplier developments in dry sand binders were studied and evaluated.

In permanent mold, variations in mold wash chemistry and application were used with air, mist, and water cooling to control solidification. On occasion, copper and ceramic inserts were designed into the mold to promote solidification directionality. The use of steel chills, contoured sections, and mold plates was normal in sand casting.

The use of all available mold components from most insulating (foamed plaster) to most rapid heat extraction (water-cooled copper) could be incorporated in mold designs to reproducibly alter solidification in order to promote the highest possible degree of internal soundness. Computer simulations of mold filling dynamics and solidification that incorporate differences in heat extraction through finite-element analysis are gradually supplanting art and instinct in process designs.

The result is a composite mold design of significant complexity using dry sand and at least several other mold materials for each configuration.

### 3.7.6 Alloys

All alloys employed in premium casting engineering work are characterized by optimal concentrations of hardening elements and restrictively controlled impurities. Although any alloy can be produced in cast form with properties and soundness conforming to a general description of premium values relative to corresponding commercial limits, only those alloys demonstrating yield strength, tensile strength, and especially elongation in a premium range belong in this grouping. They fall into two categories: high-strength

aluminum-silicon alloys containing magnesium or magnesium and copper, and alloys of the 2xx.0 series, which by restricting impurity element concentrations provide outstanding ductility, toughness, and tensile properties with notably poorer castability.

The minimum properties of premium-strength alloys might be considered 40 ksi (275 MPa) tensile strength, 30 ksi (205 MPa) yield strength, and 3.0% elongation. Much higher minima are routinely specified.

In all premium casting alloys, impurities are strictly limited for the purposes of improving ductility. In aluminum-silicon alloys, iron is controlled at or below 0.010% with measurable advantages in the range of 0.03 to 0.05%. Beryllium is present in A357.0 and 358.0 alloys, not to inhibit oxidation although that is a corollary benefit, but to alter the form of the insoluble phase to a more nodular form less detrimental to ductility.

Most of the compositions designated as premium engineered alloys had their origins in the 1950s and early 1960s. Alloy A356.0, registered in 1955, and B356.0 in 1956 were derivatives of 356.0 alloy which was originally developed in 1930. Similarly, alloy C355.0 dates from 1955, while the parent 355.0 was first used in 1930. Alloys 359.0 and 354.0 were developed in 1961. Alloy A357.0 (1962) had its origins in Tens-50 alloy that was also first registered in 1961. Examples of premium engineering castings in alloys A357.0 or D357.0 are shown in Fig. 3.15 to 3.19.

The extremely high strength and toughness capabilities of various typically 4.5% Cu alloys including 201.0, 204.0, 206.0, 224.0, and 249.0 have their roots in 295.0 alloy, which dates from 1921 and in earlier European compositions. Most were introduced or appeared in refined versions during the period from 1968 to 1974.

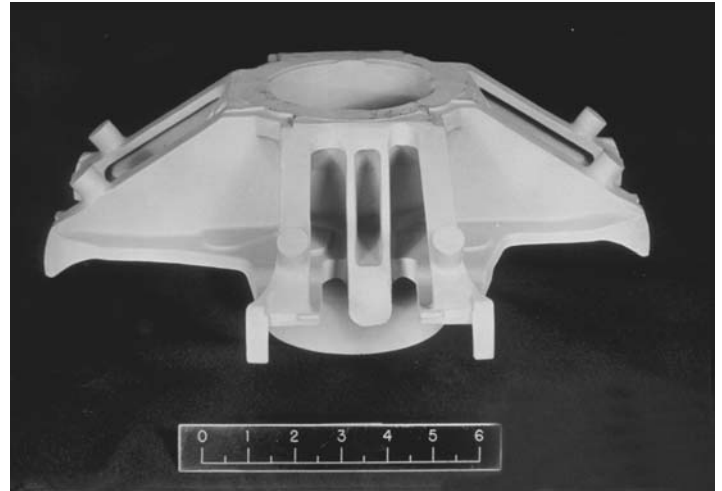


**Fig. 3.16** Premium engineered casting helicopter rotor hub

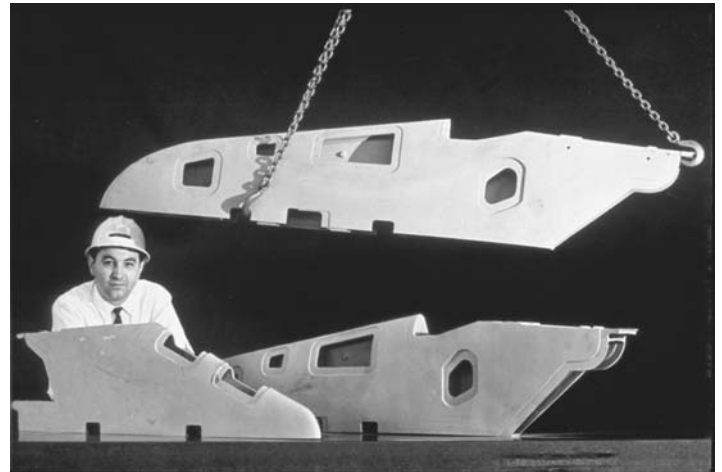


**Fig. 3.17** Premium engineered casting aircraft pylons

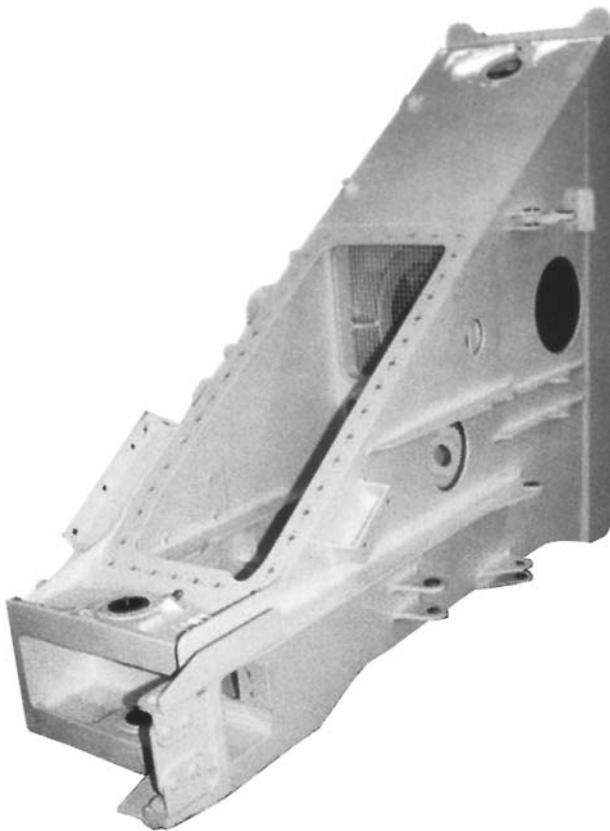


**Fig. 3.15** One-piece alloy D357.0 main landing gear door uplock support for the 767 airplane. The casting replaced a sheet metal assembly; the conversion eliminated 27 separate parts and reduced assembly time by 65%. Source: Ref 5

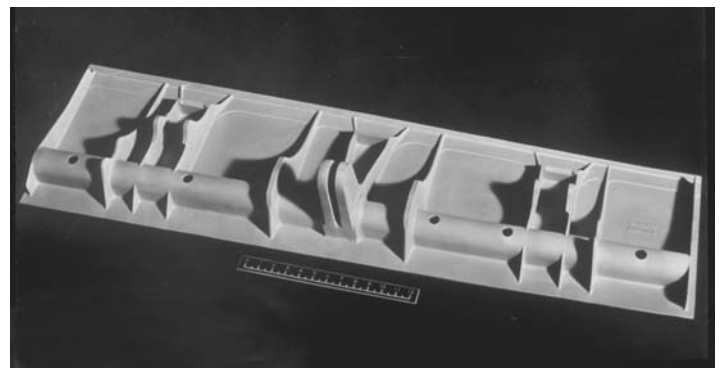


**Fig. 3.18** Premium engineered casting aircraft wing flap



### 3.7.7 Aluminum-Silicon Eutectic Modification and Grain Refinement

The use of chemical modifiers in hypoeutectic aluminum-silicon alloys has been the subject of ongoing research. Beneficial effects on solidification, feeding, and properties are well established. Research has included the effects of a large number of elements and element combinations on eutectic and phase structures. The most potent modifier, sodium, has been extensively used in all gravity casting operations. The advantageous interaction of sodium and strontium was also recognized and became the basis for the use of both elements in modification additions.

For premium engineered castings, the artifacts of modifier additions—notably increased hydrogen solubility and the introduction of large amounts of hydrogen by alloying methods—made eutectic modification counterproductive for most premium engineered castings. Casting results for rapidly solidified unmodified castings proved superior to those of chemically modified, less-sound castings produced under the same conditions.

At one time, essentially uncontrolled titanium additions were routinely made for grain refinement. Extensive studies of the ratios of titanium and boron and their intermetallic forms most effective for grain refining resulted in rapid advances in foundry practice. Later studies would provide new insights that continuously redefined the advanced standards and procedures for grain structure control in premium engineered casting production.

### 3.7.8 Mold Filling

The inevitable degradation of melt quality that occurs in drawing and pouring through conventional methods was recognized as a significant barrier to achieving premium engineered quality levels and properties. Very significant efforts had been made to evaluate different pouring and gating approaches. These included siphon

ladles, sprue/gate/runner ratios, runner overruns, dross traps, pouring cup designs, strainers and screens, and nonvortexing cross-sectional geometry of downsprues and runners. The use of optimal gating designs and rigorously controlled practices are integral components of premium casting technology.

Several developments have altered mold-filling options; these developments are described in the following paragraphs.

First, the low-pressure casting process achieved commercial importance in the United States in the 1950s. A number of challenges that were unaddressed by commercial low-pressure systems were successfully met. A cam-controlled back-pressure method based on gross casting weight was used to retain residual metal levels at the top of the feed tube. This feature prevented the inclusion spawning characteristic of normal low-pressure cycles. In-gate filtration and screening methods were also devised.

The range of part designs and alloys that were cast would be considered unusual today when the low-pressure process has become principally known for automotive wheel production. Instead, the low-pressure method was considered a means of nonturbulent mold filling with a number of additional advantages that included reduced gross/net weight and lower pouring temperature. Some examples were diesel engine and compressor pistons, air-conditioner compressor bodies, bearings, furniture parts, and missile fins. Geometric symmetry, which is normally a criterion for low-pressure production was not considered a prerequisite, and many of the castings that were produced used conventional risering rather than exclusively relying on the in-feed for shrinkage compensation.

These developments were adapted to premium engineered plaster and dry sand parts. High-speed rotors and impellers were excellent examples, but many other premium engineered casting configurations were made by low-pressure mold filling.

Second, countergravity mold-filling methods were developed involving the use of mechanical or induction pumps.

Third, various techniques have been developed and are in use for filling molds quiescently by displacement of molten metal.

Fourth, solidification time was not a significant factor in expendable mold production when extensive chilling was used, but it was always a factor in permanent mold. For this reason, and to overcome other low-pressure process limitations, vacuum riserless casting (VRC) was developed in the early 1960s. Rather than pressurize a contained molten reservoir, the application of a vacuum on the mold cavity drew metal from the bath through a short fill tube. The metal source was exposed for periodic treatment, the distance from subsurface metal entry to the casting cavity was minimal, dies were extensively chilled, and the process could be highly automated. While only relatively small and simple shapes were produced by the VRC method, productivity and mechanical properties were exceptional. More than 20 million air-conditioner pistons and millions of rocker arms were produced by this process.

Fifth, the level pour process for premium engineered castings was developed. This process had its origins in the direct chill process that was developed for fabricating ingot. It was natural that the shared concerns for metal distribution and solidification principles would result in the synthesis of process concepts.

Aluminum-tin alloy bearings, which were typically hollow or solid cylinders, could be produced by the direct chill process, but



**Fig. 3.19** Premium engineered casting aircraft canopy



segregation and safety concerns led to a variation in which metal was introduced to the bottom of a permanent mold through a moving pouring cup that traversed the length of the mold. Quiescent flow and the continuous layering of molten metal provided improved internal quality. Excellent soundness was obtained without the use of the extensive risering normally required for these long solidification range alloys, pouring temperature was reduced, and the solidified structure was more chemically homogeneous than in conventionally cast parts.

With determined engineering, the same approach was successfully used for more complex configurations with more challenging metallurgical requirements. The cost of doing so in permanent mold was not typically justified. However, aircraft and aerospace parts in the limited quantities normally associated with sand casting offered exciting opportunities for level pour technology, and a large number of prototype and production parts were produced by this method. In its final form, the assembled mold was lowered on a hydraulic platform through a trough arrangement that provided nonturbulent flow of metal through entry points that paralleled the vertical traverse of the mold. Metal flow was controlled by the dimensions of the entries and the lowering rate, which could be modulated for cross-sectional variations as a function of mold travel. Characteristic of the direct chill process on which it was based, the level pour process features quiescent molten metal flow, minimized feeding distances, and reduced pouring temperatures.

### 3.7.9 Quality Assurance

The production of premium engineered castings involves extensive nondestructive evaluation and certification. Acceptance usually requires radiographic examination, fluorescent penetrant inspection, and dimensional verification. Mechanical properties are often determined in destructive tests, usually involving machined subsized specimens taken from designated areas of randomly selected castings.

Practices developed for first article qualification must be meticulously defined, and specification restrictions and requalification procedures are imposed on changes or modifications. In some cases, the practices must be disclosed and in others may remain proprietary. Confirmation that practices have been observed may take the form of furnace and heat treatment records, for example, by government and/or customer on-site inspectors. Another possibility is that these records may become part of the certification process in which inspection records, mechanical property test results, and radiographic film are submitted with the castings.

The objective of premium engineered casting is the ultimate development of material properties, consistency, and performance. The pioneering developments of these efforts have been continuously refined, and today a number of foundries demonstrate the unique capabilities for meeting the exacting standards that are required.

### 3.7.10 Relevance of Premium Casting Engineering

Just as technologies developed in the space program have found applications in industry, premium engineered casting developments have important implications for all aluminum foundries. The principles and processes of premium casting can be cost effectively applied to conventional aluminum casting production.

From the applications standpoint, strength, ductility, and other mechanical attributes are only equal in importance to reliability. Variability in soundness and performance remains the greatest concern in engineered structural applications for which castings compete. The processes and controls for narrowing material variations in premium engineered castings form part of the basis for aggressive cooperative materials development programs in automotive and aerospace applications that emphasize process capabilities rather than reliance on nondestructive evaluation. No premium engineered castings foundry could survive the inspection losses if the process was not capable of consistently meeting specified requirements. No commercial foundry can expect to remain competitive if the casting process cannot deliver consistent quality with minimum internal and external losses without reliance on expensive and time-consuming nondestructive testing.

The goal of reducing product variability and the consistent achievement of specified product characteristics through the selected use of processes and controls developed for premium engineered castings is within the range of capability for all aluminum foundries and for the fullest range of casting types and specifications.

## 3.8 Other Process Technologies

Other process technologies of importance for aluminum alloy castings that affect properties and performance are:

- Metallurgical bonding
- Metal-matrix composites (MMCs)
- Hot isostatic pressure

### 3.8.1 Metallurgical Bonding

It is possible to mechanically or metallurgically bond dissimilar metals in aluminum casting.

The Al-Fin Process results in a continuous metallurgical structure from the insert through an intermetallic boundary to the base alloy of the casting. While inserts can be simply placed in the mold before pouring to form a mechanical union between the two materials, the union is dependent only on the intimacy of contact and the force exerted by differences in thermal contraction characteristics. Copper, ferrous, and other alloy components such as cast-in cooling coils and piston wrist pin struts become integral to the cast structure.

By preimmersing inserts in molten aluminum so that an intermetallic layer is developed by chemical attack, the insert rapidly placed in the mold can be metallurgically rather than mechanically bonded to the cast aluminum structure.

Compression ring groove inserts in diesel engine pistons and the bearing surfaces of rotating parts are often metallurgically bonded to ensure structural integrity, strength, and heat transfer. Various iron grades, steel, and stainless steel elements have been successfully and routinely bonded to aluminum casting structures. High nickel iron and steel offer advantages in the similarity of expansion coefficients so that stresses through operating temperature ranges are reduced.

Preimmersion baths of aluminum-silicon alloys provide uniform thin intermetallic layers with minimal residual retention of bath when inserts are transferred to the mold. Since iron is continuously dissolved, the bath must be periodically discarded or diluted to prevent the deposition of iron containing insoluble phases on the insert surface.

Because the insert must be positioned, the mold closed and poured before the aluminum residual to the insert surface solidifies, bonding is typically performed in permanent molds.

### 3.8.2 Cast Aluminum-Matrix Composites

Incorporating particles or fibers of dissimilar materials in cast aluminum structures substantially alters material properties. Ceramics, graphite, alumina, silicon carbide, other carbides, and nitrides wet by molten aluminum form a reinforced structure typically displaying substantially increased modulus of elasticity, higher strength, and improved wear resistance. While tensile strengths in excess of 100 ksi (700 MPa) can be achieved, the characteristic ductility of composite structures is limited.

Powder metallurgy composites are commercially important, and there is a growing technical capability and market for cast aluminum metal-matrix composite parts. Cast composites offer cost-advantaged near-net-shape capabilities in sizes and configurations not achievable in powder metallurgy or by other forming methods with the same advantages in exceptional specific stiffness (elastic modulus-to-weight ratio), strength, wear resistance, and the option of selectively reinforcing or altering local material properties.

Most cast MMC parts are produced from prealloyed/mixed alloy in conventional casting processes. Mechanical or other forms of agitation are employed to maintain the homogeneous suspension of particulate after melting. The segregation of density-differentiated particles in aluminum is strongly influenced by particle size and time. If the dispersion can be maintained through melting, holding, and mold filling, more rapid solidification characterized by permanent mold and die casting promotes the more uniform distribution of particles in the solidified structure.

Recent developments concern increasingly fine particle sizes to nanodimensions and shapes such as fibrules and microspheres, which will result in a reduced tendency for density segregation before and during solidification. Finer particulate distribution has also shown improvements in ductile behavior while preserving advantages in stiffness and strength. Another notable development involves the use of low-cost particulate such as represented by industrial waste materials such as fly ash to produce low-density, property-enhanced parts with reduced material costs.

The most important castable aluminum-base MMC compositions originate in conventional alloys to which from 10 to 20 vol% particulate silicon carbide (SiC), alumina, or other ceramic material has been added. Particle wetting and distribution are functions of ingot production or of procedures used during melting and blending. Composite ingots are remelted, uniform dispersion of particulate is mechanically or inductively ensured, and casting is accomplished using conventional foundry practices and equipment. The fluidity and flow characteristics of composite alloys are not significantly different from those of conventional unreinforced alloys so that mold designs and gating systems of routine production

can be successfully used. Production parts have been cast in sand, permanent mold, pressure die, and investment processes.

Metal-matrix composites are also cast by impregnation of fiber cake in gravity and squeeze casting processes. Impregnated cast composites begin with a permeable ceramic cake formed to comprise a section of the casting to be reinforced. The cake is intruded to obtain the composite structure.

Recent alternative developments involving matrix reinforcement concepts include the investigation of postsolidification surface treatments including flame and plasma spray deposition, and high-intensity infrared and plasma heating of ceramic overlays.

Typically, MMC scrap cannot be recovered except by separation of the composite component.

Existing or emerging applications for cast aluminum composites are:

- Brake rotors (Fig. 3.20)
- Cylinder liners (Fig. 3.21)
- Power-steering pulleys
- Connecting rods

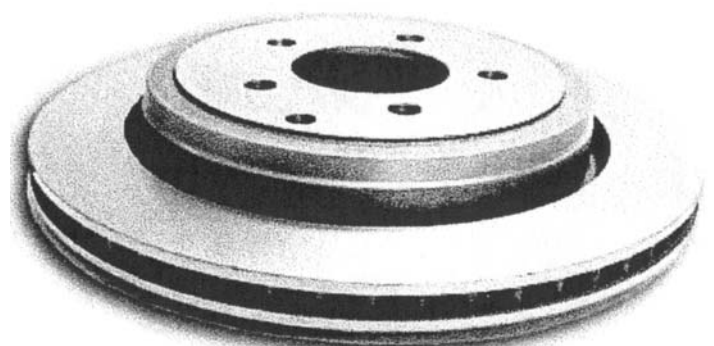


**Fig. 3.20** Alloy 359/SiC/20p metal-matrix composite brake rotor. Source: Ref 6

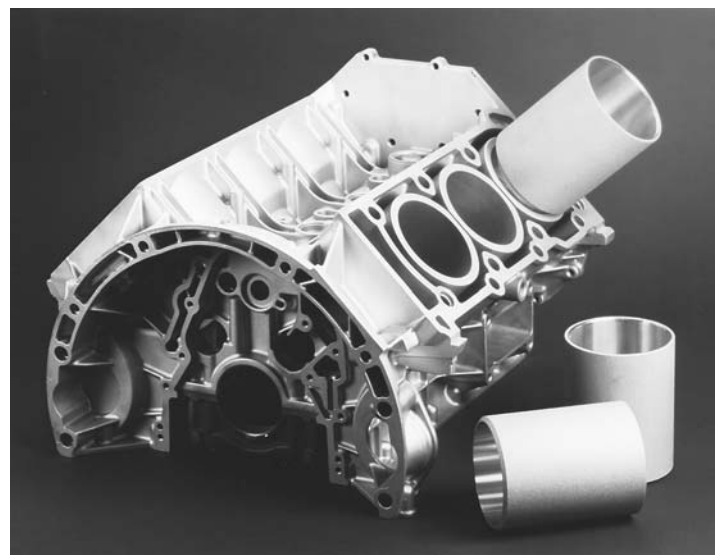


**Fig. 3.21** Metal-matrix composite (MMC) cylinder liners. The MMC offers an alternative to cast iron or hypereutectic aluminum-silicon alloy for this application.

- Bicycle frames
- Scraper blades and shoes
- Sporting equipment
- Golf club heads
- Aerospace optical systems
- Electronic/avionic thermal management components
- Pressure vessels
- Brackets
- Wave guides

### 3.8.3 Hot Isostatic Pressing (HIP)

The application of hot isostatic pressing (HIP) to aluminum alloys following casting is a key technology for improving properties by reducing or eliminating the effects of porosity and inclusions. This technology is sufficiently important that it is covered in a separate chapter (Chapter 6), following the discussion of the nature and cause of such imperfections.

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## CHAPTER 4

# The Effects of Microstructure on Properties

Microstructural features are products of metal chemistry and solidification conditions. The microstructural features, excluding defects, that most strongly affect mechanical properties are:

- Size, form, and distribution of intermetallic phases
- Dendrite arm spacing
- Grain size and shape
- Eutectic modification and primary phase refinement

### 4.1 Intermetallic Phases

Controlling element concentrations and observing stoichiometric ratios required for intermetallic phase formation results in preferred microstructures for property development. Solidification rate and the rate of postsolidification cooling promote uniform size and distribution of intermetallics and influence their morphology. Slower rates of solidification result in coarse intermetallics and second-phase concentrations at grain boundaries. Phase formation is diffusion controlled so that more rapid solidification and more rapid cooling to room temperature from solidification temperature

results in greater degrees of retained solid solution and finer dispersions of smaller constituent particles.

### 4.2 Dendrite Arm Spacing

In all commercial processes, with the exception of semisolid forming, solidification takes place through the formation of dendrites from liquid solution. The cells contained within the dendrite structure correspond to the dimensions separating the arms of primary and secondary dendrites and are exclusively controlled for a given composition by solidification rate (Fig. 4.1).

There are at least three measurements used to describe dendrite refinement:

- *Dendrite arm spacing*: The distance between developed secondary dendrite arms
- *Dendrite cell interval*: The distance between centerlines of adjacent dendrite cells
- *Dendrite cell size*: The width of individual dendrite cells

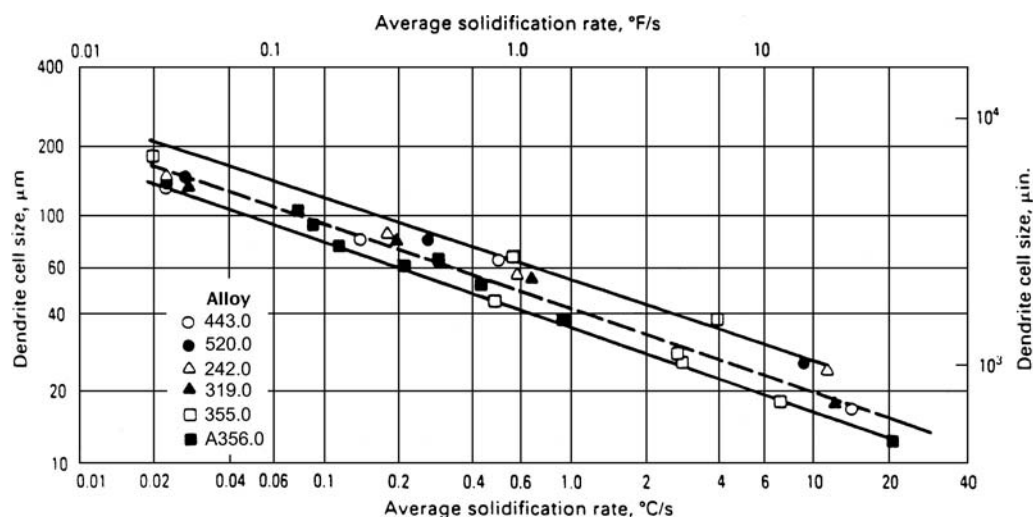


Fig. 4.1 Dendrite arm spacing and dendrite cell size as a function of local solidification rate. Source: Ref 1

The larger the dendrite arm spacing, the coarser the microconstituents and the more pronounced their effects on properties. Finer dendrite arm spacing is desirable for improved mechanical property performance (Fig. 4.2, 4.3) (Ref 2).

Cooling rates directly control dendrite arm spacing, which influences property development and substantially improves ductility:

| Casting processes   | Cooling rate |      | Dendrite arm spacing |          |
|---------------------|--------------|------|----------------------|----------|
|                     | °F/s         | °C/s | mils                 | μm       |
| Plaster, investment | 1.80         | 1    | 3.94–39.4            | 100–1000 |
| Green sand, shell   | 18.0         | 10   | 1.97–19.7            | 50–500   |
| Permanent mold      | 180.0        | 100  | 1.18–2.76            | 30–70    |
| Die                 | 1800         | 1000 | 0.20–0.59            | 5–15     |

### 4.3 Grain Refinement

Fine, equiaxed grains are desired for the best combination of strength and ductility by maximizing grain-boundary surface area and more finely distributing grain-boundary constituents (Ref 3). Coarse grain structure and columnar and feather or twin-columnar grains that form with high thermal gradients in low-alloy-content

compositions are by comparison detrimental to mechanical properties. The type and size of grains formed are functions of alloy composition, solidification rate, and the concentration of effective grain nucleation sites.

Increased solidification rate reduces grain size (Ref 4), but solidification rates in complex cast structures typically vary and the degree of grain refinement practically achievable in commercial gravity casting processes is lower than that obtained by effective heterogeneous nucleation through grain-refiner additions before casting (Fig. 4.4).

All aluminum alloys can be made to solidify with a fully equiaxed, fine-grain structure through the use of suitable grain-refining additions (Ref 5, 6). The most widely used are master alloys of titanium or of titanium and boron. Aluminum-titanium refiners generally contain from 3 to 10% Ti. The same range of titanium concentrations is used in Al-Ti-B refiners with boron contents from 0.2 to 1% and titanium-to-boron ratios ranging from 5 to 50. Selected carbides also serve grain-refining purposes in aluminum alloys (Ref 7).

Although grain refiners of these types can be considered conventional hardeners or master alloys, they differ from true master alloys added to the melt exclusively for alloying purposes. To be effective, grain refiners must introduce controlled, predictable, and operative quantities of aluminides and borides or carbides in the correct form, size, and distribution for grain nucleation. Refiners in rod form, developed for the continuous treatment of aluminum in primary operations and displaying clean, fine, unagglomerated microstructures, are available in sheared lengths for foundry use. In addition to grain-refining master alloys in waffle or rolled rod form, salts, usually in compacted form that react with molten aluminum to form combinations of  $TiAl_3$  and  $TiB_2$ , are also available.

Transduced ultrasonic energy has been shown to provide degrees of grain refinement under laboratory conditions (Ref 8, 9). No commercial use of this technology has been demonstrated. The application of this method to engineered castings is problematic.

### 4.4 Aluminum-Silicon Eutectic Modification

The properties of hypoeutectic aluminum-silicon alloys can be affected by modifying the form of the eutectic. A finer, more fibrous eutectic structure can be obtained by increased solidification rate and by the addition of chemical modifiers. Calcium, sodium, strontium, and antimony are known to influence the degree of eutectic modification that can be achieved during solidification. Figure 4.5 illustrates variations in degree of modification achieved by modifier additions.

Sodium is arguably the most potent modifier, but its effects are transient because of oxidation and vapor pressure losses. Strontium is less transient but may be less effective for modification under slow solidification rates (Fig. 4.6).

The combination of sodium and strontium offers advantages in initial effectiveness. Calcium is a weak modifier with little commercial value. Antimony provides a sustained effect, although the result is a finer lamellar rather than fibrous eutectic. The effects of sodium, strontium, and Na + Sr on modification are shown in Fig. 4.6 and 4.7.

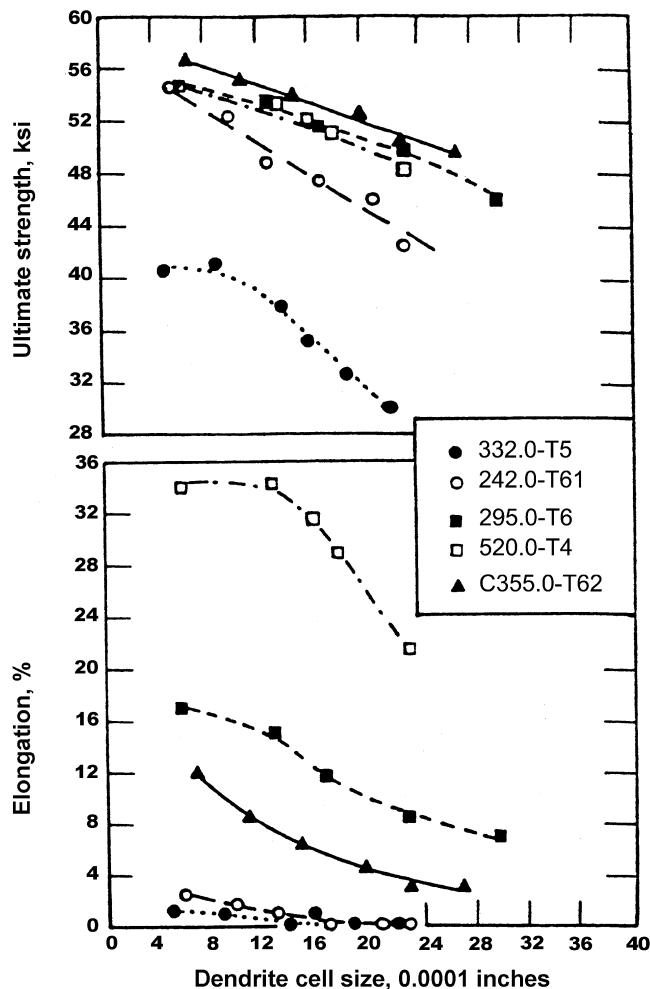


Fig. 4.2 Dendrite cell size effects on the strength and elongation of several aluminum casting alloys. Source: Ref 1

The addition of metallic sodium to molten aluminum creates turbulence that can result in increased hydrogen and entrained oxide levels. The use of hygroscopic salts including NaCl and NaF for modification also risks oxide formation and increased dissolved hydrogen content. Postaddition fluxing to restore melt quality increases the rate of sodium losses. The excessive use of sodium ( $>0.01$  wt%) increases misrun tendencies through increases in surface tension and diminished fluidity.

Strontium additions are usually made through master alloys containing up to 10% of the modifier. While these additions are made

with minimum melt degradation, strontium is associated with an increased tendency for hydrogen porosity, either through increasing hydrogen solubility or decreased surface tension.

The greatest benefits of eutectic aluminum-silicon modification are achieved in alloys containing from 5% Si to the eutectic concentration. The addition of modifying elements to these alloys results in a finer lamellar or fibrous eutectic structure. The modifying additions either suppress the growth of silicon crystals within the eutectic or equilibrate silicon-matrix growth rates, providing finer lamellae.

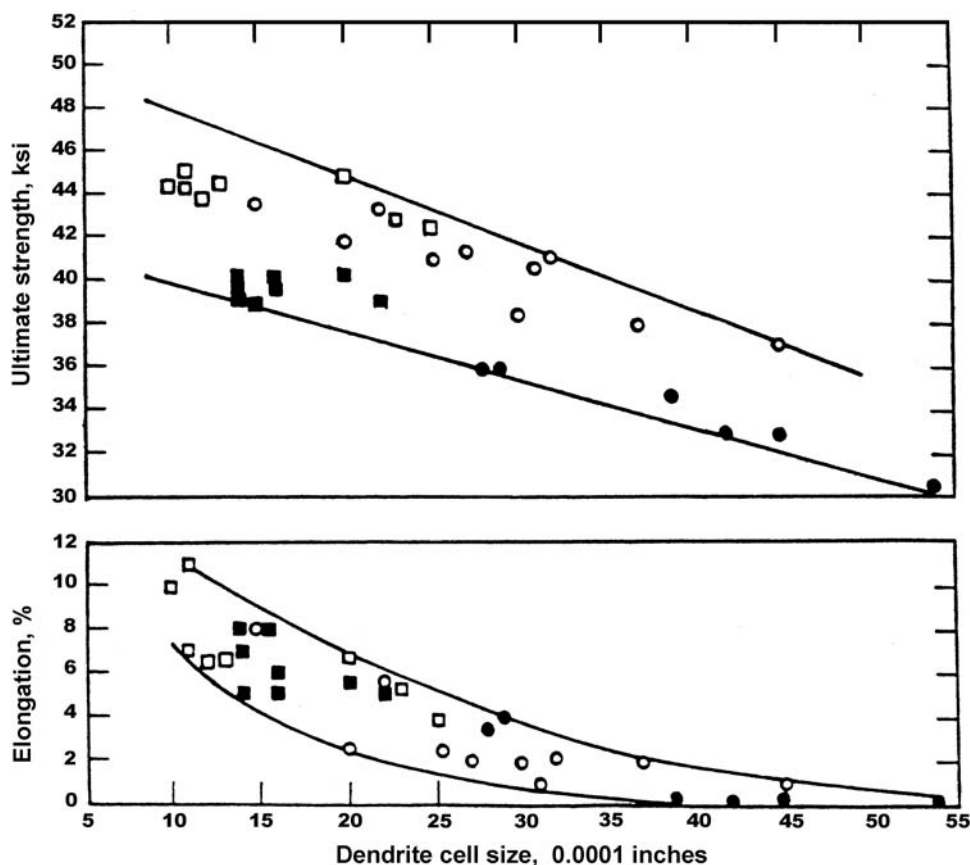


**Fig. 4.3** Correlation between dendrite cell size and tensile properties of specimens machined from production castings in alloy A356.0-T62. The different data points indicate specimens from different heats. Source: Ref 1

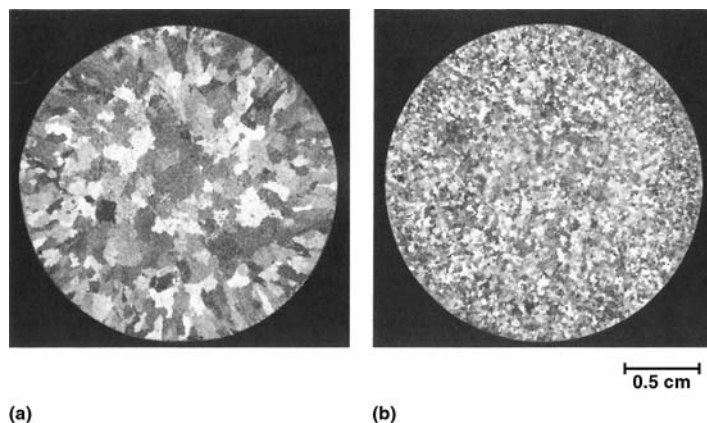


**Fig. 4.4** As-cast Al-7Si ingots showing the effects of grain refinement. (a) No grain refiner. (b) Grain refined. Both etched using Poulton's etch; both  $2\times$ . Courtesy of W.G. Lidman, KB Alloys Inc.



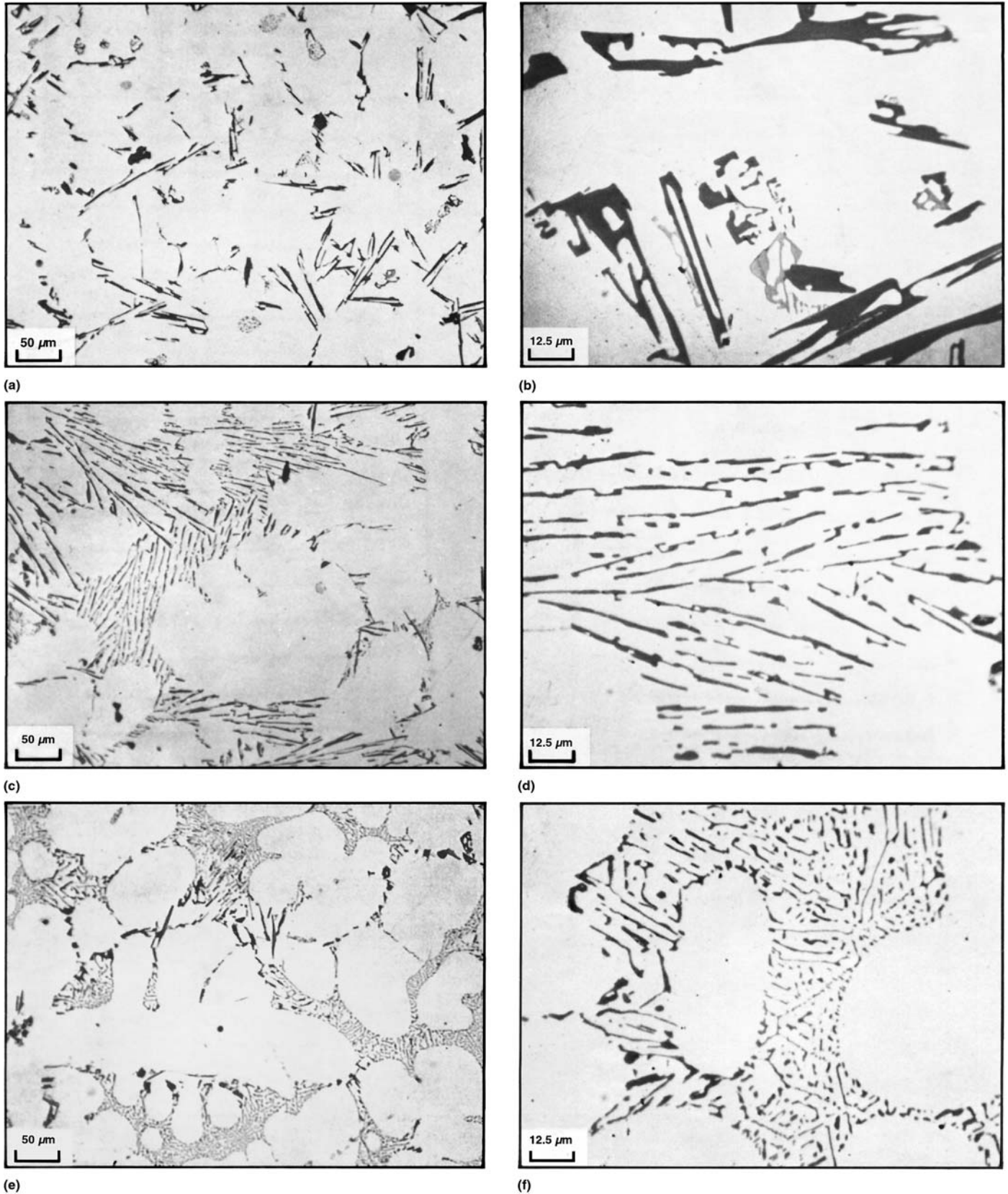
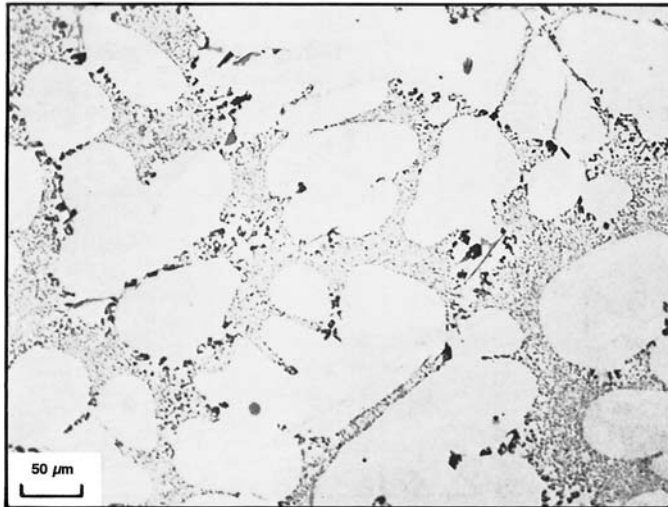
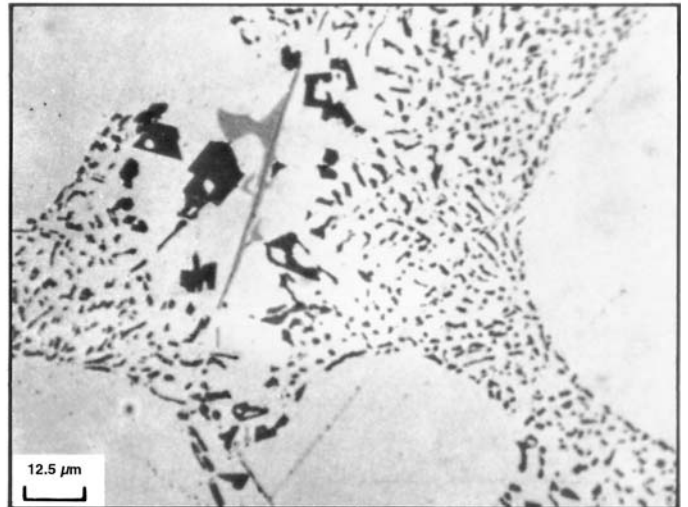


**Fig. 4.5** Variations in degrees and types of aluminum-silicon eutectic modification. (a) Class 1, fully unmodified structure. 200 $\times$ . (b) Same as (a) but at 800 $\times$ . (c) Class 2, lamellar structure. 200 $\times$ . (d) Same as (c) but at 800 $\times$ . (e) Class 3, partial modification. 200 $\times$ . (f) Same as (e) but at 800 $\times$ . (g) Class 4, absence of lamellar structure. 200 $\times$ . (h) Same as (g) but at 800 $\times$ . (i) Class 5, fibrous silicon eutectic. 200 $\times$ . (j) Same as (i) but at 800 $\times$ . (k) Class 6, very fine structure. 200 $\times$ . (l) Same as (k) but at 800 $\times$ . Source: Ref 10

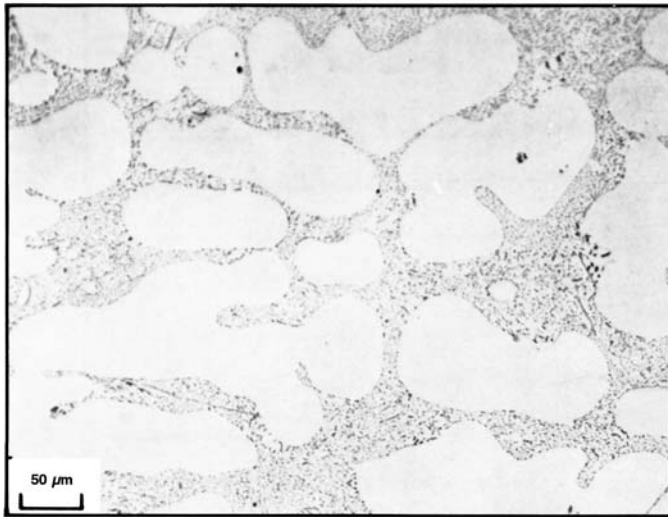




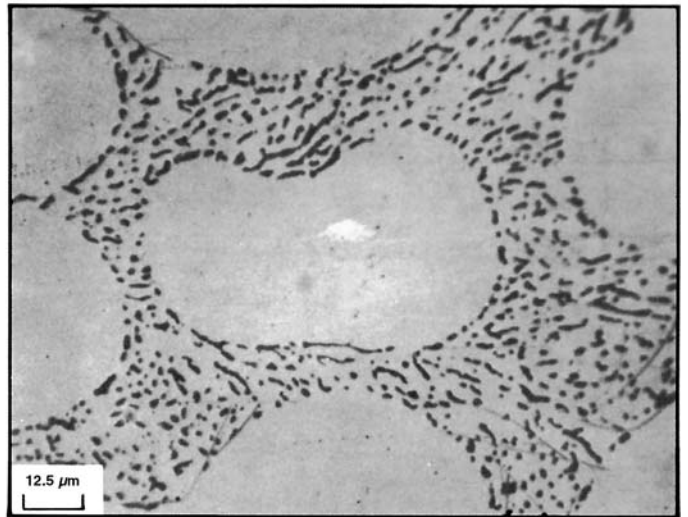
(g)



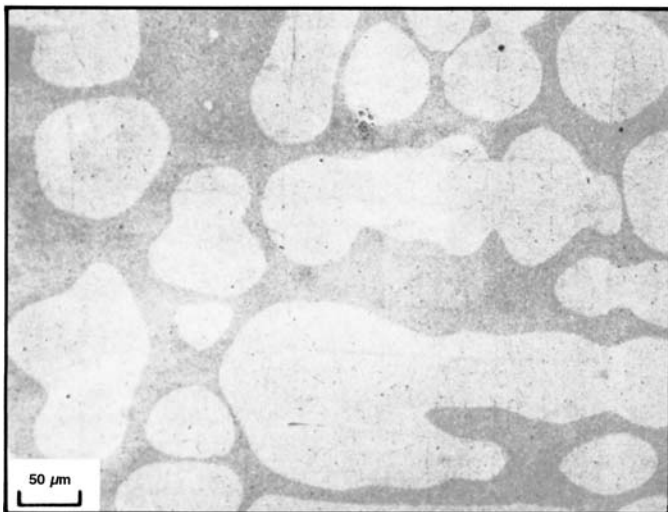
(h)



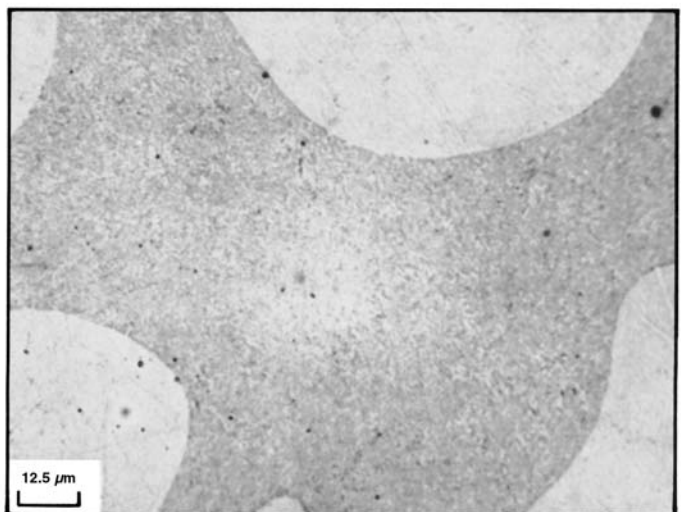
(i)



(j)



(k)



(l)

**Fig. 4.5 (continued)** (g) Class 4, absence of lamellar structure. 200X. (h) Same as (g) but at 800X. (i) Class 5, fibrous silicon eutectic. 200X. (j) Same as (i) but at 800X. (k) Class 6, very fine structure. 200X. (l) Same as (k) but at 800X. Source: Ref 10

Phosphorus interferes with the modification mechanism. It reacts to form phosphides that nullify the effectiveness of modifier additions. It is therefore desirable to use low-phosphorus metal when modification is a process objective and to make larger modifier additions to compensate for phosphorus-related losses.

Typically, modified structures display higher tensile properties and appreciably improved ductility when compared to unmodified structures (Table 4.1). Property improvement is dependent on the degree to which porosity associated with the addition of modifiers is suppressed. Improved casting results include improved feeding and superior resistance to elevated-temperature cracking.

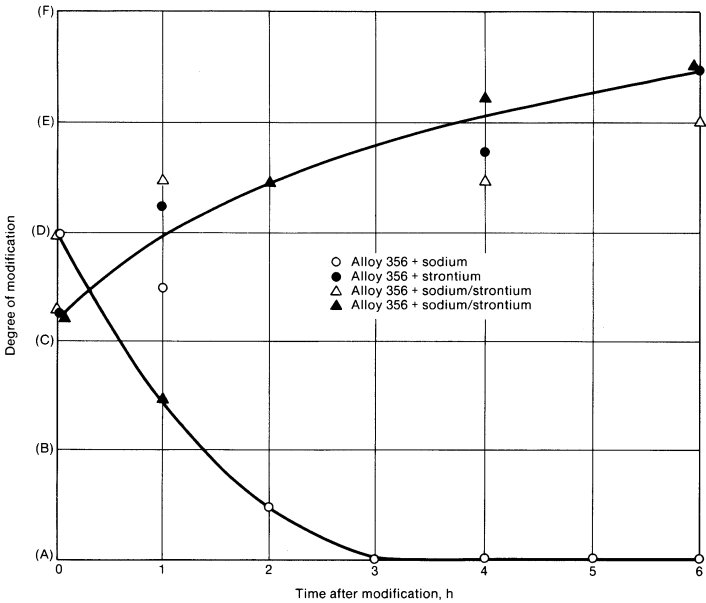


**Fig. 4.6** Effectiveness of sodium and strontium modifiers as a function of time. See Fig. 4.7 for degrees of modification

Thermal analysis is useful in assessing the degree of modification that can be displayed by the melt (Ref 11). A sample of metal

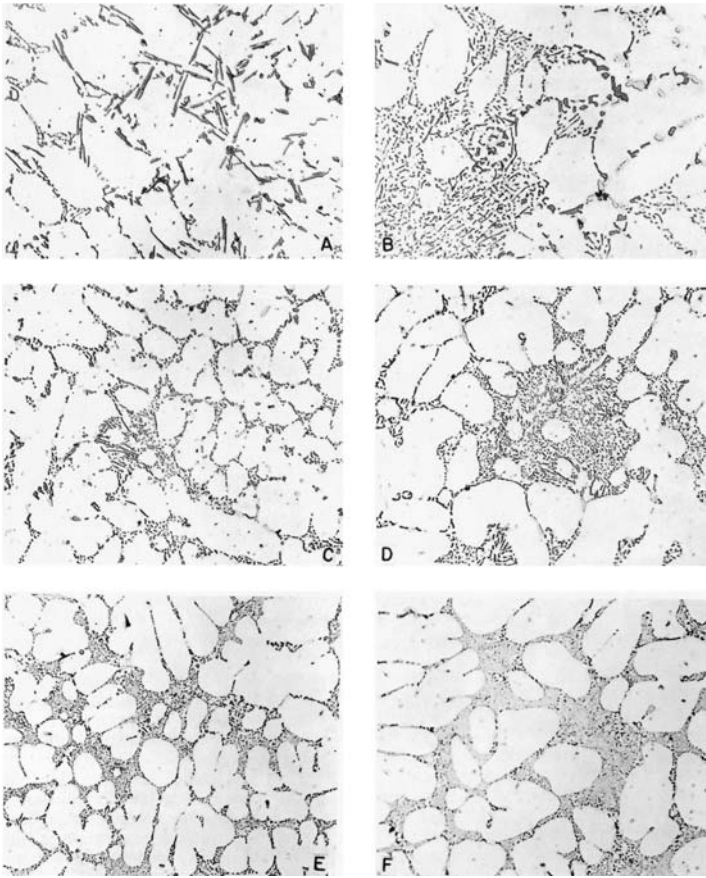


**Fig. 4.7** Varying degrees of aluminum-silicon eutectic modification ranging from unmodified (A) to well modified (F). See Fig. 4.6 for the effectiveness of various modifiers

**Table 4.1** Typical mechanical properties of modified and unmodified cast aluminum alloys

| Alloy and temper | Product                            | Modification treatment | Tensile yield strength |     | Ultimate tensile strength |     | Elongation, % |
|------------------|------------------------------------|------------------------|------------------------|-----|---------------------------|-----|---------------|
|                  |                                    |                        | ksi                    | MPa | ksi                       | MPa |               |
| 13% Si           | Sand cast test bars                | None                   | ...                    | ... | 18.0                      | 124 | 2.0           |
|                  |                                    | Na-modified            | ...                    | ... | 28.0                      | 193 | 13.0          |
|                  | Permanent mold test bars           | None                   | ...                    | ... | 28.0                      | 193 | 3.6           |
|                  |                                    | Na-modified            | ...                    | ... | 32.0                      | 221 | 8.0           |
| 359.0            | Permanent mold test bars           | None                   | ...                    | ... | 26.1                      | 180 | 5.5           |
|                  |                                    | 0.07% Sr               | ...                    | ... | 30.5                      | 210 | 12.0          |
| 356.0-T6         | Sand cast test bars                | None                   | 30.1                   | 208 | 41.9                      | 289 | 2.0           |
|                  |                                    | 0.07% Sr               | 34.5                   | 238 | 42.5                      | 293 | 3.0           |
|                  | Bars cut from chilled sand casting | None                   | 30.9                   | 213 | 41.2                      | 284 | 4.4           |
|                  |                                    | 0.07% Sr               | 31.6                   | 218 | 42.2                      | 291 | 7.2           |
| A356.0-T6        | Sand cast test bars                | None                   | 26.0                   | 179 | 40.0                      | 226 | 4.8           |
|                  |                                    | 0.01% Sr               | 30.0                   | 207 | 43.0                      | 297 | 8.0           |
| A444.0-T4        | Permanent mold test bars           | None                   | ...                    | ... | 21.9                      | 151 | 24.0          |
|                  |                                    | 0.07% Sr               | ...                    | ... | 21.6                      | 149 | 30.0          |
| A413.2           | Sand cast test bars                | None                   | 16.3                   | 112 | 19.8                      | 137 | 1.8           |
|                  |                                    | 0.005–0.05% Sr         | 15.6                   | 108 | 23.0                      | 159 | 8.4           |
|                  | Permanent mold test bars           | None                   | 18.1                   | 125 | 24.4                      | 168 | 6.0           |
|                  |                                    | 0.005–0.08% Sr         | 18.1                   | 125 | 27.7                      | 191 | 12.0          |
|                  | Test bar cut from auto wheel       | 0.05% Sr               | 17.5                   | 121 | 28.0                      | 193 | 10.6          |
|                  |                                    | 0.06% Sr               | 18.2                   | 126 | 28.0                      | 193 | 12.8          |

Source: Ref 4



is cooled slowly, permitting time and temperature to be plotted (Fig. 4.8). The effectiveness of modification treatment is defined by the degree and duration of undercooling at the solidus. Test results must be correlated with the degree of modification established metallographically for the castings since cooling rate for the sample will differ.

#### 4.5 Refinement of Hypereutectic Aluminum-Silicon Alloys

The elimination of large, coarse primary silicon crystals that are harmful in the casting and machining of hypereutectic silicon alloy compositions is a function of primary silicon refinement (Ref 13). Phosphorus added to molten alloys containing more than the eutectic concentration of silicon, made in the form of metallic phosphorus or phosphorus-containing compounds such as phosphor-copper and phosphorus pentachloride, has a marked effect on the distribution and form of the primary silicon phase (Fig. 4.9). Retained concentrations of phosphorus as low as 0.0015% are effective in achieving refinement of the primary phase.

Refinement resulting from phosphorus additions can be expected to be less transient than the effects of eutectic modification in hypoeutectic alloys. Phosphorus-treated melts can be solidified and remelted without loss of refinement. Primary silicon particle size increases gradually with time as phosphorus concentration decreases. Gas fluxing accelerates phosphorus loss when chlorine or other reactive gases are used. Brief inert gas fluxing is frequently employed to reactivate aluminum phosphide nuclei, presumably by resuspension.

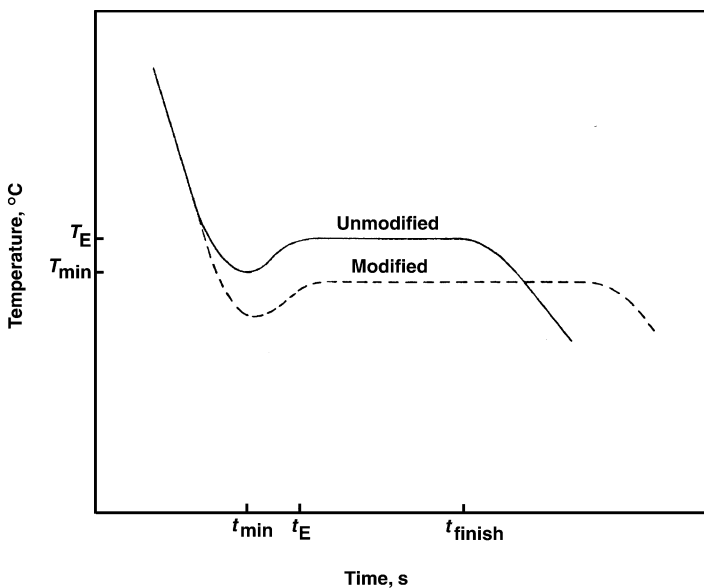
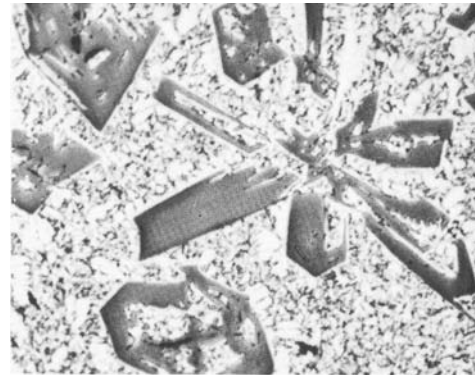


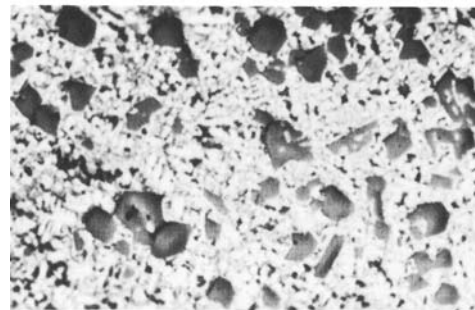
**Fig. 4.8** Cooling curve of the eutectic region of an unmodified and modified aluminum-silicon casting alloy.  $T_{\min}$ , temperature at the minimum before the eutectic plateau;  $T_g$ , eutectic growth temperature;  $t_{\min}$ , time at the minimum of the curve;  $t_E$ , time corresponding to the beginning of the eutectic plateau;  $t_{\text{finish}}$ , time corresponding to the end of the eutectic plateau. Source: Ref 12

Practices recommended for melt refinement are:

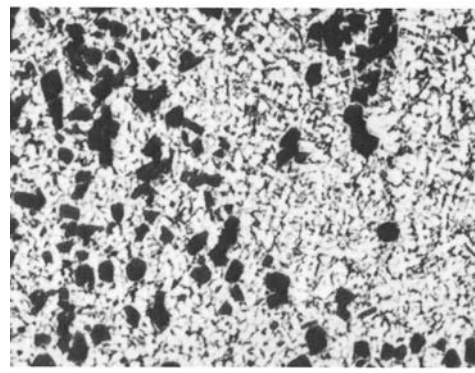
- Melting and holding temperature should be minimum.
- Calcium and sodium contents should be controlled to low concentration levels.
- Brief nitrogen or argon fluxing after the addition of phosphorus is recommended to remove the hydrogen introduced during the addition and to distribute the aluminum phosphide nuclei uniformly in the melt.



(a)



(b)



(c)

**Fig. 4.9** Effect of phosphorus refinement on the microstructure of a hypereutectic Al-22Si-1Ni-1Cu alloy. (a) Unrefined. (b) Phosphorus refined. (c) Refined and fluxed. All 100×

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## CHAPTER 5

# The Influence and Control of Porosity and Inclusions in Aluminum Castings

Solidification in complex geometrical shapes with varying section thicknesses creates conditions under which internal porosity may form. The impact of internal porosity on properties is caused by the reduction in effective area by pore volume fraction and by stress concentrations at voids leading to premature failure.

Porosity in aluminum is caused by the precipitation of hydrogen from liquid solution or by shrinkage during solidification, and more usually by a combination of these effects. There are other sources of internal voids. Mold reactions, high-temperature oxidation, blow-holes, and entrapped gas result in defects that adversely affect mechanical properties as well as physical acceptability.

Nonmetallic inclusions entrained before solidification influence porosity formation and mechanical properties.

### 5.1 Hydrogen Porosity

Hydrogen is the only gas that is appreciably soluble in aluminum and its alloys. The solubility of hydrogen in aluminum varies directly with temperature and the square root of pressure; solubility increases rapidly with increasing temperature above the liquidus. Hydrogen solubility is considerably greater in the liquid than in the solid state (Fig. 5.1). Actual liquid and solid solubilities in pure aluminum just above and below the solidus are 0.69 and 0.04 ppm. These values vary only slightly for most casting alloys.

The solubility curve for hydrogen in aluminum typically describes equilibrium conditions. No more hydrogen than indicated can be dissolved at any temperature. Control of melting conditions and melt treatment can result in substantially reduced dissolved hydrogen levels.

During cooling and solidification, dissolved hydrogen in excess of the extremely low solid solubility may precipitate in molecular form, resulting in the formation of primary and/or secondary voids. Primary or interdendritic porosity forms when hydrogen contents are sufficiently high that hydrogen is rejected at the solidification front, resulting in supercritical saturation and bubble formation. Secondary (micron-size) porosity occurs when dissolved hydrogen contents are low, and void formation occurs at characteristically subcritical hydrogen concentrations.

Hydrogen bubble formation is strongly resisted by surface tension forces, by increased liquid cooling and solidification rates that

affect diffusion, and by an absence of nucleation sites for hydrogen precipitation such as entrained oxides. The precipitation of hydrogen obeys the laws of nucleation and growth and is similar in these respects to the formation of other metallurgical phases during solidification.

The process of hydrogen precipitation consists of:

1. Diffusion of hydrogen atoms within the molten pool
2. Formation of subcritical nuclei as a function of time and cooling
3. Random emergence of stable precipitates that exceed the critical size required for sustained growth
4. Continued growth as long as dissolved hydrogen atoms remain free to diffuse to the precipitated bubble

The result is a general distribution of voids occurring throughout the solidified structure.

Finely distributed hydrogen porosity may not always be undesirable. Hydrogen precipitation may alter the form and distribution of shrinkage porosity in poorly fed parts or part sections. Shrinkage

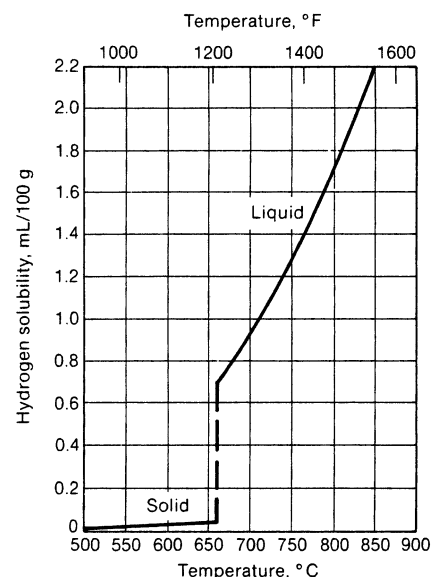


Fig. 5.1 Solubility of hydrogen in aluminum at 1 atm hydrogen pressure

is generally more harmful to casting properties. In isolated cases, hydrogen may be intentionally introduced and controlled in specific concentrations compatible with the application requirements of the casting in order to promote superficial soundness.

The following rules describe the tendency for hydrogen pore formation (Fig.5.2 to 5.5) (Ref 1):

- There is a critical or threshold hydrogen value for any composition that must be exceeded for hydrogen porosity to occur.
- Residual pore volume fraction for each alloy corresponds to hydrogen content above the threshold value.
- Pore volume fraction and pore size decrease with decreased hydrogen content above the threshold value.
- Hydrogen pore volume fraction and pore size decrease with increased cooling rate.

The critical or threshold value of hydrogen concentration is also dependent on pressure and on the number ( $n$ ) and tortuosity ( $t$ ) of liquid paths that exist in a solidifying dendritic network. The higher the product of these factors ( $nt$ ), the higher the hydrogen threshold.

The foundry industry has long used various forms of vacuum testing of molten metal samples to determine acceptability of the processed melt for any casting application. The basis for this test is the relationship between hydrogen solubility and pressure. Since hydrogen solubility is related directly to the square root of pressure, decreased pressure reduces hydrogen solubility, increasing the tendency for bubble formation in the sample. The results of the reduced pressure test can then predict in relative terms the tendency for formation of hydrogen voids in the cast part at ambient pressure. The pressure/solubility relationship recurs in this discussion be-

cause of its relevance when negative relative pressures associated with shrinkage develop in the solidifying structure.

Just as in the case of crystal formation, hydrogen precipitation may occur as a result of heterogeneous or homogeneous nucleation. The most powerful nucleants for hydrogen precipitation are oxides, especially oxides that through turbulence in gating, pouring, melt handling, and treatment entrain air or gaseous phases. In the pres-

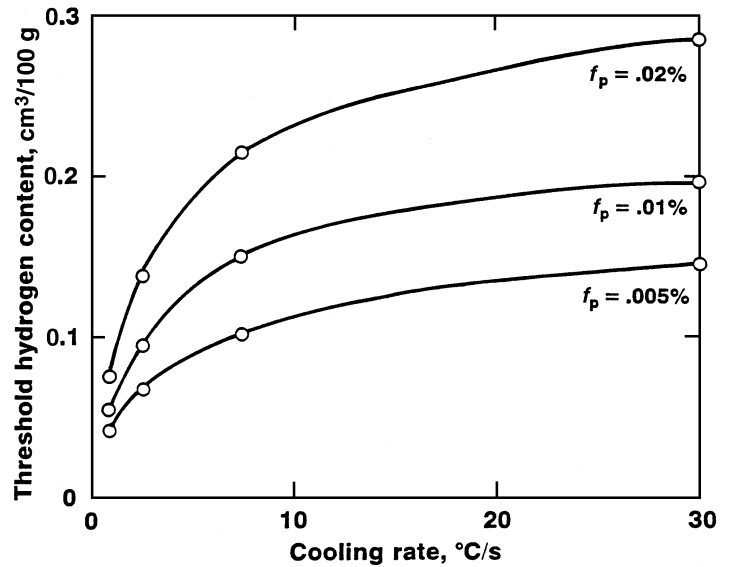


Fig. 5.3 Relationship of hydrogen content to cooling rate in A356.0 for different porosity fractions.  $f_p$ , porosity fraction

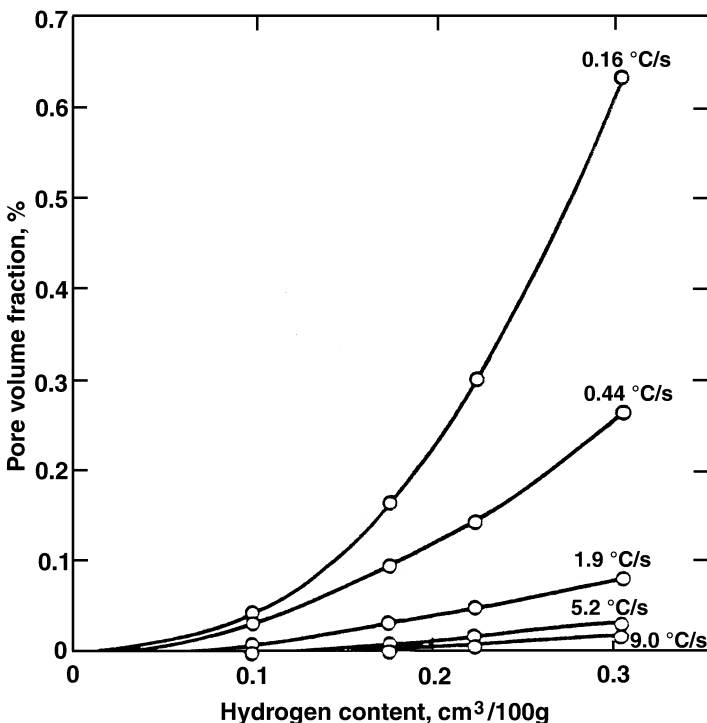


Fig. 5.2 Hydrogen content, pore size, and cooling rate relationships in Al-4Mg alloy

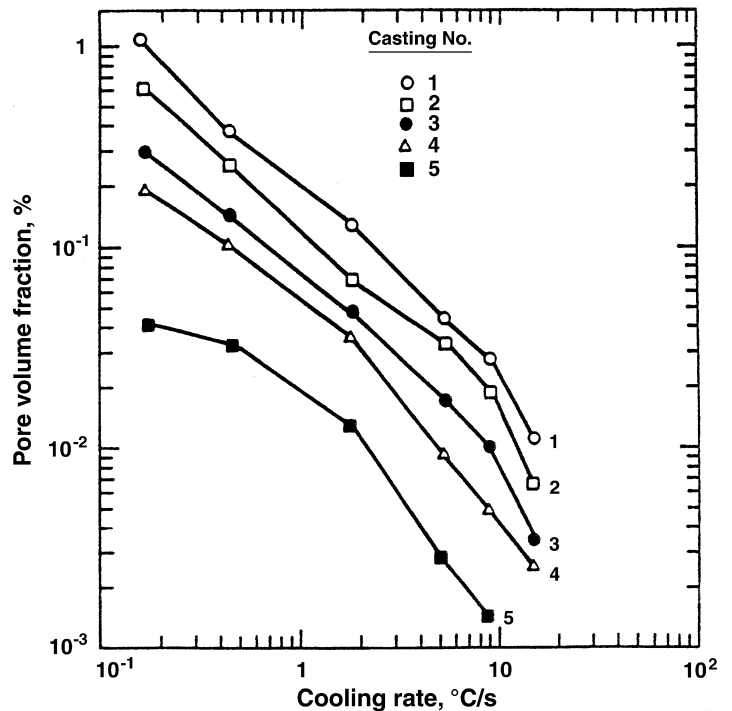


Fig. 5.4 Relationship of pore volume to cooling rate for different hydrogen contents in Al-4.7Mg alloy (similar to alloy 514.0). Hydrogen content ( $\text{cm}^3/100 \text{ g}$ ): 1, 0.31 (no grain refiner); 2, 0.31 (grain refined); 3, 0.22 (grain refined); 4, 0.18 (grain refined); 5, 0.10 (grain refined)

ence of such nuclei, hydrogen precipitates readily at even relatively low dissolved hydrogen levels. In the absence of nucleating phases such as oxides and gaseous species, surface tension forces are generally strong enough that precipitation is suppressed at even relatively high dissolved hydrogen levels. When properly performed, the vacuum solidification test discriminates between bubble formation by heterogeneous and homogeneous nucleation. The determination is made by observing the sample as it cools and solidifies:

- Immediate bubble formation when vacuum is applied indicates that the melt is contaminated by oxides and contains an indeterminate amount of hydrogen.
- Gas evolution appearing in the solidifying sample only during the last stages of solidification indicates that oxides are not present and that hydrogen is present at a relatively high concentration.
- If no evolution of gas occurs, it may be assumed that the melt is free of oxides and that hydrogen contained in liquid solution is below the threshold value for precipitation.

Sources of hydrogen contamination include:

- Atmosphere
- Incompletely dried refractories
- Remelt ingot, master alloys, metallurgical metals, and other charge components
- Fluxes
- Tools, flux tubes, and ladles
- Products of combustion (POCs) in gas-fired furnaces

Hydrogen can be introduced through the disassociation of moisture in the atmosphere and products of combustion in furnace atmospheres allowing atomic hydrogen diffusion into the melt. Turbulence, whether in melt treatment or in pouring can rapidly accelerate the rate at which hydrogen from atmospheric moisture

is absorbed and coincidentally is responsible for degradation of the liquid melt after effective treatment for hydrogen removal. At any time the protective oxide surface of the melt is disturbed, an increase in hydrogen content can be expected.

In magnesium-containing alloys, an amorphous magnesium oxide forms that is more permeable or less protective to the diffusion of hydrogen from the atmosphere to the melt. It follows that periods of high humidity increase the problems faced in dealing with hydrogen contamination and its removal and that magnesium-containing alloys are more susceptible to hydrogen absorption than others.

Incompletely dried or cured furnace refractories and refractories used to line troughing results in hydrogen absorption.

Dissolved hydrogen is present in some amount in alloyed remelt ingot and master alloys.

Moisture contamination of fluxes and hydrogen in gas fluxes increase hydrogen levels and, in the latter case, affects the efficiency of hydrogen removal.

Moisture in any form: contamination on tools, flux tubes, ingot, scrap, metallurgical metals, grain refiners, and master alloys that may be added to the heat additively affect dissolved hydrogen content up to the applicable solubility limit.

Degassing by the use of inert or active gases reduces hydrogen concentrations by diffusion into bubbles of the fluxing gas corresponding to the partial pressure of hydrogen in the fluxing gas. Spinning-rotor techniques have been developed that provide more intimate mixing, efficient gas-metal reactions, and shorter reaction times to achieve low hydrogen levels. The use of active fluxing gases and filtration removes oxides, permitting acceptable quality castings to be produced from metal with higher hydrogen contents.

## 5.2 Shrinkage Porosity

For most metals, the transformation from the liquid to the solid state is accompanied by a decrease in volume. In aluminum alloys, the volumetric shrinkage that occurs during solidification ranges from 3.5 to 8.5%. The tendency for the formation of shrinkage porosity is related to both the liquid/solid volume fraction at the time of final solidification and the solidification temperature range of the alloy.

Shrinkage occurs during solidification as a result of volumetric differences between liquid and solid states. It is important to make a distinction between the differences in liquid and solid volume that are of greatest concern to foundry personnel and the contraction that takes place after solidification as a result of solid-state contraction that most concerns die design and patternmaking.

A sphere of molten metal solidifying without rising is an easily understood example of the diverse ways in which shrinkage forms. Once the shell of the sphere has solidified and assumes sufficient strength to resist collapse, the continued process of cooling and solidification results in substantial tensile stresses in the liquid pool since the shell is contracting at the low rate dictated by the solid-state coefficient of thermal contraction, and the volume occupied by the liquid that is cooling and experiencing volume change as additional solid is formed is contracting at a far greater rate. While the liquid struggles to maintain coherency, tensile forces ultimately

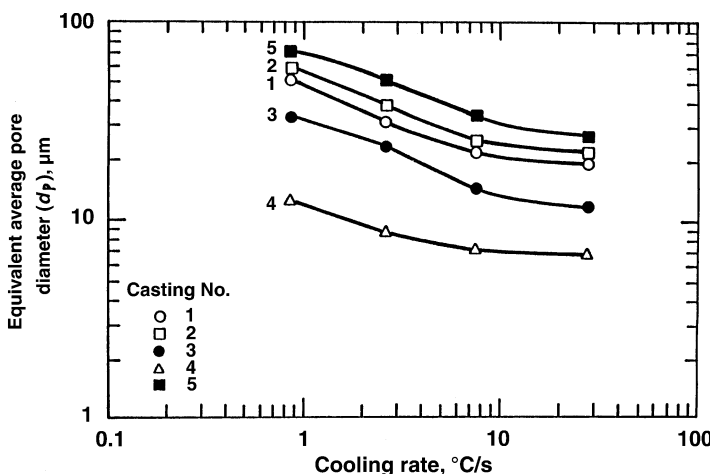


**Fig. 5.5** Relationship of pore size to cooling rate for different hydrogen contents in alloy A356.0. Hydrogen content (cm<sup>3</sup>/100 g): 1, 0.25 (no grain refiner); 2, 0.31 (grain refined); 3, 0.25 (grain refined); 4, 0.11 (grain refined); 5, 0.31 (grain refined and modified)

exceed surface tension forces associated with the liquid-solid interface and a void will form (Fig. 5.6a). Alloying elements that contribute to elevated-temperature strength such as iron, copper, and nickel increase resistance to surface collapse, leading to contained shrinkage voids. There are variations in which the solidified shell lacks the integrity to resist the negative pressures developed within the sphere. If the shell is coherent, but weak, localized collapse of the shell occurs to compensate for the volumetric change (Fig. 5.6b). Alloys with short solidification ranges often display this form of shrinkage. If localized failure of the shell occurs, interdendritic liquid will drain gravimetrically into the liquid pool that remains (Fig. 5.6c). The result is a “wormhole” or “sponge” shrinkage defect visible from the casting surface. These void concentrations are often associated with cracks that form during and after solidification. Alloys with wide solidification ranges are prone to this form of shrinkage.

In the case of a riser casting, the intention is to prevent shrinkage formation by maintaining a path for fluid flow from the higher heat mass and pressure of the riser to the encased liquid pool.

Shrinkage displacement takes place in three modes:

- Mass feeding
- Interdendritic feeding
- Solid feeding

Mass feeding is liquid displacement occurring in the absence of substantial resistance. In these cases, pressure at the solidification interface and pressure in the riser system are essentially equivalent. Pressure drop develops as obstructions to the feeding path form.

The progressive development of a dendritic network and localized solidification results in increased resistance to fluid flow until the pressure at the solidification front is reduced to zero, at which time a shrinkage void will form. Interdendritic feeding takes place in the interval between mass feeding and the point at which sufficient resistance develops that liquid flow through the solidifying dendrite network no longer occurs.

Solid feeding occurs when the incipient shrinkage void is filled by the collapse of surrounding solidified metal.

Shrinkage may assume many forms. Distributed voids or microshrinkage are found between dendrite arms as a result of failure during the last stages of interdendritic feeding. Centerline or piping voids result from gross directional effects, when, for example, large fully contained liquid pools are isolated within the casting during solidification.

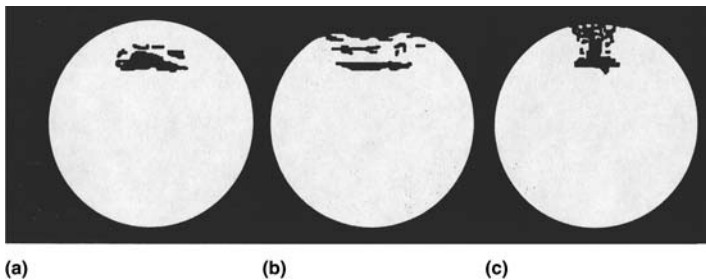


**Fig. 5.6** How shrinkage voids form in aluminum castings. (a) Initial void formation. (b) Collapse of shell increases void size. (c) “Wormhole” formation with additional shrinkage

In Al-Si-Cu alloys, rapid cooling leads to the distribution of voids in the grain boundaries, while slow cooling results in interdentritically distributed shrinkage. Shrinkage is much more likely to be localized in a eutectic composition such as 443.0 or A444.0. In any case, voids first begin to form at liquidus-solidus temperatures corresponding to 65 to 75% solid.

In short solidification range compositions such as 356.0 and 413.0, there is an improved opportunity for establishing directional solidification. Defects may take the form of extensive piping as opposed to distributed shrinkage porosity. These alloys may be characterized by a higher proportion of mass feeding relative to interdendritic feeding and are therefore less susceptible, under reasonable efforts to establish directional solidification, to the formation of widely distributed shrinkage voids.

When good foundry practices are used in long solidification range compositions such as some aluminum-copper and aluminum-magnesium alloys, solidification distance loses its importance to a more general tendency for interdendritic shrinkage. These alloys are susceptible to extensive microporosity that results from the higher proportion of feeding that takes place interdendritically. The severity of shrinkage is increased by geometrical complexity, varying section thickness, solidification rate, alloy feeding characteristics, and by limitations in effective gating and risering practice that fail to provide the gradients required for directional solidification.

Shrinkage void fraction varies in proportion to the fourth root of the pressure, leading to the conclusion that increasing pressure has little effect on shrinkage unless extremely high pressures can be employed.

Improved modification and refinement of aluminum-silicon alloys, improved grain refinement, and reduced oxide contents all improve feedability and therefore reduce shrinkage severity.

## 5.3 Inclusions

Nonmetallic inclusions are a particular concern in cast aluminum. Because of its reactivity, aluminum oxidizes readily in liquid and solid states. Oxidation rate is greater at molten metal temperatures and increases with temperature and time of exposure. Magnesium in aluminum alloys oxidizes and with time and temperature reacts with oxygen and aluminum oxide to form spinel. Table 5.1 categorizes inclusion types typically encountered.

Many oxide forms display densities similar to that of molten aluminum and sizes that reduce the effectiveness of gravimetric separation. Also, most oxides are wet by molten aluminum, reducing the effectiveness of mechanical separation methods.

Aluminum is also chemically aggressive and can react with compounds in refractory formulations or with the coatings used to protect crucibles, ladles, and tools resulting in the entrainment of exogenous nonmetallics.

While the oxide that initially forms on the surface of molten aluminum is highly protective and self-limiting, any agitation or turbulence in the treatment and handling of molten aluminum increases the risk of oxide entrainment and the immediate reformation of additional oxides. Oxide concentration can increase when alloying additions are stirred into the melt, when reactive elements



and compounds are immersed, when metal is drawn for pouring, and when metal is poured and conducted by the gating system into the mold cavity. Induction melting is highly energy efficient and effective for melting fines and poor-quality scrap, but electromagnetically induced eddy currents result in high levels of entrained oxides.

The prevention of inclusions is the product of equipment and practices that minimize oxidation, avoid entrainment, and effectively remove particulate by fluxing reactions or filtration.

Degassing with inert (argon) or quasi-inert (nitrogen) gases are only partially effective in the removal of included matter. Rotary degassing improves inclusion-removal efficiency, but the use of active fluxing gases such as chlorine or other halogens is necessary to dewet included oxides, facilitating their separation by the sweeping action of the fluxing gas. The use of appropriate solid fluxes has the same effect.

Molten aluminum can be filtered by various means with varying effectiveness. Strainers, screens, steel wool, porous foam, and fused ceramics can be used in the gating system as long as the combination of pore size, level of inclusion contamination, and surface area does not excessively restrict metal flow. Cake-mode ceramic and deep-bed filters are used in furnaces and crucibles.

The removal of oxides can be seen to suppress hydrogen pore formation as shown in Table 5.2.

Inclusions occur as varying types with differing sizes and shapes. Aluminum oxides are of different crystallographic or amorphous forms as films, flakes, and agglomerated particles. Magnesium oxide is typically present as fine particulate. Spinel can be small

hard nodules or large complex shapes. Aluminum carbide and aluminum nitride can be found in smelted aluminum, but are usually of size and concentration of no significance in aluminum castings. Refractory and other exogenous inclusions may be identified by their appearance and composition.

Inclusions, such as shrinkage and hydrogen porosity, reduce properties by detracting from the effective cross-sectional area when stress is applied and by the concentration of stresses at the inclusion interface (Fig. 5.7).

## 5.4 Combined Effects of Hydrogen, Shrinkage, and Inclusions

Hydrogen precipitation and shrinkage porosity formation are usually considered separate and independent phenomena. There are interactive mechanisms that affect both.

Small amounts of dissolved hydrogen significantly increase pore size when shrinkage voids form. In this respect, the effects of gas and shrinkage on pore volume fraction can be considered additive.

Since shrinkage voids must by definition result in areas of reduced pressure relative to atmospheric, hydrogen solubility is reduced in the surrounding liquid facilitating the precipitation of hydrogen into the forming void. The important measures of these pores—morphology, pore density, pore size, and volume fraction of pores—are affected by hydrogen.

The conventional wisdom is that hydrogen voids are always rounded, smooth surface defects, while shrinkage voids invariably

**Table 5.1 Inclusion sources and types in aluminum alloy castings**

| Classification                            | Types observed                                                                       | Potential source(s)                                                                                                                                              |
|-------------------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nonmetallic exogenous                     | Various refractory particles, $Al_4C_3$ , etc.                                       | Refractory degradation, remelt ingot, refractory/metal reactions                                                                                                 |
| Nonmetallic in situ                       | $MgO$ , $Al_2O_3$ films, clusters, and disperoids;<br>$MgAl_2O_4$ films and clusters | Melting, alloying: metal transfer turbulence                                                                                                                     |
| Homogeneous halide salts<br>Particle/salt | $MgCl_2$ - $NaCl$ - $CaCl_2$ , etc.<br>$MgCl_2$ - $NaCl$ - $CaCl_2$ / $MgO$ , etc.   | Poor separation of fluxing reaction products<br>Salt generated during chlorine fluxing of magnesium-containing alloys, filter and metal-handling system releases |

**Table 5.2 Effect of filtration on vacuum density test results and hydrogen content**

| Test No. | 50 mm Hg vacuum gas test<br>density, g/cm <sup>3</sup> |                 | 5 mm Hg vacuum gas test<br>density, g/cm <sup>3</sup> |                 | Dissolved hydrogen content,<br>mL/100 g |                 |
|----------|--------------------------------------------------------|-----------------|-------------------------------------------------------|-----------------|-----------------------------------------|-----------------|
|          | Before filtering                                       | After filtering | Before filtering                                      | After filtering | Before filtering                        | After filtering |
| 1        | 2.05                                                   | 2.67            | 2.28                                                  | 2.64            | 0.76                                    | 0.70            |
| 2        | 2.14                                                   | 2.69            | 2.45                                                  | 2.69            | 0.61                                    | 0.69            |
| 3        | 2.16                                                   | 2.72            | 2.48                                                  | 2.70            | 0.51                                    | 0.53            |
| 4        | 2.25                                                   | 2.78            | 1.99                                                  | 2.76            | 0.38                                    | 0.43            |
| 5        | 2.29                                                   | 2.74            | 2.07                                                  | 2.60            | 0.39                                    | 0.38            |
| 6        | 2.24                                                   | 2.74            | 1.97                                                  | 2.71            | 0.36                                    | 0.41            |
| 7        | 2.30                                                   | 2.73            | 1.94                                                  | 2.66            | 0.31                                    | 0.36            |
| 8        | 2.48                                                   | 2.74            | 2.27                                                  | 2.76            | 0.33                                    | 0.31            |
| 9        | 2.34                                                   | 2.73            | 2.06                                                  | 2.61            | 0.30                                    | 0.35            |
| 10       | 2.37                                                   | 2.73            | 1.99                                                  | 2.74            | 0.30                                    | 0.31            |
| 11       | 2.59                                                   | 2.78            | 2.29                                                  | 2.77            | 0.29                                    | 0.27            |
| 12       | 2.58                                                   | 2.76            | 2.47                                                  | 2.76            | 0.28                                    | 0.28            |
| 13       | 2.25                                                   | 2.74            | 2.26                                                  | 2.76            | 0.27                                    | 0.31            |
| 14       | 2.50                                                   | 2.76            | 2.13                                                  | 2.77            | 0.27                                    | 0.28            |
| 15       | 2.62                                                   | 2.76            | 2.35                                                  | 2.78            | 0.23                                    | 0.26            |
| 16       | 2.53                                                   | 2.73            | 2.34                                                  | 2.73            | 0.28                                    | 0.28            |
| 17       | 2.56                                                   | 2.72            | 2.32                                                  | 2.68            | 0.27                                    | 0.32            |
| 18       | 2.19                                                   | 2.76            | 2.16                                                  | 2.76            | 0.19                                    | 0.19            |

have the characteristic crystalline, jagged appearance that characterizes the dendrite structure. However, hydrogen porosity can conform to dendrite-arm regions, which give bubble formation the characteristic appearance of a shrinkage void. Shrinkage occurring under extremely low gradients may assume a smooth-walled configuration. The precipitation of hydrogen into a forming shrinkage void likewise influences the surface morphology. It is impossible to completely separate the effects of shrinkage and dissolved gas in the formation of microporosity.

Hydrogen may be intentionally added to counteract the more harmful effects of shrinkage on casting acceptability. For parts requiring only cosmetic as-cast appearance, there would appear to be no compelling reason not to add hydrogen by any number of means to improve superficial quality. However, for parts requiring structural integrity, machining, leak resistance, or other specific mechanical or physical characteristic, the intentional addition of hydrogen is unacceptable.

The precipitation of hydrogen during solidification offsets the negative relative pressures that develop when shrinkage voids form. The equalization of internal and external pressures brought about by hydrogen precipitation into internal shrinkage voids minimizes the tendency for surface collapse and wormhole shrinkage in the examples used earlier and alters the size and distribution of voids in a manner generally benefiting external appearance at the expense of internal quality and integrity.

The formation of hydrogen voids and the effects of hydrogen on internal shrinkage are influenced by entrained inclusions that nucleate precipitation. Because inclusions strongly facilitate bubble formation even at very low levels of dissolved hydrogen, it is im-

portant to consider the interaction rather than to attempt to correlate absolute hydrogen content with defect formation.

Layered feeding in castings can be exploited to improve casting results. The first metal that establishes stable contact with the mold wall begins solidifying and is fed not by the risering system but by immediately adjacent molten metal layers. In sand castings (low gradient), the last liquid to freeze may not be localized along the centerline. When the gradient is low and the freezing range large, liquid-solid mushy zones may exist throughout the casting in various stages of solidification, and changes in fraction solid from surface to center may be small. Nevertheless, localized gradients and the availability of thermally differentiated liquid at or near the solidification interface during and after mold filling result in unexpected soundness in areas in which shrinkage voids might otherwise be expected to occur. This principal is routinely applied in the casting of wrought alloy ingot by continuous and discontinuous direct chill casting processes. In these processes, the solidifying interface is constantly fed by newly introduced thermally differentiated molten alloy, and a degree of heat-flow equilibrium is established to provide solidification conditions that ensure minimum solidification zone growth accompanied by unlimited liquid feed and an adequate thermal gradient for the promotion of structural soundness. These principles are reflected in gating designs that approximate layering effects without resorting to more costly methods of promoting internal quality.

Finite-element modeling aimed at predicting mold and metal temperature distributions during and after mold filling, solidification patterns, and the required position, size, and configuration of risers has achieved valuable progress.

Porosity in castings, whether hydrogen voids, shrinkage, or the more usual defects that can be associated with both conditions, can be understood and prevented by:

- Melt treatment must be performed for effective removal of oxides and other entrained nonmetallics and the reduction in dissolved hydrogen concentration.
- Metal handling, pouring, and the design of the gating system must preserve minimum required molten metal quality.
- The gating and risering system with variable heat extraction techniques and application of the principles of directional solidification must be capable of minimizing or preventing shrinkage porosity.

It is important that void appearance and distribution be considered in defining the nature of porosity defects. The interactive effects of hydrogen, inclusions, and shrinkage should be considered in the development of appropriate corrective actions when unacceptable levels of porosity are experienced. Typically, hydrogen porosity appears as evenly distributed voids while shrinkage is more localized or concentrated. The distinctions are facilitated through radiographic analysis.

The presence of internal voids diminishes property capability (Fig. 5.8). The void fraction reduces the effective cross-sectional area under stress and void topography concentrates applied stresses to substantially lower tensile and yield strengths and elongation. The effect of void content on the tensile strengths of selected alloys is shown in Fig. 5.9.

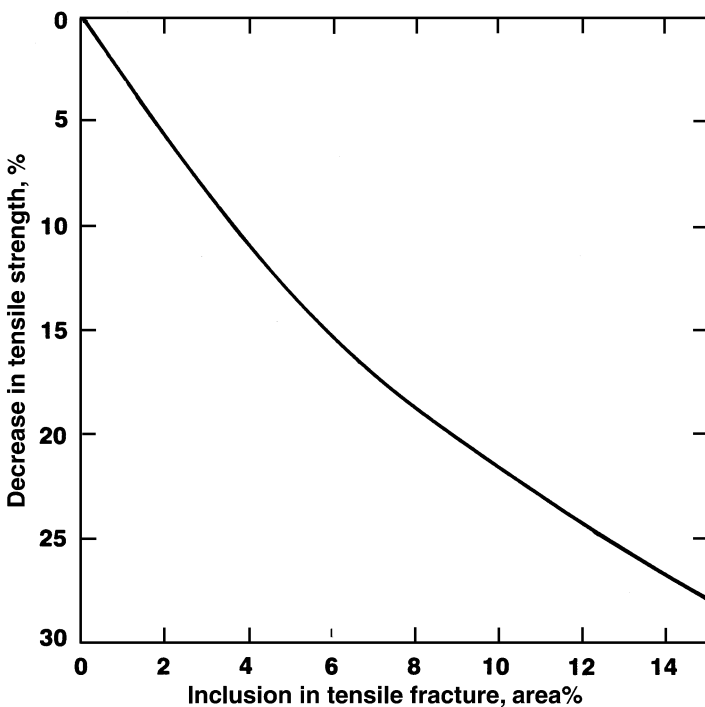


**Fig. 5.7** Effect of inclusions on tensile strength of Al-12Si sand cast test bars. Inclusions decrease the tensile strength about twice as much as would be predicted on the basis of the decrease in cross section. Tensile strength at 0% inclusions = 27 ksi (186 MPa).

## 5.5 Radiographic Inspection

Radiography and fluoroscopy are extensively used by the aluminum foundry industry to reveal internal discontinuities. Other means of assessing internal quality such as sectioning castings, metallography, and microradiography are destructive and offer only plane surfaces for examination. Radiographic methods permit non-destructive whole casting evaluation and the discrimination of shrinkage, hydrogen porosity, and more and less dense inclusions within limits of resolution.

X-ray testing is performed as a process-control tool and as a compliance test of casting acceptability. Ultrasonic and other acoustic techniques have not been proven for engineered aluminum castings.

Radiography is used to:

- Facilitate the optimization of gating design, processes, and practices in pilot stages through rapid comprehensive correlations with casting quality
- Inspect castings during production, as specified by the customer or foundry quality-control standards

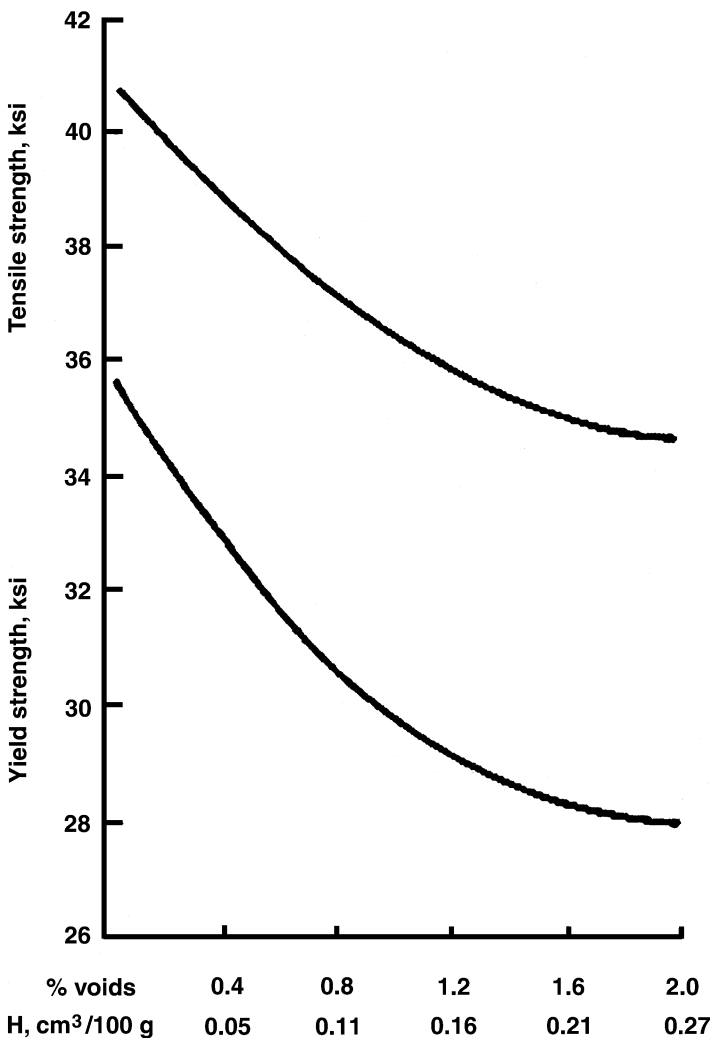


**Fig. 5.8** Effect of hydrogen porosity on the tensile and yield strengths of alloy 356.0-T6 sand castings

- Confirm that specified internal quality standards have been met
- Inspect weldments and weld repairs

ASTM E 155, "Reference Radiographs for the Examination of Aluminum and Magnesium Castings," is the recommended refer-

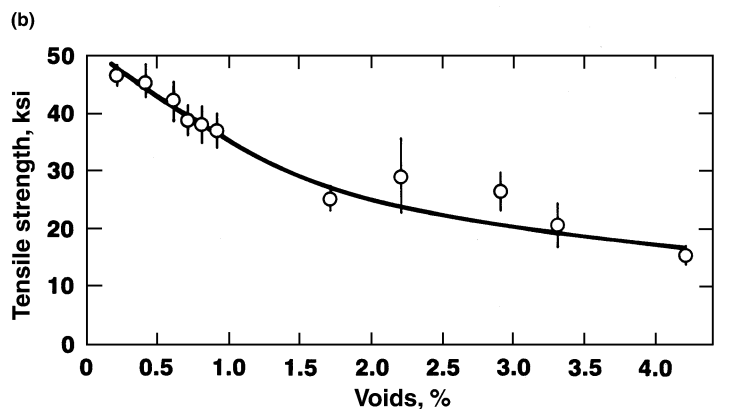
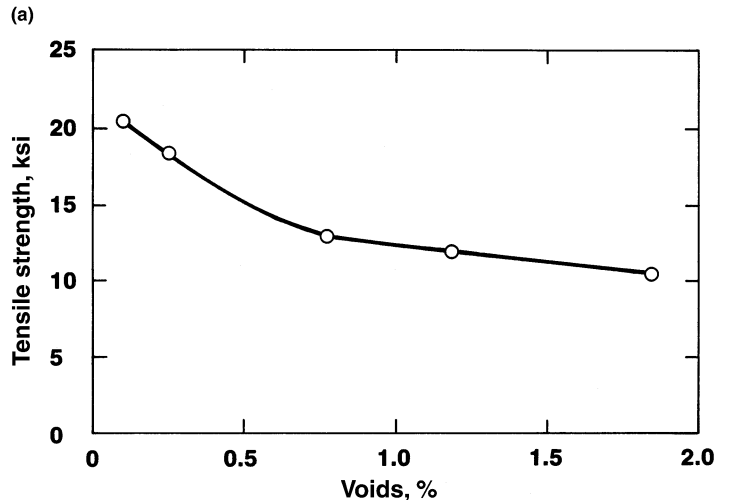
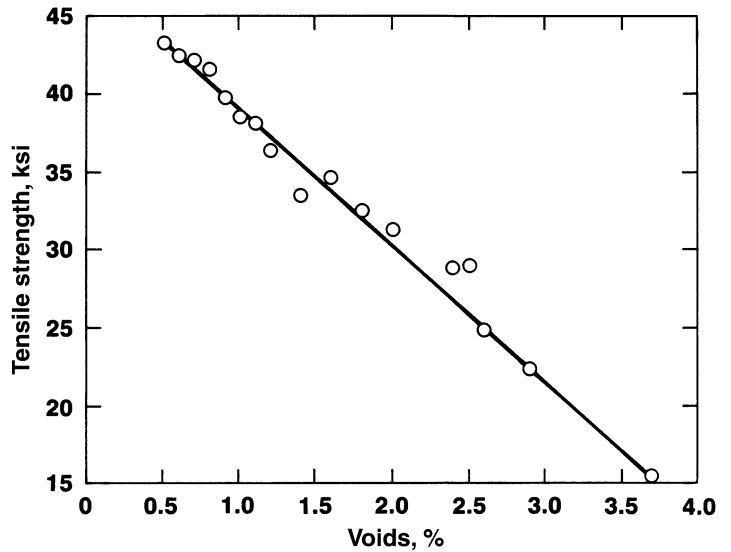


**Fig. 5.9** Effect of void content on the tensile strengths of selected aluminum casting alloys. Large decreases in tensile strength are associated with relatively small increases in the amount of voids. (a) Alloy 355.0-T61. (b) Alloy 443.0-F. (c) Alloy 520.0-T4

ence for the interpretation of discontinuities as revealed by radiographic inspection. This ASTM standard and the Aluminum Association standards for aluminum sand and permanent mold casting are the recommended references for those needing more detailed information on radiographic inspection.

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## CHAPTER 6

# Hot Isostatic Processing

One very significant process refinement available to deal with internal porosity is hot isostatic pressing, commonly referred to as HIP or HIPping. This process deserves special attention for applications requiring very high quality and performance.

### 6.1 The HIP Process

Hot isostatic processing of castings is recognized as a means of providing improved internal soundness or integrity, increased density, and improved properties. The HIP process is applicable to a wide range of products in which these benefits justify its cost (Fig. 6.1). The process was developed to significantly improve the mechanical properties and fatigue strength of aluminum alloy sand and permanent mold castings. It has proved capable of substantially eliminating microporosity resulting from the precipitation of hydrogen and the formation of internal shrinkage during solidification. The process has no effect on cracks, shrinkage, and other defects that communicate to the casting surface.

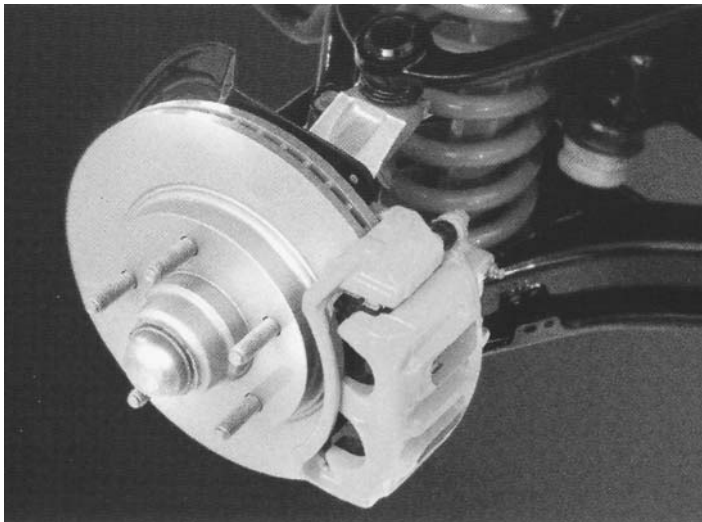


**Fig. 6.1** Hot isostatically pressed cast aluminum brake caliper. Development of lower-cost HIP process alternatives since the 1990s is expanding its potential use into a broad range of applications, including aluminum automotive castings such as steering knuckles, brake calipers (pictured), and control arms. Source: Ref 1

The method makes possible the salvage of castings that have been rejected for reasons of internal porosity. This advantage is of more significant importance in the manufacture of castings subject to radiographic inspection when required levels of soundness are not achieved in the casting process. Furthermore, alloys not of a castability consistent with normal foundry requirements, but offering the potential for improved properties, may be cast in such a manner that application of the densification process would result in parts of acceptable quality and superior performance.

The principles of HIP are:

- At elevated temperatures and under increased pressure, limited but significant dissolution of hydrogen in the aluminum alloy matrix occurs, permitting the collapse and healing of void surfaces formed by hydrogen precipitation during solidification.
- At elevated temperatures and under increased pressure, precipitated hydrogen in excess of the solubility limit is compressed and repartitioned, or redistributed, resulting in increased structural density and integrity.
- At elevated temperatures and under increased pressure, shrinkage voids uncontaminated by hydrogen are compressed and healed by the collapse of the surrounding structures when yield strength is reduced sufficiently for plastic deformation to occur during the densification cycle.
- In the case of shrinkage voids contaminated by hydrogen, resolution of hydrogen and the collapse and metallurgical bonding of internal void surfaces occur by a combination of these effects.

Initial efforts to reduce porosity and increase density involved the application of pressure in metal dies. Mechanical densification as a concept for processing castings was abandoned as a result of a number of limitations. These included the cost of dies, processing costs equal to a forge finishing operation added to casting and processing costs, and the nonfeasibility of designing compression dies for complex casting configurations.

Hot isostatic pressure application was developed as a means of achieving both technical and economic objectives. Hot isostatic pressing takes place in an autoclave in which parts are exposed under pressure at elevated temperatures in a controlled atmosphere. Various production castings and powder metallurgical products are routinely HIPped in large commercial facilities.

## 6.2 The Effect of HIP on Tensile Properties

Densification (HIP) to various extents generally enhances tensile and yield strengths and improves ductility, most markedly in compositions more susceptible to internal porosity under normal casting conditions.

A comparison of tensile test results for cast plates with and without densification treatment is shown in Table 6.1; both the Alcoa A359 process (Ref 2) and the Densal II Process (Bodycote International) (Ref 3) are represented.

For the castings given the Alcoa A359 treatment, the internal quality of 332.0, A356.0, and A357.0 permanent mold castings had been intentionally degraded by a high level of hydrogen in the melt before the A359 process was applied. The Densal II treatment was applied to a commercially produced A356.0-T62 vacuum riserless casting/pressure riserless casting (VRC/PRC).

The data show that tensile and yield strength were improved by densification in every case of the degraded castings, and elongation was improved in most cases. For the Densal-treated castings, strength was not consistently affected significantly, but elongation was greatly enhanced.

Some of the Alcoa test plates given the hydrogen-degrading treatment beforehand exhibited progressively decreasing tensile properties from the bottom to the top of the casting; the data in Table 6.1 are presented in sequence of position in the castings and reflect this gradation. The A359 process treatment of these plates resulted in much more uniform properties.

Large numbers of additional tests by Alcoa, Bodycote, and others, and involving experimental and production castings have now been performed to confirm that HIP generally increases tensile and yield strengths and elongation. Experience also confirms that the treatment provides greater uniformity of tensile properties within most parts.

## 6.3 The Effect of HIP on Fatigue Performance

It was the significant positive effect of mechanical densification on fatigue properties that encouraged the commercial development of the HIP processes, and that beneficial effect is well illustrated by data for both the A359 and Densal II processes.

Table 6.2 summarizes the results of fatigue tests of six castings representing four different alloys given the Alcoa A359 process; all tests were run at 20 ksi (138 MPa). The Alcoa A359 HIP treatment resulted in an average increase of about 200%, with the range being 35 to 360%.

Complete fatigue curves were developed for only one alloy, 332.0-F, and that is shown in Fig. 6.2. The advantage for HIPped casting is apparent at all stress levels, and the endurance limit for the HIPped casting is almost 20% above that of the untreated casting.

From Table 6.2, it is clear that in cases where tests were run of untreated and treated samples at the same stress level of 20 ksi (140 MPa), the Alcoa A359 HIP treatment resulted in an average increase of about 200%. For 332.0-F, where the entire fatigue curve was determined (Fig. 6.2), the advantage for HIPped material was apparent at all stress levels, and the endurance limit for the HIPped material was almost 20% above that of the untreated casting.

Table 6.3 and Fig. 6.3 through 6.5 illustrate the effect of the Densal II HIP process on fatigue life.

The data in Table 6.3 illustrate that fatigue life was improved for D357.0-T6 castings with both acceptable and unacceptable levels of porosity based on radiographic examination, and that the effect was significantly greater for the casting with the greater porosity as indicated by the x-rays.

In a Weibull analysis for an A356.0-T6 casting (Fig. 6.3), Boileau, Zindel, and Allison (Ref 6) show a rather consistent order of magnitude increase in fatigue life for the HIPped sample. As illustrated in Fig. 6.4, such consistent increases were not found for VRC/PRC and sand castings, and in fact only small increases favoring the HIPped samples are apparent; perhaps this reflects the higher quality of the VRC/PRC casting in the first place. Data from Bodycote (Fig. 6.5) seem to support the significant advantage of their Densal process at all stress levels for 359.0-T6, with an apparent improvement in endurance limit of almost 50%.

Based on the data available, it is reasonable to anticipate that HIP will likely improve fatigue properties, and that the magnitude of the improvement may be greatest in cases where significant porosity is present, especially near the surfaces.

## 6.4 Radiographic Inspection of HIPped Castings

Radiographs of laboratory-prepared permanent mold cast plates indicated that most but not all porosity was eliminated or reduced beyond x-ray resolution (Fig. 6.6 and 6.7). Voids that communicated to the surface including shrinkage porosity extending into the casting from the riser were not affected. Some voids in close proximity to the surface, but lacking communication, collapsed, resulting in indentations.

Comparison radiographs of whole production castings also reflected the dramatic improvement in radiographic quality through HIP. In many instances, improvements in radiographic quality were consistent with the most challenging specification requirements.

The HIP cycle could be used in solution heat treatment. Processing costs and the incompatibility of cycles in which solution heat treatment requires up to six times that required for densification makes that impractical, but parts could be partially solution heat treated and then transferred at temperature to the autoclave for completion of HIP and solution treatments.

Casting methods can be used to minimize the presence of undensifiable porosity on casting surfaces, leading to the wider applicability of HIP to cast parts. Surface treatments may also be used to enhance the densification of surface related porosity.

Process success is a consequence of the combined effect of external pressure and temperature that causes the collapse of internal voids through plastic deformation. Hydrogen solubility is directly related to the square root of the pressure and calculations indicate that at 930 °F (500 °C), hydrogen solubility increases 32 times at an external pressure of 15 ksi (105 MPa). Since the solubility of hydrogen in aluminum at 930 °F (500 °C) is approximately 0.003 mL per 100 g, the amount of hydrogen that can be dissolved through HIP treatment approximates 0.10 mL per 100 g. At reasonable hydrogen levels, void compression and the redistribution or repartition of precipitated hydrogen through HIP results in essentially closed porosity. Extensive reheat treatment at ambient

Table 6.1 Effect of HIP on tensile properties of representative aluminum alloy castings

Values are averages for an unspecified number of tests of specimens from castings.

| Alloy                         | Temper                  | Casting process                  | Untreated         |       |                   |       | HIPped                   |      |             |      | Improvement HIPped/unHIPped, % |      |                   |      |
|-------------------------------|-------------------------|----------------------------------|-------------------|-------|-------------------|-------|--------------------------|------|-------------|------|--------------------------------|------|-------------------|------|
|                               |                         |                                  | Ultimate strength |       | Yield strength(a) |       | Elongation (2D or 4D), % |      | HIP process |      | Ultimate strength              |      | Yield strength(a) |      |
|                               |                         |                                  | ksi               | MPa   | ksi               | MPa   | ksi                      | MPa  | ksi         | MPa  | ksi                            | MPa  | ksi               | MPa  |
| 332.0                         | T6                      | Permanent mold                   | 33.0              | 228   | 31.1              | 214   | 0.5                      | 0.5  | A359        | 38.8 | 268                            | 34.0 | 234               | 0.5  |
|                               |                         |                                  | 28.1              | 194   | ...               | ...   | 0.5                      | 0.5  | A359        | 35.6 | 246                            | 34.1 | 235               | 0.5  |
|                               |                         |                                  | 27.0              | 186   | ...               | ...   | 0.5                      | 0.5  | A359        | 35.5 | 245                            | 33.6 | 232               | 0.5  |
|                               |                         | Average                          | 29.4              | 202.5 | 31.1              | 214.0 | 0.5                      | 0.5  |             | 36.6 | 253                            | 33.9 | 234               | 0.5  |
| T6                            | Typical, permanent mold |                                  | 36                | 248   | 28                | 193   | 17.0                     |      |             |      |                                |      |                   |      |
| A356.0                        | T6                      | Sand                             | 37.6              | 259   | 34.4              | 237   | 2.0                      | 2.0  | Densal II   | 36.5 | 252                            | 33.1 | 228               | 2.0  |
|                               |                         |                                  | 38.1              | 263   | 35.2              | 243   | 5.3                      | 5.3  |             | 36.4 | 251                            | 35.4 | 244               | 5.9  |
|                               |                         | Average                          | 37.8              | 261   | 34.8              | 240   | 3.7                      | 3.7  |             | 36.5 | 252                            | 34.2 | 236               | 3.9  |
| A356.0                        | T61                     | Permanent mold                   | 35.6              | 246   | 27.1              | 187   | 4.5                      | 4.5  | A359        | 38.8 | 268                            | 30.8 | 212               | 4.5  |
|                               |                         |                                  | 34.8              | 240   | 27.3              | 188   | 4.0                      | 4.0  | A359        | 37.4 | 258                            | 30.7 | 212               | 3.5  |
|                               |                         |                                  | 34.0              | 234   | 27.4              | 189   | 4.0                      | 4.0  | A359        | 36.7 | 253                            | 30.3 | 209               | 3.0  |
|                               |                         |                                  | 33.2              | 229   | 27.3              | 188   | 2.5                      | 2.5  | A359        | 36.9 | 254                            | 30.1 | 208               | 3.0  |
|                               |                         |                                  | 30.2              | 208   | 25.7              | 177   | 2.0                      | 2.0  | A359        | 36.4 | 251                            | 29.3 | 202               | 3.5  |
|                               |                         |                                  | 39.8              | 275   | 29.4              | 203   | 6.5                      | 6.5  | A359        | 42.7 | 295                            | 31.6 | 218               | 10.0 |
|                               |                         |                                  | 37.9              | 261   | 30.3              | 209   | 4.5                      | 4.5  | A359        | 42.4 | 292                            | 32.6 | 225               | 6.5  |
|                               |                         |                                  | 36.5              | 252   | 29.2              | 201   | 2.5                      | 2.5  | A359        | 41.6 | 287                            | 31.3 | 216               | 6.5  |
|                               |                         |                                  | 35.5              | 245   | 28.5              | 197   | 2.5                      | 2.5  | A359        | 41.6 | 287                            | 31.6 | 218               | 6.0  |
|                               |                         |                                  | 33.6              | 232   | 27.8              | 192   | 3.0                      | 3.0  | A359        | 41.2 | 284                            | 32.7 | 226               | 6.0  |
|                               |                         | Average                          | 35.1              | 242   | 28                | 193   | 4                        | 4    |             | 39.6 | 273                            | 31.1 | 214               | 5    |
| T61                           | Typical, permanent mold |                                  | 41                | 283   | 30                | 207   | 10.0                     |      |             |      |                                |      |                   |      |
| A356.0                        | T62                     | VRC/PRC                          | 44.5              | 307   | 34.5              | 238   | 9.0                      | 9.0  | Densal II   | 43.8 | 302                            | 32.8 | 226               | 10.4 |
| T62                           | Typical, permanent mold |                                  |                   |       |                   |       |                          |      |             |      |                                |      |                   |      |
| A357.0                        | T62                     | Permanent mold                   | 43.6              | 301   | 38.9              | 268   | 1.0                      | 1.0  | A359        | 47.7 | 329                            | 40.8 | 281               | 3.0  |
|                               |                         |                                  | 41.1              | 283   | 38.3              | 264   | 0.5                      | 0.5  | A359        | 47.2 | 326                            | 42.1 | 290               | 2.5  |
|                               |                         |                                  | 35.5              | 245   | ...               | ...   | 0.5                      | 0.5  | A359        | 46.7 | 322                            | 41.1 | 283               | 2.0  |
|                               |                         | Average                          | 40.1              | 276   | 38.6              | 266   | 0.7                      | 0.7  |             | 47.2 | 326                            | 41.3 | 285               | 3    |
| T62                           | Typical, permanent mold |                                  | 62                | 428   | 38                | 262   | 17.0                     | 17.0 |             |      |                                |      |                   |      |
| D357.0                        | T6                      | Investment (Acceptable x-rays)   | 51.8              | 357   | 39.1              | 270   | 7.9                      | 7.9  | Densal II   | 50.2 | 346                            | 39.1 | 270               | 4.2  |
|                               |                         |                                  | 50.7              | 350   | 36.2              | 250   | 6.7                      | 6.7  |             | 50.2 | 346                            | 38.0 | 262               | 6.7  |
|                               |                         |                                  | 50.9              | 351   | 39.7              | 274   | 4.2                      | 4.2  |             | 51.8 | 357                            | 39.7 | 274               | 7.4  |
|                               |                         |                                  | 50.2              | 346   | 38.9              | 268   | 5.1                      | 5.1  |             |      |                                |      |                   |      |
|                               |                         | Average                          | 50.9              | 351   | 38.6              | 266   | 6.0                      | 6.0  |             | 50.7 | 350                            | 39.0 | 269               | 6.1  |
| D357.0                        | T6                      | Investment (unacceptable x-rays) | 43.1              | 297   | 37.8              | 261   | 1.2                      | 1.2  | Densal II   | 50.5 | 348                            | 37.4 | 258               | 4.9  |
|                               |                         |                                  | 44.9              | 310   | 36.2              | 250   | 2.1                      | 2.1  |             | 50.9 | 351                            | 41.5 | 286               | 4.0  |
|                               |                         |                                  | 41.5              | 286   | 35.2              | 243   | 1.5                      | 1.5  |             | 50.3 | 347                            | 39.7 | 274               | 3.5  |
|                               |                         |                                  | ...               | ...   | ...               | ...   | ...                      | ...  |             | 50.5 | 348                            | 39.4 | 272               | 3.8  |
|                               |                         |                                  | ...               | ...   | ...               | ...   | ...                      | ...  |             | 52.1 | 359                            | 41.9 | 289               | 5.4  |
|                               |                         |                                  | ...               | ...   | ...               | ...   | ...                      | ...  |             | 49.7 | 343                            | 40.7 | 281               | 3.5  |
|                               |                         |                                  | ...               | ...   | ...               | ...   | ...                      | ...  |             | 49.2 | 339                            | 25.2 | 174               | 3.5  |
|                               |                         | Average                          | 43.2              | 298   | 36.4              | 251   | 1.6                      | 1.6  |             | 50.5 | 348                            | 40.0 | 276               | 4.1  |
| Average improvement by HIPing |                         |                                  |                   |       |                   |       |                          |      |             |      |                                |      |                   |      |
|                               |                         |                                  |                   |       |                   |       |                          |      |             |      | 10%                            |      | 10                | 5%   |
|                               |                         |                                  |                   |       |                   |       |                          |      |             |      |                                |      | 17                | 148  |
|                               |                         |                                  |                   |       |                   |       |                          |      |             |      |                                |      |                   | 70%  |

(a) For tensile yield strengths, offset = 0.2%. Source: Ref 2-4

**Table 6.2** Effect of HIP by Alcoa Process on fatigue life of representative aluminum alloy castings

Hot isostatic pressing (HIP) by Alcoa 359 process

| Alloy                                                | Temper | Type of casting(a) | Lot ID     | Fatigue stress, ksi |                              | Fatigue life                                                                                                                                   |                                                                                                                            | Improvement<br>HIPped/UnHIPped(b) |
|------------------------------------------------------|--------|--------------------|------------|---------------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
|                                                      |        |                    |            | ksi                 | MPa                          | Untreated<br>cycles                                                                                                                            | HIPped(b)<br>cycles                                                                                                        |                                   |
| 242.0                                                | F      | PM pistons         | 317843,4   | 20.0                | 138                          | $0.6 \times 10^6$<br>$1.0 \times 10^6$<br>$1.45 \times 10^6$<br>$2.35 \times 10^6$<br><b>Average</b><br><b><math>1.35 \times 10^6</math></b>   | $1.55 \times 10^6$<br>$1.75 \times 10^6$<br>$1.9 \times 10^6$<br>$2.1 \times 10^6$<br><b><math>1.82 \times 10^6</math></b> | <b>35%</b>                        |
| 332.0                                                | F      | PM casting         | 317439,437 | 20.0<br>20.0        | 138<br>138<br><b>Average</b> | $6 \times 10^4$<br>...<br><b><math>6 \times 10^4</math></b>                                                                                    | $2.05 \times 10^5$<br>$1.6 \times 10^5$<br><b><math>1.82 \times 10^5</math></b>                                            | <b>203%</b>                       |
| 354.0                                                | T61    | Sand cast part     | 317433,2   | 20.0                | 138                          | $2.1 \times 10^5$<br>$1.6 \times 10^5$<br>$0.94 \times 10^5$<br>...<br><b>Average</b><br><b><math>1.55 \times 10^5</math></b>                  | $7.6 \times 10^5$<br>$7.1 \times 10^5$<br>$6.2 \times 10^5$<br>$4.8 \times 10^5$<br><b><math>6.39 \times 10^5</math></b>   | <b>312%</b>                       |
| 354.0                                                | T61    | PM cast part       | 317429,428 | 20.0                | 138                          | $7.2 \times 10^5$<br>$6.3 \times 10^5$<br>$4.5 \times 10^5$<br>$2.1 \times 10^5$<br><b>Average</b><br><b><math>5.24 \times 10^5</math></b>     | $3.05 \times 10^6$<br>$2.8 \times 10^6$<br>$2.3 \times 10^6$<br>$1.5 \times 10^6$<br><b><math>2.41 \times 10^6</math></b>  | <b>360%</b>                       |
| A356.0                                               | T61    | Sand cast part     | 317435,434 | 20.0                | 138                          | $1.35 \times 10^5$<br>$0.97 \times 10^5$<br>$0.92 \times 10^5$<br>$0.85 \times 10^5$<br><b>Average</b><br><b><math>1.02 \times 10^5</math></b> | $4.3 \times 10^5$<br>$3.1 \times 10^5$<br>$2.05 \times 10^5$<br>$1.6 \times 10^5$<br><b><math>2.79 \times 10^5</math></b>  | <b>174%</b>                       |
| A356.0                                               | T61    | PM cast part       | 317431,430 | 20.0                | 138                          | $1.95 \times 10^5$<br>$1.4 \times 10^5$<br>$1.3 \times 10^5$<br>$1.15 \times 10^5$<br><b>Average</b><br><b><math>1.45 \times 10^5</math></b>   | $4.4 \times 10^5$<br>$3.3 \times 10^5$<br>$2.9 \times 10^5$<br>$2.1 \times 10^5$<br><b><math>3.33 \times 10^5</math></b>   | <b>130%</b>                       |
| Average increase in fatigue life at 20 ksi (138 MPa) |        |                    |            |                     |                              |                                                                                                                                                |                                                                                                                            | <b>202%</b>                       |

(a) Casting process and part shape if known; PM, permanent mold. (b) Percent improvement by HIP in fatigue strength or endurance limit as compared to unHIPped material from same lot. Source: Ref 5

pressure can, in the worst cases, result in the reformation of internal porosity. In the case of castings with high hydrogen contents, this effect is seen following the heat treatment of HIPped parts.

The extent of outgassing occurring through diffusion in the HIP treatment cycle is insignificant.

Hot isostatic pressing is capable of upgrading mechanical properties and internal soundness and dramatically improving fatigue performance in a wide range of sand and permanent mold cast parts. The process can result in the salvage of unsatisfactory quality castings, an upgrading of mechanical properties for purposes of specification compliance, and substantial improvement in radiographic inspection capability.

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6. J.M. Boileau, J.W. Zindel, and J.E. Allison, “The Effects of Solidification Time on the Mechanical Properties in a Cast A356-T6 Aluminum Alloy,” Technical Paper Series 970019, Applications of Aluminum in Vehicle Design, SAE International, 1997

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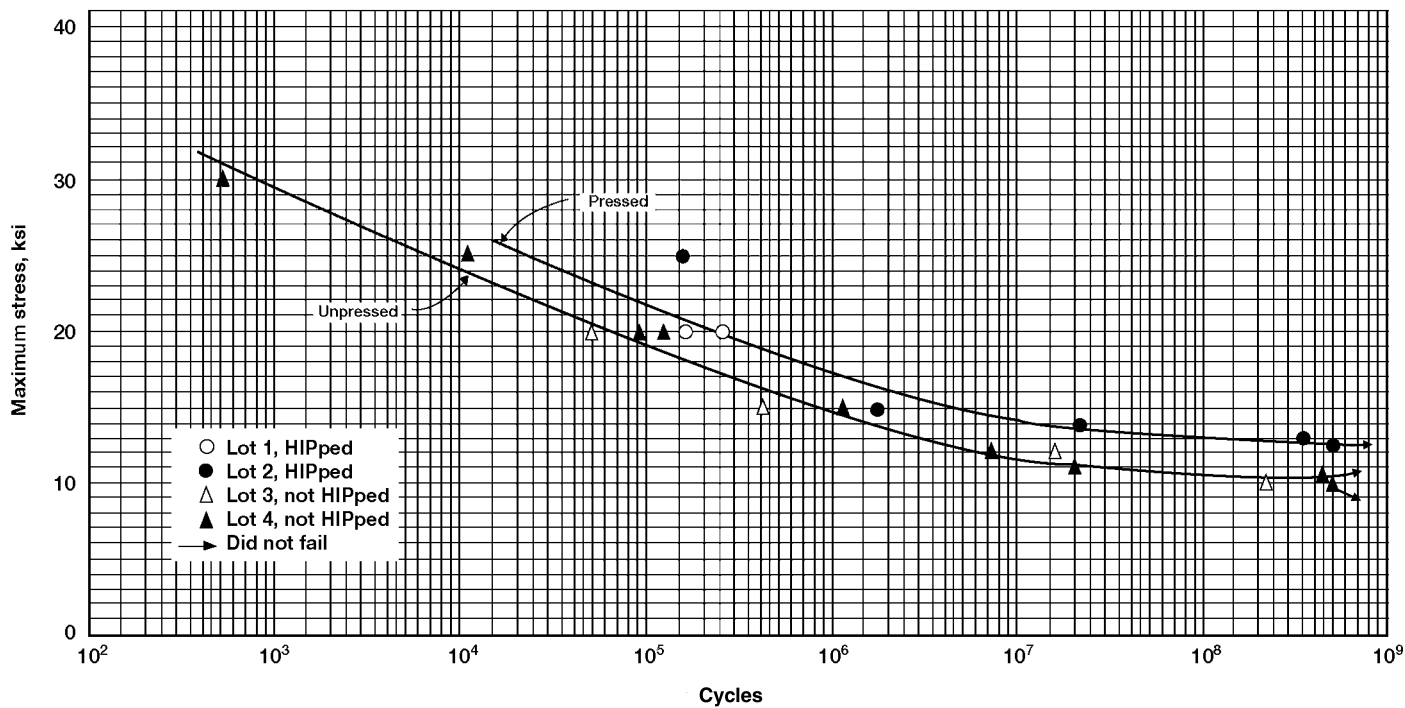


Fig. 6.2 Effect of Alcoa A359 HIP process on the rotating beam fatigue life of a 332.0-F casting (specimen per Fig. A3.2 in Appendix 3)

Table 6.3 Effect of HIP by Densal II on fatigue life of representative aluminum alloy castings

| Alloy  | Temper | Type of casting                  | Fatigue stress, smooth |     | Fatigue life     |               | Improvement(a) |
|--------|--------|----------------------------------|------------------------|-----|------------------|---------------|----------------|
|        |        |                                  | ksi                    | MPa | Untreated cycles | HIPPed cycles |                |
| D357.0 | T6     | Investment (acceptable x-rays)   | 26.4                   | 182 | 19,337           | 177,169       | 187%           |
|        |        |                                  |                        |     | 63,515           | 174,555       |                |
|        |        |                                  |                        |     | 69,824           | 161,533       |                |
|        |        |                                  |                        |     | 94,191           | 130,645       |                |
|        |        |                                  |                        |     | 60,986           | 84,000        |                |
|        |        |                                  |                        |     | 80,524           | 199,535       |                |
|        |        |                                  |                        |     | 39,271           | 121,004       |                |
|        |        |                                  |                        |     | 31,126           | 164,405       |                |
|        |        |                                  |                        |     | 34,240           | 125,950       |                |
|        |        |                                  |                        |     | 29,200           | 144,569       |                |
|        |        |                                  |                        |     | ...              | 163,364       |                |
|        |        |                                  |                        |     | Average          | 52,221        |                |
|        |        |                                  |                        |     |                  | 149,703       |                |
|        |        |                                  |                        |     |                  |               |                |
| D357.0 | T6     | Investment (unacceptable x-rays) | 26.4                   | 182 | 15,509           | 136,361       | 606%           |
|        |        |                                  |                        |     | 19,718           | 133,401       |                |
|        |        |                                  |                        |     | 16,501           | 49,067        |                |
|        |        |                                  |                        |     | 13,447           | 63,190        |                |
|        |        |                                  |                        |     | 13,795           | 130,114       |                |
|        |        |                                  |                        |     | 5,121            | 143,122       |                |
|        |        |                                  |                        |     | 19,210           | 142,519       |                |
|        |        |                                  |                        |     | 10,147           | 154,453       |                |
|        |        |                                  |                        |     | 10,763           | 160,191       |                |
|        |        |                                  |                        |     | 2,444            | 178,372       |                |
|        |        |                                  |                        |     | 60,707           | 63,357        |                |
|        |        |                                  |                        |     | ...              | 146,253       |                |
|        |        |                                  |                        |     | ...              | 152,991       |                |
|        |        |                                  |                        |     | ...              | 172,748       |                |
|        |        |                                  |                        |     | ...              | 119,570       |                |
|        |        |                                  |                        |     | ...              | 69,473        |                |
|        |        |                                  |                        |     | ...              | 22,604        |                |
|        |        |                                  |                        |     | ...              | 125,499       |                |
|        |        |                                  |                        |     | Average          | 17,033        |                |
|        |        |                                  |                        |     |                  | 120,183       |                |
|        |        |                                  |                        |     |                  |               |                |

(a) Percent improvement by HIP in fatigue strength or endurance limit as compared to unHIPPed material from same lot. Source: Ref 4

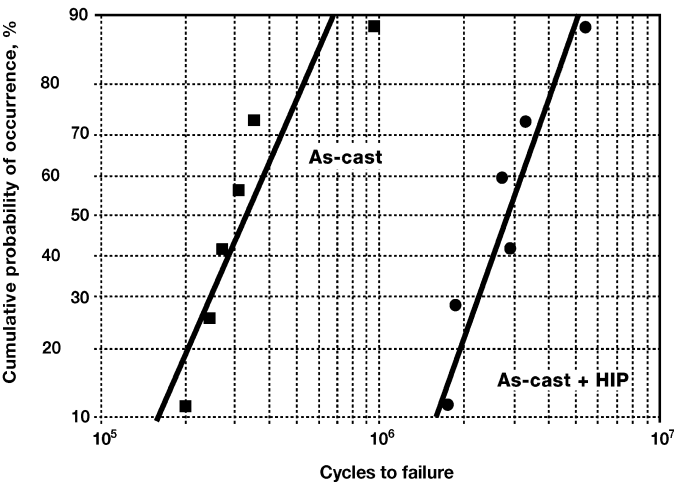


Fig. 6.3 Weibull analysis of fatigue data for A357.0-T6 aluminum alloy castings with and without Densal II HIP. Source: Ref 6

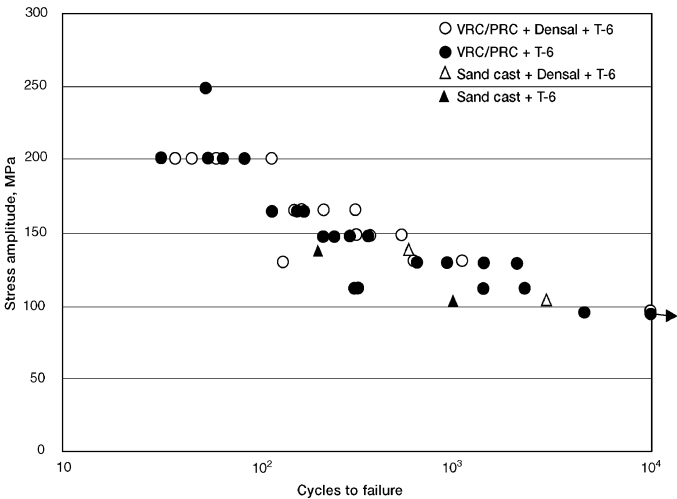


Fig. 6.4 Fatigue *S-N* curves for VCR/PCR and sand cast A356.0-T6 aluminum alloy castings with and without Densal II HIP

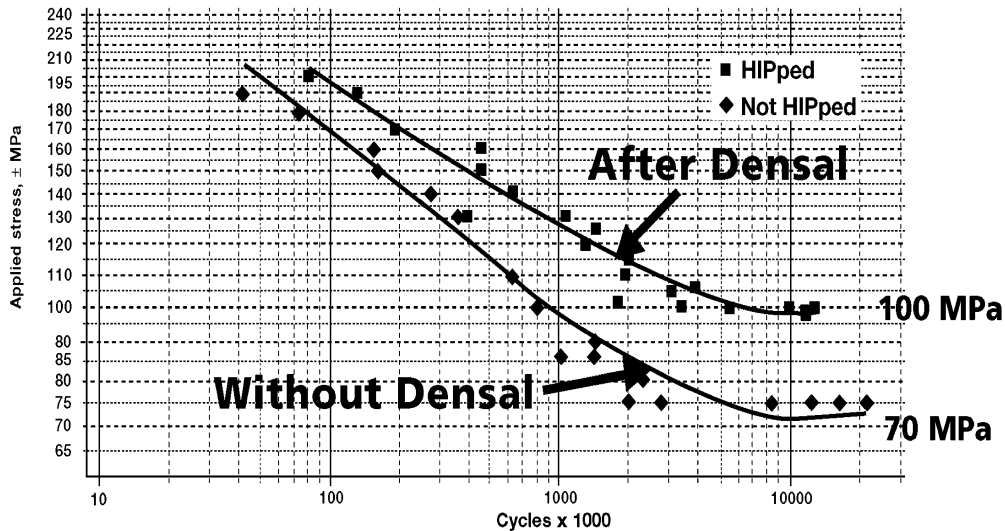


Fig. 6.5 Rotating bending fatigue *S-N* curves ( $R = -1.0$ ) for gravity die cast 359.0-T64 aluminum alloy casting with and without Densal II HIP

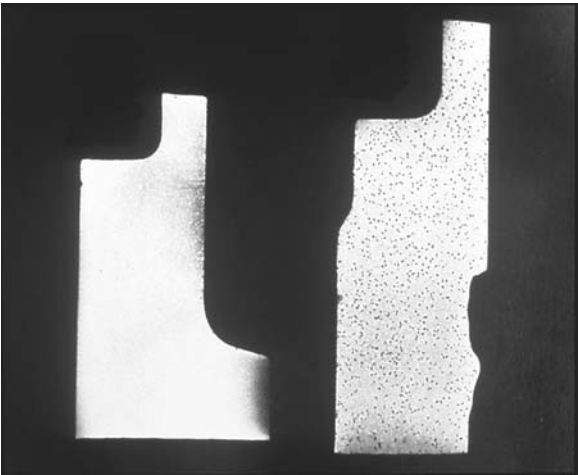


Fig. 6.6 Radiographs showing an untreated A356 alloy cast section with heavy porosity (right) and after hot isostatic pressing (left)

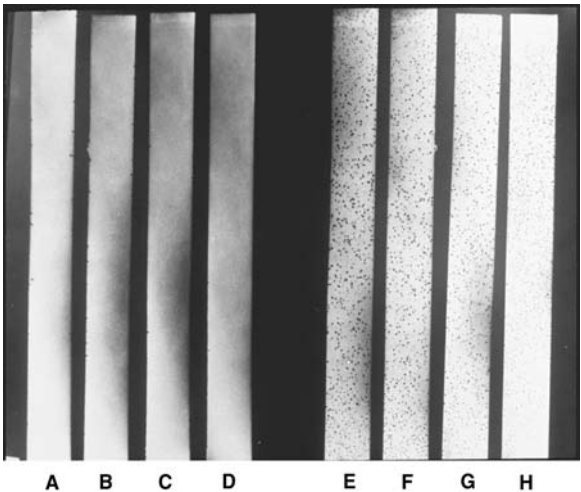


Fig. 6.7 Thin-section radiographs taken from A356 plate casting sections at one-inch intervals: A–D after HIP treatment, E–H as cast

## CHAPTER 7

# Heat Treatment of Aluminum Castings

The metallurgy of aluminum and its alloys offers a range of opportunities for employing thermal treatment practices to obtain desirable combinations of mechanical and physical properties. Through temper selection, it is possible to achieve properties that are largely responsible for the current use of aluminum alloy castings in virtually every field of application.

The term heat treatment is used to describe all thermal practices intended to modify the metallurgical structure of products in such a way that physical and mechanical characteristics are controllably altered to meet specific engineering criteria.

One or more of the following objectives form the basis for temper selection:

- Increase hardness
- Improve machinability
- Improve wear resistance
- Increase strength and/or produce the mechanical properties specified for a particular material condition

- Stabilize mechanical and physical properties
- Ensure dimensional stability
- Alter electrical characteristics
- Alter corrosion resistance
- Relieve residual stresses

The versatility of aluminum is reflected by the number of alloys that have been developed and commercially used. A wide range in desirable combinations of mechanical and physical properties can be achieved through the heat treatment of many of these alloys.

To achieve any of these objectives, parts may be annealed, solution heat treated, quenched, precipitation hardened, overaged, or treated in combinations of these practices (Fig. 7.1). In some simple shapes, bearings for example, thermal treatment may also include postquench plastic deformation through compression.

As noted in Chapter 2, the Aluminum Association has standardized the definitions and nomenclature applicable to thermal prac-

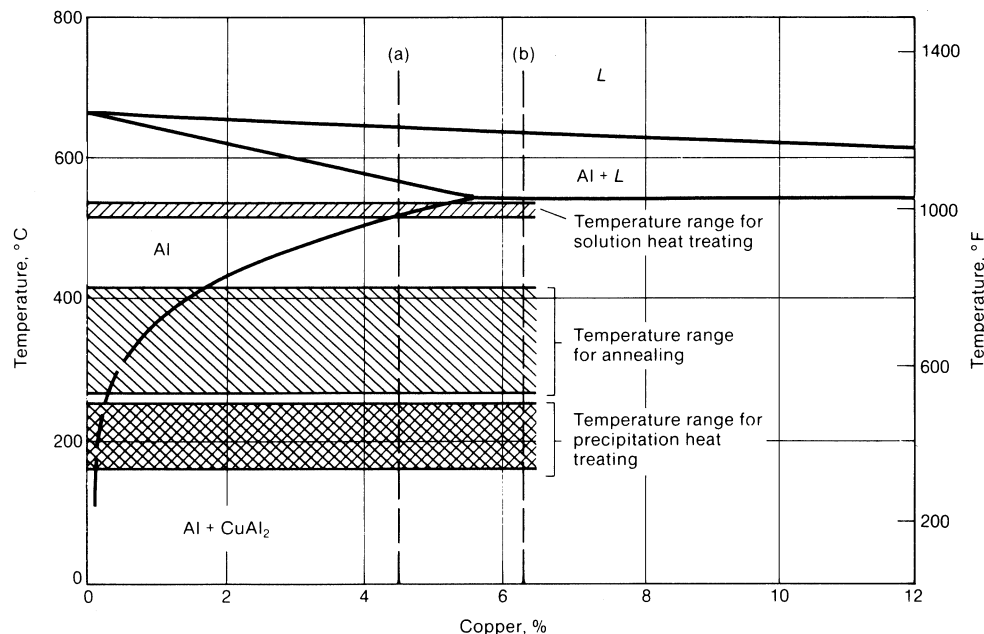


**Fig. 7.1** Typical temperature ranges for various thermal operations for aluminum alloy castings superimposed on a binary aluminum-copper phase diagram. The vertical dashed lines represent alloys containing (a) 4.5% Cu and (b) 6.3% Cu.

tice types and maintains a registry of standard heat treatment practices and designations for industry use:

- F, as-cast
- O, annealed
- T2, annealed (obsolete designation; use O instead)
- T4, solution heat treated and quenched
- T5, artificially aged from the as-cast condition
- T6, solution heat treated, quenched, and artificially aged
- T7, solution heat treated, quenched, and overaged

For tempers T4 through T7, additional digits such as T5x, T5xx, T6x, etc. may be used to define practice variations. The T101 temper has been assigned to a compressively cold-worked condition applicable only to alloy x850.0.

Specific criteria for heat treatment and the practices that will be used are often separately negotiated between buyer and seller.

The heat treatment of aluminum alloys is based on the varying solubilities of metallurgical phases in a crystallographically monotropic system. Since solubility of the eutectic phase increases with increasing temperature to the solidus, the formation and distribution of precipitated phases can be manipulated to influence material properties.

In addition to phase and morphology changes associated with soluble elements and compounds, other (sometimes desirable) effects accompany elevated-temperature treatment. Microsegregation in all solidified structures is minimized or eliminated. Residual stresses caused by solidification or by prior quenching are reduced, insoluble phases may be physically altered, and susceptibility to corrosion may be affected.

## 7.1 Solution Heat Treatment

Exposure to temperatures corresponding to maximum safe limits relative to the lowest melting temperature for a specific heat treatable composition results in dissolution of soluble phases that formed during and after solidification. The rate of heating to solution temperature is technically unimportant. When more than one soluble phase is present such as in Al-Si-Cu-Mg and Al-Zn-Cu-Mg systems, stepped heat treatment may be required to avoid melting of lower-melting-temperature phases.

The most complete degree of solution that can be practically and economically achieved is desirable for optimal properties. Different casting processes and foundry practices result in microstructural differences with relevance to heat treatment practice. Coarser microstructures associated with slow-solidification-rate processes require longer exposure at solution heat treatment temperature for solution to be achieved. The time required at temperature is typically progressively shorter for investment, sand, and permanent mold castings, but thin-walled sand castings produced with extensive use of chills can also often display finer microstructures. For these reasons, solution heat treatment practices may be optimized for any specific part to achieve solution with the shortest reasonable cycle once a production practice is finalized. Most foundries and heat treaters will select a solution heat treatment

practice with a large margin of safety to avoid the delays and costs of reheat treatment when property limits are not met.

Because of the changing slope of the characteristic solvus as temperature approaches the eutectic melting point, solution heat treatment temperature is critical in determining the degree of solution that can be attained. There is, furthermore, the effect of temperature on diffusion rates, which directly influences degree of solution as a function of time at temperature.

Within temperature ranges defined for solution heat treatment by applicable specification lies a significant corresponding range of solution potentials. The knowledgeable heat treatment facility or foundry seeking to obtain superior properties will bias solution heat treatment temperature within specification limits to obtain the highest practical degree of solution. Superior properties can be achieved with furnaces, thermocouples, and furnace controls that are capable of operating within close temperature ranges near the eutectic melting region, recognizing the resistance of cast structures to melting based on diffusion considerations. While temperatures just below the eutectic melting point are desirable for optimal property development, it is critically important that eutectic melting resulting in brittle intergranular eutectic networks be avoided.

Insoluble phases including those containing impurity elements are normally thought to be unaffected by solution heat treatment. However, limited changes do occur. The surfaces of primary and eutectic silicon particles are characteristically rounded during solution heat treatment. The solution heat treatment of alloy A444.0, which contains no soluble phase, is justified solely by this phenomenon and its effect on ductility. Limited solubility also results in similar physical boundary changes in other insoluble intermetallics.

## 7.2 Quenching

The objective of quenching is retention of the highest possible degree of solution with the lowest level of induced residual stresses and the least warpage or distortion consistent with commercial or specified requirements. Quenching is a distinct step in thermal practice leading to the metastable, supersaturated solution heat treated condition, T4. Specific parameters may be associated with the heating of parts to achieve solution, and separate parameters apply to the steps required to achieve the highest postquench degree of retained solution. Rapid cooling from solution temperature to room temperature is critical, difficult, and often the least-controlled step in thermal processing.

Specifications often define or recommend quench delay limits. In practice, the shortest possible delay is desirable. Specialized equipment such as bottom-drop and continuous furnaces offer these advantages. Excessive delays result in temperature drop and the rapid formation of coarse precipitates in a temperature range at which the effects of precipitation are ineffective for hardening purposes. The slope of the temperature-time relationship during quenching from solution temperature should be sufficiently steep that limits of precipitate solubility are not intersected (Fig. 7.2). Even though castings are characteristically more tolerant of quench delay than wrought products because of coarser structures and



longer diffusion times, excessive quench delays nevertheless result in less-than-optimal strengthening potential.

Water is the quench medium of choice for aluminum alloys, and its temperature has a major effect on results. Most commercial quenching is accomplished in water entered near the boiling point, but room temperature, 150 °F (65 °C), and 180 °F (80 °C) are common standardized alternatives. Effects of thickness and quench temperature on average cooling rates at midplane are shown in Fig. 7.3. Figure 7.4 shows differences in mechanical properties that result from quenching in water at different temperatures.

Since higher potential strength is associated with the most rapid quenching and, in general, corrosion and stress-corrosion performance are enhanced by rapid quenching, it would appear that room-temperature water should routinely be employed. More severe quenching offers diminishing benefits in property potentials and significant increases in residual stresses and distortion. Quench temperature is the dominant factor in these considerations.

The key to the compromise between goals involving property development and the physical consequences of quenching is heat-extraction uniformity, which is in turn a complex function of the operable heat-extraction mechanism. Nucleant, vapor film, and convective boiling occur with dramatically different heat-extraction rates at different temperature intervals, section thickness, and surface conditions. Load density, positioning, and casting

geometry influence the results. As section thicknesses increase, the metallurgical advantage of quench rates obtained by water temperatures less than 150 °F (65 °C) diminish, but the cooling rate advantage of 150 °F (65 °C) versus 212 °F (100 °C) water quench temperature is retained independent of section thickness.

In addition to developing racking and loading methods that space and orient parts for most uniform quenching, quenchant additions are often made to:

- Promote stable vapor film boiling by the deposition of compounds on the surface of parts as they are submerged in the quench solution
- Suppress variations in heat flux by increasing vapor film boiling stability through chemically decreased surface tension
- Moderate quench rate for a given water temperature

Quenching rates are also affected by surface condition of the parts. More rapid quenching occurs with oxidized, stained, and rough surfaces while bright, freshly machined, and etched surfaces quench more slowly.

The common use of water as a quenching medium is largely based on its superiority in heat extraction relative to other materials. Nevertheless, quenching has been accomplished in oil, salt baths, and in organic solutions. For many compositions, fan or mist

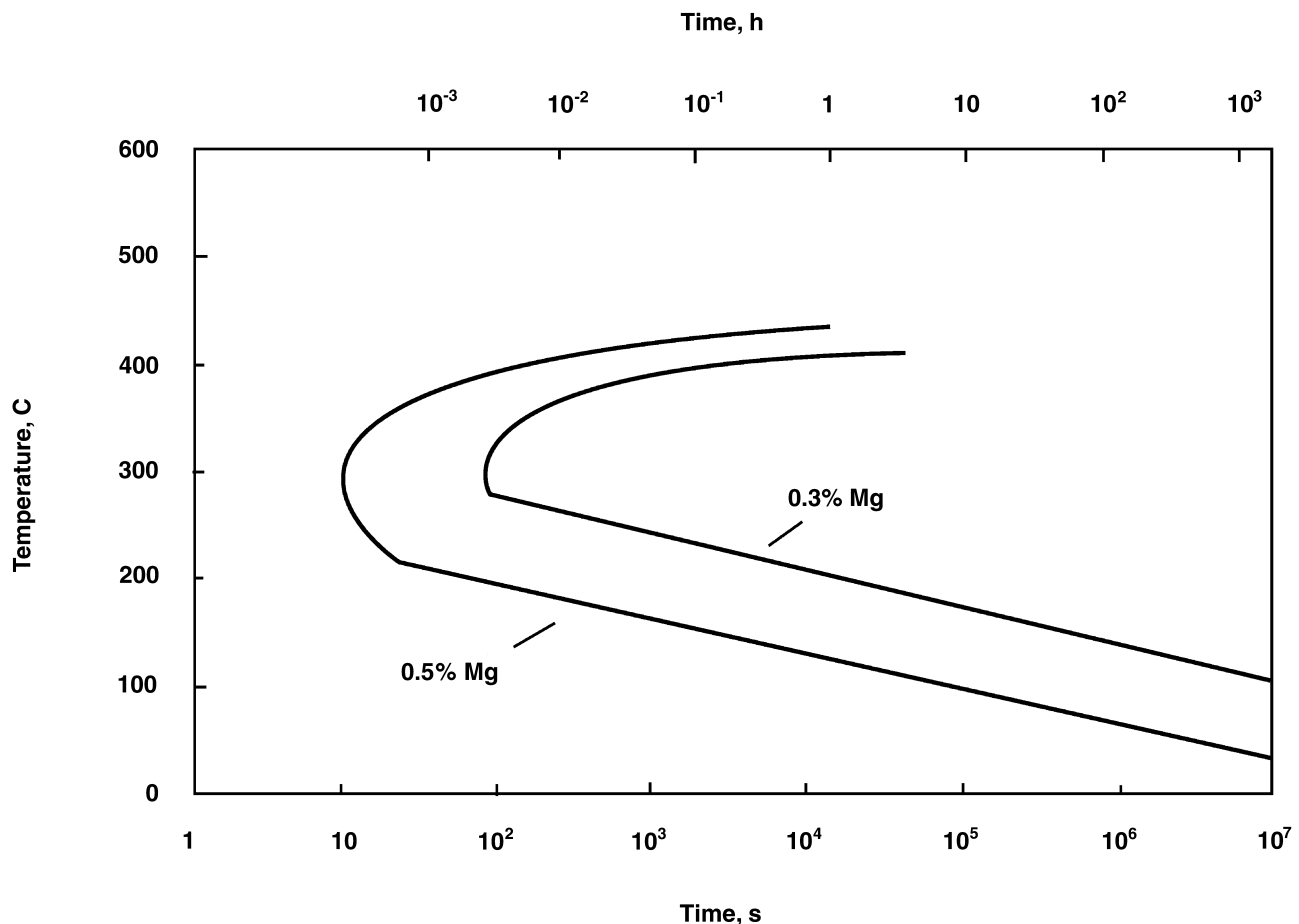


Fig. 7.2 Time-temperature-precipitation chart for aluminum alloys containing 7% Al and varying amounts of magnesium

quench is feasible as a means of obtaining dramatic reductions in residual stress levels at considerable sacrifice in hardening potential.

In general, parts that have been solution heat treated and quenched display tensile properties and elongation superior to those of the as-cast, F, condition. It is unique in improving strength, hardness, and ductility. Typical thermal treatments sacrifice strength and hardness for elongation or develop strength and hardness at the expense of ductility. The T4 condition is, however, rarely employed. Instead, the advantages of aging or precipitation hardening are obtained by additional thermal treatment following quenching. Among these advantages are increased strength and hardness with a corresponding sacrifice in ductility, improved machinability, the development of more stable mechanical properties, and reduced residual stresses.

### 7.3 Precipitation Heat Treating/Aging

Natural or artificial precipitation hardening following solution heat treatment and quench most powerfully differentiates the properties of cast aluminum products. Hardening is defined as changes in metallurgical structure resulting in increased resistance to deformation.

Most aluminum alloys age harden to some extent naturally after quenching; that is, properties change as a function of time at room temperature solely as a result of Guinier-Preston (GP) zone formation within the lattice structure. The extent of change is highly alloy dependent. For example, room-temperature aging in alloys such as A356.0 and C355.0 occurs within 48 h with insignificant changes thereafter. Alloy 520.0, normally used in the T4 condition, age hardens over a period of years, and a number of Al-Zn-Mg alloys that are employed without heat treatment exhibit rapid changes in properties over three or four weeks and harden at progressively reduced rates thereafter.

The process of hardening is accelerated by artificially aging at temperatures ranging from approximately 200 to 500 °F (90 to 260 °C), depending on the alloy and the properties desired. In natural and artificial aging, supersaturation, which characterizes the room-temperature solution condition, is relieved by the precipitation of solute that proceeds in stages with specific structural effects. At room or low aging temperatures or during transition at higher temperatures, the principal change is the diffusion of solute atoms to high-energy sites such as dislocations, dislocation tangles, and vacancies within the crystal lattice producing distortion of lattice planes and forming concentrations of subcritical crystal nuclei.

With continued exposure at aging temperature, these sites reach, or fail to reach, critical nucleation size, a stage leading to the

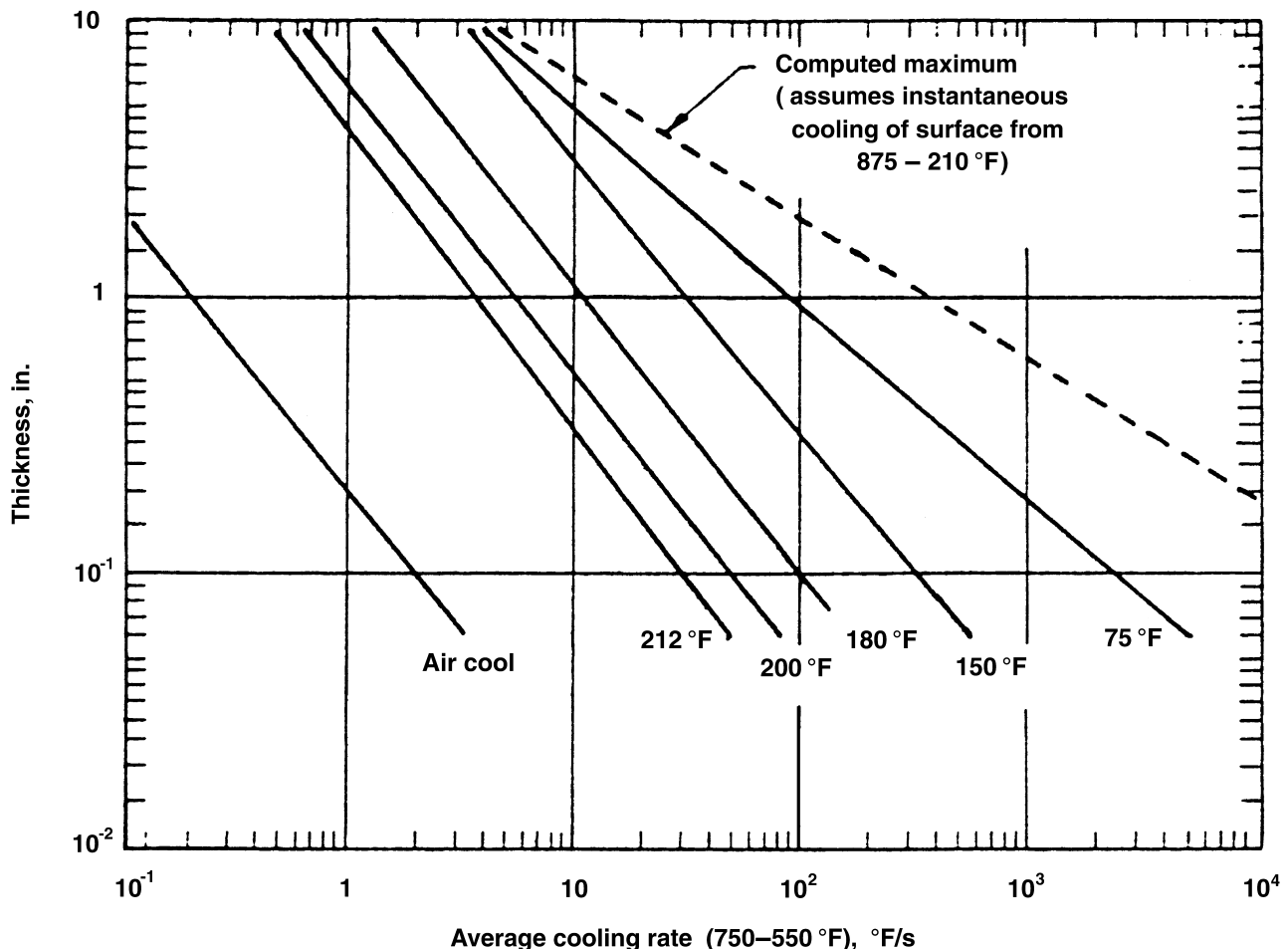
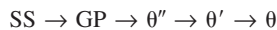


Fig. 7.3 Midplane cooling rates for varying water quench temperatures and aluminum alloy casting thicknesses

formation of discrete particles displaying the identifiable crystallographic character of the precipitated phase. With additional treatment, these transitional phase particles grow with an increase in coherency strains until with sufficient time and temperature, interfacial bond strength is exceeded. Coherency is lost, and with it, the strengthening effects associated with precipitate formation and growth. Continued growth of the now equilibrium phase occurs with the loss of hardness and strength corresponding to the over-aged condition.

### 7.3.1 Aluminum-Copper

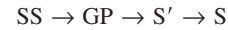
The soluble phase in aluminum-copper alloys is copper aluminide ( $\text{CuAl}_2$ ). At temperatures above 212 °F (100 °C), GP zones that form by diffusion of copper atoms in the supersaturated solid solution (SS) are replaced by  $\theta''$ , sometimes referred to as GP[2], with an ordered three-dimensional atomic arrangement. Continued diffusion and growth lead to the formation of the transition phase  $\theta'$ , which has the same composition and structure as the stable  $\theta$  phase and maintains coherency with the crystal lattice. Finally, as discrete transition phase regions continue to grow,  $\theta'$  transforms to stable, noncoherent equilibrium  $\theta$ :



### 7.3.2 Aluminum-Copper-Magnesium

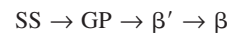
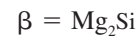
A similar sequence occurs in the artificial age hardening of Al-Cu-Mg alloys. The addition of magnesium accelerates and inten-

sifies room-temperature aging, and the progression is from GP zones to the transition and stable equilibrium phases:



### 7.3.3 Aluminum-Silicon-Magnesium

Magnesium silicide is the soluble phase in important alloys such as 356.0, A356.0, and A357.0 alloys. Unlike the hardening that accompanies the development of coherent lattice strains, this phase acts to increase the energy required for deformation of the crystal lattice. Spherical zones convert to needle-shaped particles at points corresponding to peak hardening. Further aging produces rod-shaped particles. The transition from  $\beta'$  to equilibrium  $\text{Mg}_2\text{Si}$  occurs without further diffusion:



### 7.3.4 Aluminum-Zinc-Magnesium

Several hardening phases may be formed in Al-Zn-Mg alloys. Most alloys of this type room-temperature age for extended periods. The presence of M and T in precipitation-hardened alloys such as 712.0, 713.0, and 771.0 is largely dictated by composition, but both may be present. M' is less effective in strength development, and transition to the stable forms occurs rapidly at conventional aging temperatures:

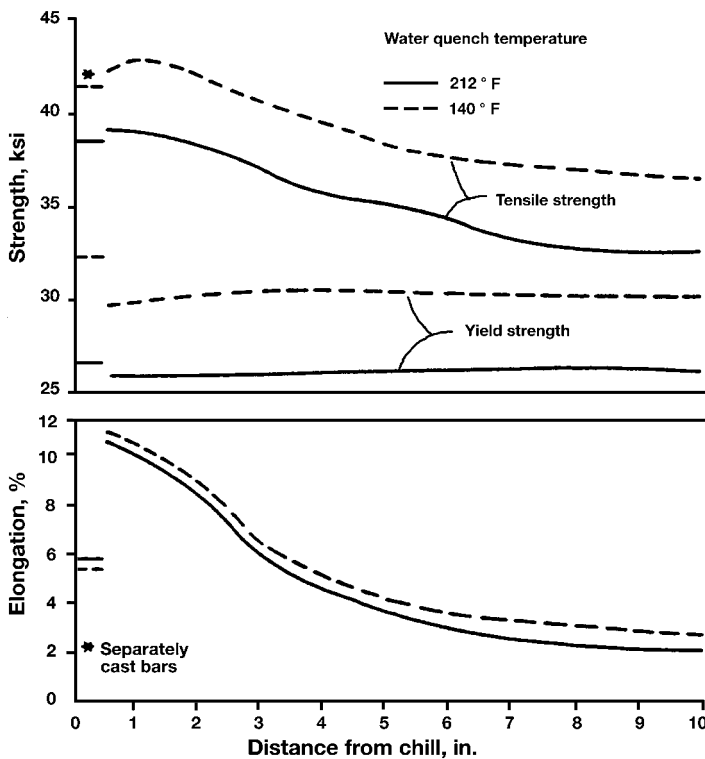
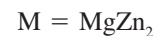


**Fig. 7.4** Tensile properties of end-chilled A356-T6 at different quench temperatures. 0.75 in. (19 mm) thick test slab, aged 310 °F (155 °C) for 5 h

The practice to be employed in artificial aging is entirely dependent on the desired level of property/strength development. Aging curves facilitate process selection. The heat treater may reasonably predict the results of aging by reference to these curves (see Data Set 1). It should be noted that longer times at lower aging temperature generally result in higher peak strengths. The aging response, or rate of property change as a function of time at peak strength, is also of interest. The flatter curves associated with lower aging temperatures allow greater tolerance in the effects of time/temperature variations.

Unlike solution heat treatment, the time required to reach aging temperature may be significant, but is seldom included in age-cycle control. The energy imparted during heating to precipitation-hardening temperature may be integrated into the control sequence to more accurately control results and minimize cycle time.

The overaged T7 condition is less common than is the T6 temper, but there are good reasons for its use in many applications. Precipitation hardening as practiced for the T6 condition results in reductions of 10 to 35% in residual stresses imposed by quenching. While overaging, by definition, is carrying the aging cycle to a point beyond peak hardness, it is also most often conducted at a higher temperature than employed for the fully hardened condition. A substantial further decrease in residual stresses is associated with the higher-temperature aging treatment. Furthermore, parts become more dimensionally stable as a result of more complete degrowth, and increased stability in performance is ensured when service involves exposure at elevated temperatures.

## 7.4 Annealing

Annealing, originally assigned the designation T2, now the O temper, is rarely employed but serves a useful purpose in providing parts with extreme dimensional and physical stability and the lowest level of residual stresses. The annealed condition is also characterized by low strength levels, softness, and correspondingly poor machinability. Typical annealing practices are for relatively short (2 to 4 h) exposures at a minimum temperature of 650 °F (340 °C). Higher-temperature practices are employed for more complete relaxation of residual stresses. The cooling rate from annealing temperature must be controlled in such a way that residual stresses are not reinduced and that resolution effects are avoided. Typical practice is to cool from annealing temperature in the furnace or in still air.

## 7.5 Stability

Stability is defined as the condition of unchanging structural and physical characteristics as a function of time under service conditions. The metastable T4 condition is subject to hardening, extensive in some alloys and limited in others, at room and higher temperatures. With exposure to elevated temperatures, significant additional physical and mechanical property changes are to be expected. They include dimensional change or growth and changes in susceptibility to corrosion and stress corrosion that can be associated with transitional states in some alloys.

The most stable conditions obtainable are annealed, overaged, aged, and as-cast, in that order. Underaged and solution heat treated parts are least stable.

## 7.6 Residual Stresses

Thermal treatment not only affects mechanical properties, but also directly influences residual stress levels.

Residual stresses are caused by differences in postsolidification cooling between surface and interior regions. They are induced by cooling from solidification temperature, quenching from solution heat treatment temperature, and by changes in temperature at any intermediate step. Residual stresses are functions of differential cooling rates, section thickness, and material strength. More severe

and more rapid temperature change results in large differences in the cooling rates of surface and internal regions of the casting structure. When the part is cooled from elevated temperature, the normal distribution of residual stresses when the part has reached room temperature is compression at the surface and counterbalancing tension in core regions (Fig. 7.5). Increasing thickness and alloy strength increases the magnitude of residual stresses.

Stresses induced by quenching from solution heat treatment temperature are many times more important than casting stresses or stresses imposed in any other conventional process. Decreasing the severity of quench from solution heat treatment results in a lower level of residual stresses but with correspondingly decreased material strength. Air quenching may provide a useful compromise in applications requiring unusual dimensional stability.

Residual stresses may only be relaxed by exposure to elevated temperature followed by slow cooling or by plastic deformation. Plastic deformation, routinely practiced for stress relief in wrought products, has little application in the complex designs of engineered products such as castings, so that stress relief becomes more exclusively a function of thermal treatment. Overaging results in significant reductions in residual stresses, and annealing provides a practical minimum in residual stress levels. The residual stresses retained after annealing or aging is limited by the yield strength of the material at treatment temperature.

## 7.7 Troubleshooting Heat Treatment Problems

### 7.7.1 Acceptance Criteria

Mechanical properties that include ultimate tensile strength, yield strength, and elongation are the usual criteria by which material acceptability is determined after heat treatment. Mechanical property limits statistically define normalcy for a given composition cast by a specific process or a composition cast by a specific process that has been heat treated to a specified temper.

Separately cast tensile specimens, poured from the melt from which the casting lot is poured, are typically used for all casting processes. When castings are heat treated, these specimens accompany the castings they represent through all phases of thermal operations. Specifications may also require or rely exclusively on the testing of specimens excised and machined from the casting.

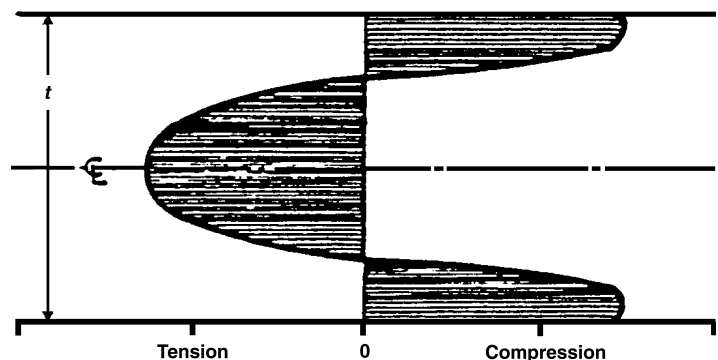


Fig. 7.5 Characteristic residual stress distribution after solution heat treatment and quench.  $t$ , thickness



Minimum mechanical property limits are usually defined by the terms of general procurement specifications, such as those developed by government agencies and technical societies. These documents specify testing frequency, tensile specimen type, casting lot definitions, testing procedures, and test limits. These requirements may also be separately negotiated.

Brinell hardness (10 mm ball, 500 kg load, 30 s) is only approximately related to yield strength, and while it is used routinely as an easily measurable nondestructive indicator of material condition, it is not normally guaranteed.

Electrical conductivity only approximates the relationship of chemistry, structure, and thermal treatment in cast or cast and heat treated aluminum structures. Electrical conductivity is used in rotors and anodes as an acceptance criterion. It may also be used to estimate susceptibility to stress-corrosion cracking.

### 7.7.2 Diagnosis

When specified mechanical property limits are not met after heat treatment, analytical procedures and judgments are applied to establish a corrective course of action based on evidence or assumptions concerning the cause of failure. Variations in chemical composition, even within specified limits, can have measurable effects. Metallurgical considerations such as chemical segregation, phase size and distribution, grain and dendrite cell sizes, and the modification or degree of refinement of eutectic and hypereutectic structures alter properties. For heat treated and aged tempers, variables include solution time and temperature, temperature of quenching medium, quench delay, and aging cycle. Annealing times and temperatures and postanneal cooling conditions are important for O temper material.

It is important to establish that the tensile specimens involved were representative and that test procedures conformed to the requirements of applicable test method standards:

- The stress-strain diagram should be used to confirm that test procedures including strain rate were appropriate.
- Failure should not be associated with surface damage such as nicks and scratches or machining errors.
- Specimens may contain nonrepresentative defects.
- The fracture surface should be examined to determine that no anomalous condition contributed to failure.
- The entire fracture must be contained within the center half of the gage length.
- Replacement and retest provisions are defined by specification and standards.

Furnace records and time-temperature charts should be consulted to confirm that specified practices were observed.

The chemical composition of alloys of aluminum is determined by light emission spectroscopy. Quantometers simplify and standardize chemical element concentrations. In some cases, wet chemistry or alternative techniques such as atomic absorption are employed. Less accurate methods including x-ray fluorescence are used to discriminate composition ranges.

Chemical composition is a major variable in mechanical property development. When mechanical properties have failed specifica-

tion limits and no other practice discrepancies are determined, alloy content should be carefully examined.

The role of trace elements in mechanical property development is important since these are often not separately defined in alloy specifications except as "others each" and "others total." Sodium and calcium are embrittling in 5xx.0 alloys. Low-temperature-melting elements, such as lead, tin, and bismuth may, under some conditions, form embrittling intergranular networks with similar effects. Insoluble impurity elements are generally responsible for decreases in elongation.

Low concentrations of soluble elements in heat treatable compositions naturally result in the more frequent distribution of mechanical property values in the lower specification range. Element relationships such as Cu-Mg, Si-Mg, Fe-Si, Fe-Mn, and Zn-Cu-Mg are also important considerations in defining the causes of abnormal mechanical property response to thermal treatment. Mechanical property failure may be caused by structural unsoundness and not by inadequate heat treatment. It is not appropriate to believe that unsound castings and tensile specimens will consistently meet specified mechanical property limits. All defects adversely affect strength and elongation. Shrinkage, hydrogen porosity, cracks, inclusions, and other casting-related defects influence mechanical properties adversely, and their effects should be considered before addressing the possibility of heat treatment problems.

The quality of solution heat treatment may be assessed in several ways. There is, of course, the rounding effect on "insoluble phases" that can be observed metallographically and serves as evidence of elevated-temperature exposure. The elimination of microsegregation or coring in many alloys is another indication of elevated-temperature treatment. The effective solution of soluble phases can be determined microscopically. Undissolved solute can be distinguished from the appearance of precipitate that forms at high temperatures and that result from quench delay or an inadequate or incomplete quench by particle size and distribution. There is also a tendency for precipitate that forms as a result of quench delay or inadequate quench to concentrate at grain boundaries as opposed to more normal distribution through the microstructure for properly solution heat treated and aged material.

While the overaged condition is microscopically apparent, underaging is difficult to assess because of the submicroscopic nature of transitional precipitates. Evidence of acceptable aging practice is best obtained from aging furnace records that might indicate errors in the age cycle. While underaging may be corrected by additional aging, for all other heat treatment aberrations, except those associated with objectionable conditions such as high-temperature oxidation or eutectic melting, resolution heat treatment is an acceptable corrective action. Eutectic melting occurs when the eutectic melting temperature is exceeded in solution heat treatment, resulting in characteristic rosettes of resolidified eutectic.

High-temperature oxidation is a misnamed condition of hydrogen diffusion affecting surface layers during solution heat treatment. It results from excessive moisture in the furnace atmosphere, sometimes aggravated by oil, grease, sulfur, or other furnace or casting surface contamination.

There are no technical reasons for discouraging even repeated reheat treatment to obtain acceptable mechanical properties. In the case of aluminum-copper alloys, it is essential that resolution heat

treatment be conducted at a temperature equivalent to or higher than the original practice to ensure effective resolution; however, it should be apparent that when the results of repeated reheat treatment prove to be equally unsatisfactory that other conditions are responsible for mechanical property failure.

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## CHAPTER 8

# Properties and Performance of Aluminum Castings

This chapter takes a detailed look at a wide range of the properties and performance of aluminum casting alloys, including cast aluminum matrix composites, utilizing the following organization of information:

- 8.1 Compositions
- 8.2 Physical properties
- 8.3 Typical and minimum (design) mechanical properties
  - 8.3.1 Typical properties
  - 8.3.2 Design properties (including MMPDS/MIL-HDBK-5)
  - 8.3.3 Effects of subzero and elevated temperatures
  - 8.3.4 Impact of emerging technologies and premium practices on properties
- 8.4 Fatigue resistance
- 8.5 Fracture resistance
- 8.6 Subcritical crack growth
- 8.7 Corrosion resistance
- 8.8 Properties of aluminum matrix composites

### 8.1 Compositions and Influence of Composition on Characteristics

The compositions of commercial aluminum casting alloys are given in Chapter 2, Table 2.1 (Ref 1, 2).

A summary of the major characteristics of the individual alloys is presented in Table 8.1.

### 8.2 Physical Properties of Aluminum Casting Alloys

The physical properties of aluminum casting alloys at room temperature are summarized in Table 8.2 (Ref 3–7). Alloy con-

stants permitting the calculation of the coefficients of thermal expansion over various ranges of temperature are provided in Table 8.3.

The effect of elements in and out of solid solution on the resistivity of aluminum casting alloys is illustrated by the data in Table 8.4 (Ref 8).

The densities and moduli of elasticity of all aluminum alloys, including castings, are directly dependent on the alloying content and those properties of the alloying elements themselves. The dependence is such that these properties may be estimated for alloys for which they have been measured directly by summing the percentages of each element multiplied by their own density and/or moduli respectively (i.e., the rule of averages). Table 8.5 is a summary of the densities and average moduli of elasticity of aluminum and the more commonly used alloying elements to aid in such estimates. Values calculated in this manner should be considered estimates, and care should be taken to note the exceptions to the rule for modulus, for example, magnesium, for which the effect is greater than would be expected based on its modulus alone.

The damping characteristics of two aluminum casting alloys, 319.0 and 356.0, as determined in cantilever-beam vibration tests (Ref 11), are presented in Fig. 8.1, where they are compared with the band for wrought alloys. It is clear that the damping characteristics of casting alloys in terms of the log decrement of decay from these tests are in the same broad range as those of the wrought alloys. Data for aluminum wrought alloys with cladding are included in the figure to indicate that 1xx.0 castings and others with very low yield strengths may have appreciably higher damping capacity than the typical 3xx.0 castings.

The growth characteristics of a number of aluminum casting alloys are represented by the curves in Data Set 2. Growth, or more appropriately, dimensional change with time that may be contractive as well as expansive, occurs as a result of microstructural phase changes, principally precipitation from solid solution that occurs with time in service, especially in elevated-temperature applications. Growth is an important consideration for parts for which close dimensional tolerances are a requirement.

Table 8.1 Relative casting and finishing characteristics of cast aluminum alloys

Ratings: 1, excellent; 2, very good; 3, good; 4, fair; 5, poor.

| Alloy  | Type of casting | Casting characteristics    |           |                               |                    |                       | Finishing characteristics |             |               |                      |            | Anodizing |            |                      | Performance characteristics   |                    |
|--------|-----------------|----------------------------|-----------|-------------------------------|--------------------|-----------------------|---------------------------|-------------|---------------|----------------------|------------|-----------|------------|----------------------|-------------------------------|--------------------|
|        |                 | Resistance to hot cracking | Shrinkage | Fluidity/die filling capacity | Pressure tightness | Anti-soldering to die | Machinability             | Weldability | Polishability | Electro-plateability | Appearance |           | Protection | Corrosion resistance | Elevated-temperature strength | Resistance to wear |
|        |                 |                            |           |                               |                    |                       |                           |             |               |                      |            |           |            |                      |                               |                    |
| 201.0  | S, P            | 4                          | 4         | 3                             | 3                  | ...                   | 1                         | 4           | 1             | ...                  | 2          | ...       | 2          | 4                    | 1                             | ...                |
| 204.0  | S               | 4                          | ...       | 3                             | 3                  | ...                   | 1                         | 4           | 2             | ...                  | 3          | ...       | 4          | 4                    | 1                             | ...                |
| 208.0  | S               | 2                          | ...       | 2                             | 2                  | ...                   | 3                         | 3           | 3             | 1                    | 3          | ...       | 3          | 4                    | 3                             | ...                |
| 213.0  | S, P            | 3                          | 3         | 2                             | 3                  | ...                   | 2                         | 2           | ...           | ...                  | ...        | ...       | ...        | 4                    | 1                             | ...                |
| 222.0  | S, P            | 4                          | 4         | 3                             | 4                  | ...                   | 1                         | 3           | 2             | 1                    | 3          | ...       | 3          | 4                    | 1                             | ...                |
| 238.0  | P               | 2                          | 3         | 2                             | 2                  | ...                   | 2                         | 3           | ...           | ...                  | ...        | ...       | ...        | 4                    | ...                           | ...                |
| 240.0  | S, P            | 4                          | 4         | 3                             | 4                  | ...                   | 3                         | 4           | ...           | ...                  | ...        | ...       | ...        | 4                    | ...                           | ...                |
| 242.0  | S               | 4                          | 3         | 4                             | 4                  | ...                   | 2                         | 3           | 2             | 1                    | 3          | ...       | 4          | 4                    | 2                             | ...                |
| A242.0 | S               | 4                          | 4         | 3                             | 4                  | ...                   | 2                         | 3           | 2             | ...                  | 3          | ...       | ...        | 4                    | 2                             | ...                |
| 295.0  | S               | 4                          | 4         | 4                             | 3                  | ...                   | 2                         | 4           | 2             | ...                  | 2          | ...       | 3          | 4                    | 3                             | ...                |
| 296.0  | P               | 4                          | 3         | 4                             | 3                  | ...                   | 4                         | 4           | 2             | ...                  | 3          | ...       | ...        | 4                    | 2                             | ...                |
| 308.0  | P               | 2                          | 2         | 2                             | 2                  | ...                   | 3                         | 3           | 3             | ...                  | 4          | ...       | ...        | 3                    | 3                             | ...                |
| 319.0  | S, P            | 2                          | 2         | 2                             | 2                  | ...                   | 3                         | 2           | 4             | 3                    | 4          | ...       | 3          | 3                    | 3                             | ...                |
| 328.0  | S               | 1                          | ...       | 1                             | 2                  | ...                   | 3                         | 1           | 3             | ...                  | 4          | ...       | 2          | 3                    | 2                             | ...                |
| 332.0  | P               | 1                          | 2         | 1                             | 2                  | ...                   | 3                         | 2           | 4             | 3                    | 4          | ...       | ...        | 3                    | 1                             | ...                |
| 333.0  | P               | 1                          | 1         | 2                             | 2                  | ...                   | 4                         | 3           | 3             | 3                    | 4          | ...       | ...        | 3                    | 2                             | ...                |
| 336.0  | P               | 1                          | 2         | 2                             | 3                  | ...                   | 4                         | 2           | 4             | 4                    | 4          | ...       | ...        | 3                    | 1                             | ...                |
| 354.0  | P               | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 4             | 2                    | 4          | ...       | ...        | 3                    | 2                             | ...                |
| 355.0  | S               | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 3             | 1                    | 4          | ...       | 2          | 3                    | 2                             | ...                |
| C355.0 | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 3             | 1                    | 4          | ...       | 2          | 3                    | 2                             | ...                |
| 356.0  | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 4             | 1                    | 4          | ...       | 2          | 3                    | 2                             | ...                |
| A356.0 | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 4             | 1                    | 4          | ...       | 2          | 3                    | 3                             | ...                |
| 357.0  | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 4             | 1                    | 4          | ...       | 2          | 3                    | 3                             | ...                |
| A357.0 | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 4             | 1                    | 4          | ...       | 2          | 3                    | 2                             | ...                |
| 359.0  | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 2           | 4             | 1                    | 4          | ...       | ...        | 3                    | 1                             | ...                |
| 360.0  | D               | 1                          | 1         | 3                             | 2                  | 2                     | 3                         | ...         | 3             | 2                    | 4          | ...       | 3          | 2                    | ...                           | 2                  |
| A360.0 | D               | 1                          | 1         | 3                             | 2                  | 2                     | 3                         | ...         | 3             | 2                    | 3          | ...       | 3          | 2                    | 1                             | 2                  |
| 380.0  | D               | 2                          | 1         | 2                             | 2                  | 1                     | 3                         | ...         | 3             | 1                    | 4          | ...       | 3          | 3                    | 3                             | 4                  |
| A380.0 | D               | 2                          | 2         | 2                             | 2                  | 1                     | 3                         | ...         | 3             | 1                    | 4          | ...       | 3          | 3                    | 3                             | 4                  |
| 383.0  | D               | 1                          | ...       | 1                             | 2                  | 2                     | 2                         | ...         | 3             | 1                    | 3          | ...       | 3          | 3                    | 2                             | 2                  |
| 384.0  | D               | 2                          | 2         | 1                             | 3                  | 2                     | 2                         | ...         | 3             | 2                    | 4          | ...       | 3          | 2                    | 2                             | 2                  |
| 390.0  | D               | 3                          | 2         | 1                             | 4                  | 2                     | 5                         | ...         | 5             | 3                    | 5          | ...       | 3          | 3                    | 3                             | 1                  |
| A390.0 | S, P            | 3                          | 3         | 3                             | 3                  | 2                     | 5                         | 4           | 5             | 3                    | 5          | ...       | 3          | 3                    | 3                             | ...                |
| B390.0 | D               | 4                          | ...       | 1                             | 4                  | 2                     | 5                         | ...         | 5             | 3                    | 5          | ...       | ...        | 5                    | 3                             | ...                |
| 392.0  | D               | 4                          | ...       | 1                             | 3                  | 2                     | 5                         | ...         | 5             | 3                    | 5          | ...       | ...        | 2                    | 3                             | ...                |
| D      | D               | 4                          | ...       | 1                             | 3                  | 2                     | 5                         | ...         | 5             | 3                    | 5          | ...       | 5          | 2                    | 3                             | 3                  |
| 413.0  | D               | 1                          | 2         | 1                             | 1                  | 1                     | 4                         | ...         | 5             | 3                    | 5          | ...       | ...        | ...                  | ...                           | ...                |
| A413.0 | D               | 1                          | ...       | 1                             | 1                  | 1                     | 4                         | ...         | 5             | 3                    | 5          | ...       | ...        | ...                  | ...                           | ...                |
| 443.0  | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 4           | 4             | ...                  | 4          | ...       | 2          | 4                    | 4                             | ...                |
| A443.0 | S               | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 4           | 4             | ...                  | 4          | ...       | 2          | 4                    | 4                             | ...                |
| B443.0 | S               | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 4           | 4             | ...                  | 4          | ...       | 2          | 4                    | 4                             | ...                |
| C443.0 | D               | 3                          | 3         | 4                             | 3                  | 4                     | 5                         | ...         | 4             | ...                  | 4          | ...       | 2          | 4                    | 4                             | 4                  |
| A444.0 | S, P            | 1                          | 1         | 1                             | 1                  | ...                   | 3                         | 1           | 4             | ...                  | 4          | ...       | ...        | 4                    | 4                             | ...                |
| 511.0  | S               | 4                          | 5         | 4                             | 5                  | ...                   | 1                         | 4           | 2             | ...                  | 2          | ...       | ...        | 1                    | 3                             | ...                |
| 512.0  | S, P            | 3                          | 4         | 4                             | 4                  | ...                   | 1                         | 4           | 2             | ...                  | 2          | ...       | ...        | 1                    | 3                             | ...                |
| 513.0  | P               | 4                          | 5         | 4                             | 4                  | ...                   | 1                         | 5           | 1             | ...                  | 1          | ...       | ...        | 1                    | 3                             | ...                |
| 514.0  | S               | 4                          | 5         | 4                             | 5                  | ...                   | 1                         | 4           | 1             | ...                  | 1          | ...       | ...        | 1                    | 3                             | ...                |
| 518.0  | D               | 5                          | 5         | 5                             | 5                  | 5                     | 1                         | ...         | 1             | 5                    | 1          | ...       | 1          | 1                    | 4                             | 4                  |
| 520.0  | S               | 2                          | 5         | 4                             | 5                  | ...                   | 1                         | 3           | 1             | ...                  | 1          | ...       | 1          | 1                    | 5                             | ...                |
| 535.0  | S               | 4                          | 5         | 4                             | 5                  | ...                   | 1                         | 3           | 1             | ...                  | 1          | ...       | 1          | 1                    | 3                             | ...                |
| A535.0 | S               | 4                          | 5         | 4                             | 4                  | ...                   | 1                         | 4           | 1             | ...                  | 1          | ...       | ...        | 1                    | 3                             | ...                |
| B535.0 | S               | 4                          | 5         | 4                             | 4                  | ...                   | 1                         | 4           | 1             | ...                  | 1          | ...       | ...        | 1                    | 3                             | ...                |
| 705.0  | S               | 5                          | 4         | 4                             | 4                  | ...                   | ...                       | 4           | 1             | ...                  | 1          | ...       | ...        | 1                    | 4                             | ...                |
| 707.0  | S               | 5                          | 4         | 4                             | 4                  | ...                   | ...                       | 4           | 2             | ...                  | 2          | ...       | 2          | 2                    | 4                             | ...                |
| 710.0  | S               | 5                          | 3         | 4                             | 4                  | ...                   | 1                         | 4           | 2             | ...                  | 2          | ...       | 3          | 2                    | 4                             | ...                |
| 711.0  | S, P            | 5                          | 4         | 5                             | 3                  | ...                   | 1                         | 3           | 1             | ...                  | 1          | ...       | 3          | 3                    | 5                             | ...                |
| 712.0  | S               | 4                          | 4         | 3                             | 4                  | ...                   | 1                         | 4           | 2             | ...                  | 2          | ...       | 3          | 3                    | 4                             | ...                |
| 713.0  | S               | 4                          | 4         | 3                             | 3                  | ...                   | 1                         | 3           | 1             | ...                  | 1          | ...       | 3          | 2                    | 4                             | ...                |
| 771.0  | S, P            | 4                          | 4         | 3                             | 3                  | ...                   | 1                         | ...         | 1             | ...                  | 1          | ...       | 2          | 4                    | 4                             | ...                |
| 772.0  | S, P            | 4                          | 4         | 3                             | 3                  | ...                   | 1                         | ...         | 1             | ...                  | 1          | ...       | 2          | 4                    | 4                             | ...                |
| 850.0  | S, P            | 4                          | 4         | 4                             | 4                  | ...                   | 1                         | 4           | 3             | ...                  | ...        | ...       | 5          | 3                    | 4                             | ...                |
| 851.0  | S, P            | 4                          | 4         | 4                             | 4                  | ...                   | 1                         | 4           | 3             | ...                  | ...        | ...       | 5          | 3                    | 5                             | ...                |
| 852.0  | S, P            | 4                          | 4         | 4                             | 4                  | ...                   | 1                         | 4           | 3             | ...                  | ...        | ...       | 5          | 3                    | 5                             | ...                |

Source: Ref 3–5



### 8.3 Typical and Minimum Mechanical Properties of Aluminum Alloy Castings

The typical and minimum (design) mechanical properties of aluminum casting alloys are presented and discussed in the following sections:

- 8.3.1 Published typical mechanical properties
- 8.3.2 Published minimum (design) mechanical properties
- 8.3.3 Effects of subzero and elevated temperatures on mechanical properties
- 8.3.4 Influence of premium practices and emerging casting technologies on mechanical properties

#### 8.3.1 Published Typical Mechanical Properties

The published aluminum industry typical mechanical properties of aluminum casting alloys are presented in Table 8.6 in English units and in Table 8.7 in metric units (Ref 3–7).

In using the values from Table 8.6 and 8.7, one should bear in mind that the published typical values are normally based on the analysis of the results of separately cast test bars (Appendix 3, Fig. A3.1), not of specimens taken from actual cast components. The casting practices for separately cast test bars are typically more uniform and controlled than for the broad array of cast parts, and so the published typical values may be higher than can be realistically expected from individual cast parts. The industry guideline is that the strengths of actual cast parts may be as low as 75% of the values for separately cast test bars.

In these tables, the typical properties are defined as the average of the range for all compositions of the respective alloy and temper. In most cases, the metric values are converted directly from the English values by multiplying by the appropriate conversion factors and rounding to the nearest megapascal (MPa).

Published typical stress-strain curves for a variety of aluminum alloys are presented in Data Set 3 (Ref 12).

#### 8.3.2 Published Minimum and Design Mechanical Properties

The published aluminum industry specification minimum mechanical properties of aluminum casting alloys in both English and metric units are presented in Table 8.8 (Ref 3–7).

These properties are consistent with the specified minimum tensile requirements cited in the several ASTM standards as published in the *Annual Book of ASTM Standards*, Volume 02.02, namely:

| ASTM designation | Title                                                             |
|------------------|-------------------------------------------------------------------|
| B 26/B 26M       | Standard Specification for Aluminum Alloy Sand Castings           |
| B 85             | Standard Specification for Aluminum Alloy Die Castings            |
| B 108            | Standard Specification for Aluminum Alloy Permanent Mold Castings |
| B 618            | Standard Specification for Aluminum Alloy Investment Castings     |
| B 686            | Standard Specification for Aluminum Alloy Castings, High-Strength |

It is important to note that there are no published industry statistically reliable minimum values for die castings of any alloy. This reflects the fact that the properties of individual cast parts may vary rather widely depending on their configuration and the specific casting process. It is recommended that users of aluminum die castings plan to carry out a statistical analysis of the properties of the specific cast part they intend to use as part of the design program.

As with typical properties, it is important to keep in mind that, except where explicitly stated, the specification minimum properties are based on tests of separately cast test bars (i.e., cast at the same time as the specific cast parts). Thus it is to be expected that in many if not all locations in specific cast parts, the properties may be lower than those determined from the separately cast test bars. The industry practice is to consider that the properties of actual conventional castings may be as low as 75% of the cast test bar specification values.

Also, as with the typical properties of aluminum castings, the metric minimum values have been created by converting directly from the English values by multiplying by the appropriate conversion factors and rounding to the nearest megapascal (MPa). It may be noted that this situation is different than for wrought aluminum alloy products, for which hard metric minimum values (i.e., calculated from the original metric test data and rounded) have been determined.

#### 8.3.3 Effects of Subzero and Elevated Temperatures on Mechanical Properties

The published typical tensile properties of several aluminum casting alloys at temperatures as high as 700 °F (370 °C) for holding times as long as 10,000 h are presented in Data Set 4 (Ref 14). For some alloys, data are also included for room temperature after the alloys have been exposed to extended heating at temperatures up to 500 °F (260 °C). Also included where available are data at subzero temperatures as low as –452 °F (–270 °C), near absolute zero. Creep properties are presented in Data Set 5 (also from Ref 14).

Like most other aluminum alloys, the casting alloys have not only higher strengths but also higher elongations at subzero temperatures than at room temperature. While data are available for only one alloy (A356.0-T6) at temperatures below –320 °F (–196 °C), it is clear that this trend continues at lower temperatures, essentially to absolute zero. Aluminum casting alloys may be used under arctic conditions and for cryogenic applications without any fear of low-ductility or brittle fracture.

The effects of temperatures above room temperature also parallel expectations from other aluminum alloys. Typically, as temperature increases above about 212 °F (100 °C), strengths decrease at an increasing rate until they level out around 500 to 600 °F (260 to 315 °C). Strengths also decrease with increasing time at tempera-

**Table 8.2** Typical physical properties of cast aluminum alloys

Metric unit values generally derived from engineering/English unit values

| Alloy        | Temper | Density             |                   | Specific gravity | Average coefficient of thermal expansion |                                 | Approx melting range(a) |         | Thermal conductivity                           |                     |
|--------------|--------|---------------------|-------------------|------------------|------------------------------------------|---------------------------------|-------------------------|---------|------------------------------------------------|---------------------|
|              |        | lb/in. <sup>3</sup> | g/cm <sup>3</sup> |                  | 68–212 °F, 10 <sup>–6</sup> /°F          | 20–100 °C, 10 <sup>–6</sup> /°C | °F                      | °C      | At 77 °F<br>Btu · in./h · ft <sup>2</sup> · °F | At 25 °C<br>W/m · K |
| Sand casting |        |                     |                   |                  |                                          |                                 |                         |         |                                                |                     |
| 100.0(c)     | F      | 0.096               | 2.70              | 2.70             | 12.8                                     | 22.6                            | 970–1160                | 520–630 | 1155                                           | 168                 |
| 201.0(d)     | T6     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200               | 570–650 | 840                                            | 121                 |
|              | T7     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200               | 570–650 | 840                                            | 121                 |
|              | T43    | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200               | 570–650 | ...                                            | ...                 |
| 204.0        | T4     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200               | 570–650 | 840                                            | 121                 |
| A206.0       | T4     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | ...                     | ...     | ...                                            | ...                 |
|              | T6     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | ...                     | ...     | 640                                            | 92                  |
| 208.0        | F      | 0.101               | 2.80              | 2.80             | 12.2                                     | 22.0                            | 970–1160                | 520–630 | 840                                            | 121                 |
| 222.0        | F      | 0.107               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | 925                                            | 133                 |
|              | O      | 0.107               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | 1095                                           | 158                 |
|              | T61    | 0.101               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | 895                                            | 129                 |
| 224.0        | T62    | 0.102               | 2.81              | 2.81             | ...                                      | ...                             | 1020–1190               | 550–645 | 810                                            | 117                 |
|              | T72    | 0.102               | 2.81              | 2.81             | ...                                      | ...                             | 1020–1190               | 550–645 | ...                                            | ...                 |
| 240.0        | F      | 0.100               | 2.78              | 2.78             | 12.3                                     | 22.1                            | 950–1110                | 515–605 | 665                                            | 96                  |
| 242.0        | F      | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | ...                                            | ...                 |
|              | O      | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 925                                            | 133                 |
|              | T571   | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 925                                            | 133                 |
|              | T61    | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 925                                            | 133                 |
|              | T77    | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 1040                                           | 150                 |
|              |        |                     |                   |                  |                                          |                                 |                         |         |                                                |                     |
| A242.0       | T75    | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | ...                                            | ...                 |
| 295.0        | T4     | 0.102               | 2.81              | 2.81             | 12.7                                     | 22.9                            | 970–1190                | 520–645 | 955                                            | 138                 |
|              | T6     | 0.102               | 2.81              | 2.81             | 12.7                                     | 22.9                            | 970–1190                | 520–645 | 955                                            | 138                 |
|              | T62    | 0.102               | 2.81              | 2.81             | 12.7                                     | 22.9                            | 970–1190                | 520–645 | 980                                            | 141                 |
|              | T7     | 0.102               | 2.81              | 2.81             | 12.7                                     | 22.9                            | 970–1190                | 520–645 | ...                                            | ...                 |
| 319.0        | F      | 0.101               | 2.79              | 2.79             | 11.9                                     | 21.4                            | 960–1120                | 520–605 | 780                                            | 112                 |
|              | T5     | 0.101               | 2.79              | 2.79             | 11.9                                     | 21.4                            | 960–1120                | 520–605 | ...                                            | ...                 |
|              | T6     | 0.101               | 2.79              | 2.79             | 11.9                                     | 21.4                            | 960–1120                | 520–605 | ...                                            | ...                 |
| 328.0        | F      | 0.098               | 2.70              | 2.70             | 11.9                                     | 21.4                            | 1025–1105               | 555–595 | 665                                            | 96                  |
|              | T6     | 0.098               | 2.70              | 2.70             | 11.9                                     | 21.4                            | 1025–1105               | 555–595 |                                                |                     |
| 355.0        | F      | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | ...                                            | ...                 |
|              | T51    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1155                                           | 166                 |
|              | T6     | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1010                                           | 145                 |
|              | T61    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1010                                           | 145                 |
|              | T62    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1010                                           | 145                 |
|              | T7     | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1125                                           | 162                 |
|              | T71    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1040                                           | 150                 |
|              |        |                     |                   |                  |                                          |                                 |                         |         |                                                |                     |
| C355.0       | T6     | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1040                                           | 150                 |
| 356.0        | F      | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
|              | T51    | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1155                                           | 166                 |
|              | T6     | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1040                                           | 150                 |
|              | T7     | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1110                                           | 160                 |
|              | T71    | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
| A356.0       | F      | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–610 | ...                                            | ...                 |
|              | T51    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–610 | ...                                            | ...                 |
|              | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–610 | 1040                                           | 150                 |
|              | T61    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–610 | 1040                                           | 150                 |
|              | T71    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–610 | ...                                            | ...                 |
| 357.0        | F      | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1040                                           | 150                 |
|              | T51    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
|              | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1040                                           | 150                 |
|              | T7     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
|              | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 555–610 | 1100                                           | 158                 |
|              | T61    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 555–610 | 1040                                           | 150                 |

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

| Electrical conductivity(h) |              |             |             |                         |                    |                      |                    |                 |
|----------------------------|--------------|-------------|-------------|-------------------------|--------------------|----------------------|--------------------|-----------------|
| At 68 °F                   |              | At 25 °C    |             | Electrical resistivity  |                    | Specific heat        |                    | Poisson's ratio |
| Volume %IACS               | Weight %IACS | Volume MS/m | Weight MS/m | At 68 °F Ohm-Cir.mil/ft | At 20 °C Ohm-mm²/m | At 68 °F Btu/lb · °F | At 20 °C J/kg · °C |                 |
|                            |              |             |             |                         |                    |                      |                    |                 |
| Sand casting (continued)   |              |             |             |                         |                    |                      |                    |                 |
| 54                         | 177          | 31          | 103         | 19                      | 0.032              | 0.210                | 879                | 0.33            |
| 30                         | 99           | 17          | 57          | 35                      | 0.057              | 0.220                | 922                | 0.33            |
| 33                         | 108          | 19          | 63          | 32                      | 0.052              | 0.220                | 922                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.220                | 922                | 0.33            |
| 29                         | 95           | 17          | 55          | 36                      | 0.059              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 31                         | 102          | 18          | 59          | 34                      | 0.056              | 0.230                | 963                | 0.33            |
| 34                         | 112          | 20          | 65          | 31                      | 0.051              | 0.230                | 963                | 0.33            |
| 41                         | 135          | 24          | 78          | 25                      | 0.042              | 0.230                | 963                | 0.33            |
| 33                         | 108          | 19          | 63          | 32                      | 0.052              | 0.230                | 963                | 0.33            |
| 30                         | 99           | 17          | 57          | 35                      | 0.057              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 23                         | 76           | 13          | 44          | 45                      | 0.075              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 33                         | 108          | 19          | 63          | 32                      | 0.052              | 0.230                | 963                | 0.33            |
| 34                         | 112          | 20          | 65          | 31                      | 0.051              | 0.230                | 963                | 0.33            |
| 33                         | 108          | 19          | 63          | 32                      | 0.052              | 0.230                | 963                | 0.33            |
| 38                         | 125          | 22          | 73          | 27                      | 0.045              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 35                         | 115          | 20          | 67          | 30                      | 0.049              | 0.230                | 963                | 0.33            |
| 35                         | 115          | 20          | 67          | 30                      | 0.049              | 0.230                | 963                | 0.33            |
| 35                         | 115          | 20          | 67          | 30                      | 0.049              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 28                         | 92           | 16          | 53          | 37                      | 0.061              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 30                         | 99           | 17          | 57          | 35                      | 0.057              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 43                         | 141          | 25          | 82          | 24                      | 0.040              | 0.230                | 963                | 0.33            |
| 38                         | 125          | 22          | 73          | 27                      | 0.045              | 0.230                | 963                | 0.33            |
| 37                         | 122          | 21          | 71          | 28                      | 0.047              | 0.230                | 963                | 0.33            |
| 38                         | 125          | 22          | 73          | 27                      | 0.045              | 0.230                | 963                | 0.33            |
| 42                         | 138          | 24          | 80          | 25                      | 0.041              | 0.230                | 963                | 0.33            |
| 39                         | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| 39                         | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 43                         | 141          | 25          | 82          | 24                      | 0.040              | 0.230                | 963                | 0.33            |
| 40                         | 131          | 23          | 76          | 26                      | 0.043              | 0.230                | 963                | 0.33            |
| 42                         | 138          | 24          | 80          | 25                      | 0.041              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 40                         | 131          | 23          | 76          | 26                      | 0.043              | 0.230                | 963                | 0.33            |
| 39                         | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 39                         | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 39                         | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| ...                        | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 40                         | 131          | 23          | 76          | 26                      | 0.043              | 0.230                | 963                | 0.33            |
| 39                         | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

| Alloy                    | Temper | Density             |                   | Specific gravity | Average coefficient of thermal expansion |                                 | Approx melting range(a)            |         | Thermal conductivity |          |
|--------------------------|--------|---------------------|-------------------|------------------|------------------------------------------|---------------------------------|------------------------------------|---------|----------------------|----------|
|                          |        | lb/in. <sup>3</sup> | g/cm <sup>3</sup> |                  | 68–212 °F, 10 <sup>−6</sup> /°F          | 20–100 °C, 10 <sup>−6</sup> /°C | °F °C                              |         | At 77 °F             | At 25 °C |
|                          |        |                     |                   |                  |                                          |                                 | Btu · in./h · ft <sup>2</sup> · °F | W/m · K |                      |          |
| Sand casting (continued) |        |                     |                   |                  |                                          |                                 |                                    |         |                      |          |
| 359.0                    | T6     | 0.097               | 2.67              | 2.67             | 11.6                                     | 20.9                            | 1045–1115                          | 565–600 | 955                  | 138      |
|                          | T62    | 0.097               | 2.67              | 2.67             | 11.6                                     | 20.9                            | 1045–1115                          | 565–600 | ...                  | ...      |
| 443.0                    | F      | 0.097               | 2.69              | 2.69             | 12.3                                     | 22.1                            | 1065–1170                          | 575–630 | 1010                 | 145      |
|                          | O      | 0.097               | 2.69              | 2.69             | 12.3                                     | 22.1                            | 1065–1170                          | 575–630 | 1125                 | 162      |
| B443.0                   | F      | 0.097               | 2.69              | 2.69             | 12.3                                     | 22.1                            | 1065–1170                          | 575–630 | 1010                 | 145      |
| A444.0                   | F      | 0.097               | 2.68              | 2.68             | 12.1                                     | 21.8                            | 1070–1170                          | 575–630 | 1095                 | 158      |
|                          | T4     | 0.097               | 2.68              | 2.68             | 12.1                                     | 21.8                            | 1070–1170                          | 575–630 | 1100                 | 158      |
| 511.0                    | F      | 0.100               | 2.66              | 2.66             | 13.1                                     | 23.6                            | 1090–1185                          | 590–640 | 980                  | 141      |
| 512.0                    | F      | 0.096               | 2.65              | 2.65             | 12.7                                     | 22.9                            | 1090–1170                          | 590–630 | 1010                 | 145      |
| 514.0                    | F      | 0.096               | 2.65              | 2.65             | 13.4                                     | 24.1                            | 1110–1185                          | 600–640 | 954                  | 137      |
| 520.0                    | T4     | 0.093               | 2.57              | 2.57             | 13.7                                     | 24.7                            | 840–1120                           | 450–600 | 605                  | 87       |
| 535.0                    | F      | 0.095               | 2.62              | 2.62             | 13.1                                     | 23.6                            | 1020–1165                          | 550–630 | 695                  | 100      |
|                          | T5     | 0.095               | 2.62              | 2.62             | 13.1                                     | 23.6                            | 1020–1165                          | 550–630 | ...                  | ...      |
| A535.0                   | F      | 0.090               | 2.54              | 2.54             | 13.4                                     | 24.1                            | 1020–1150                          | 550–620 | 695                  | 100      |
| 705.0                    | F      | 0.100               | 2.76              | 2.76             | 13.1                                     | 23.6                            | 1105–1180                          | 600–640 | 720                  | 104      |
| 707.0                    | F      | 0.100               | 2.77              | 2.77             | 13.2                                     | 23.8                            | 1085–1165                          | 585–630 | 720                  | 104      |
|                          | T5     | 0.100               | 2.77              | 2.77             | 13.2                                     | 23.8                            | 1085–1165                          | 585–630 | ...                  | ...      |
|                          | T7     | 0.100               | 2.77              | 2.77             | 13.2                                     | 23.8                            | 1085–1165                          | 585–630 | ...                  | ...      |
| 710.0                    | F      | 0.102               | 2.81              | 2.81             | 13.4                                     | 24.1                            | 1105–1195                          | 600–650 | 955                  | 138      |
|                          | T5     | 0.102               | 2.81              | 2.81             | 13.4                                     | 24.1                            | 1105–1195                          | 600–650 | ...                  | ...      |
| 712.0                    | F      | 0.101               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1135–1200                          | 600–640 | 1100                 | 158      |
|                          | T5     | 0.101               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1135–1200                          | 600–640 | ...                  | ...      |
| 713.0                    | F      | 0.100               | 2.81              | 2.81             | 13.4                                     | 24.1                            | 1100–1180                          | 595–630 | 1070                 | 154      |
|                          | T5     | 0.100               | 2.81              | 2.81             | 13.4                                     | 24.1                            | 1100–1180                          | 595–630 | ...                  | ...      |
| 771.0                    | F      | 0.102               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1120–1190                          | 550–645 | 955                  | 138      |
|                          | T5     | 0.102               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1120–1190                          | 550–645 | ...                  | ...      |
|                          | T52    | 0.102               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1120–1190                          | 550–645 | ...                  | ...      |
|                          | T53    | 0.102               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1120–1190                          | 550–645 | ...                  | ...      |
|                          | T6     | 0.102               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1120–1190                          | 550–645 | ...                  | ...      |
|                          | T71    | 0.102               | 2.81              | 2.81             | 13.7                                     | 24.7                            | 1120–1190                          | 550–645 | ...                  | ...      |
|                          |        |                     |                   |                  |                                          |                                 |                                    |         |                      |          |
| 850.0                    | T5     | 0.104               | 2.88              | 2.88             | 13.0                                     | 23.4                            | 435–1200                           | 225–650 | 1290                 | 186      |
| 851.0                    | T5     | 0.103               | 2.83              | 2.83             | 12.6                                     | 22.7                            | 440–1165                           | 230–630 | 1155                 | 166      |
| 852.0                    | T5     | 0.104               | 2.88              | 2.88             | 12.9                                     | 23.2                            | 400–1175                           | 210–635 | 1215                 | 175      |
| Permanent mold casting   |        |                     |                   |                  |                                          |                                 |                                    |         |                      |          |
| 100.0                    | F      | 0.096               | 2.70              | 2.70             | 12.8                                     | 22.6                            | 970–1160                           | 520–630 | 1165                 | 168      |
| 201.0                    | T6     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200                          | 570–650 | 840                  | 121      |
|                          | T7     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200                          | 570–650 | 840                  | 121      |
|                          | T43    | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200                          | 570–650 | ...                  | ...      |
| 204.0                    | T4     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | 1060–1200                          | 570–650 | 695                  | 100      |
| A206.0                   | T4     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | ...                                | ...     | ...                  | ...      |
|                          | T6     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | ...                                | ...     | 840                  | 121      |
|                          | T7     | 0.101               | 2.80              | 2.80             | 10.7                                     | 19.3                            | ...                                | ...     | ...                  | ...      |

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9



Table 8.2 (continued)

| Electrical conductivity(b)         |              |             |             |                            |                                    |                         |                       |                 |
|------------------------------------|--------------|-------------|-------------|----------------------------|------------------------------------|-------------------------|-----------------------|-----------------|
| At 68 °F                           |              | At 25 °C    |             | Electrical resistivity     |                                    | Specific heat           |                       | Poisson's ratio |
| Volume %IACS                       | Weight %IACS | Volume MS/m | Weight MS/m | At 68 °F<br>Ohm-Cir.mil/ft | At 20 °C<br>Ohm-mm <sup>2</sup> /m | At 68 °F<br>Btu/lb · °F | At 20 °C<br>J/kg · °C |                 |
| Sand casting (continued)           |              |             |             |                            |                                    |                         |                       |                 |
| 35                                 | 115          | 20          | 67          | 30                         | 0.049                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 37                                 | 122          | 21          | 71          | 28                         | 0.047                              | 0.230                   | 963                   | 0.33            |
| 42                                 | 138          | 24          | 80          | 25                         | 0.041                              | 0.230                   | 963                   | 0.33            |
| 37                                 | 122          | 21          | 71          | 28                         | 0.047                              | 0.230                   | 963                   | 0.33            |
| 41                                 | 135          | 24          | 78          | 25                         | 0.042                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 36                                 | 118          | 21          | 69          | 29                         | 0.048                              | 0.230                   | 963                   | 0.33            |
| 38                                 | 125          | 22          | 73          | 27                         | 0.045                              | 0.230                   | 963                   | 0.33            |
| 35                                 | 115          | 20          | 67          | 30                         | 0.049                              | 0.230                   | 963                   | 0.33            |
| 21                                 | 69           | 12          | 40          | 50                         | 0.082                              | 0.230                   | 963                   | 0.33            |
| 23                                 | 76           | 13          | 44          | 45                         | 0.075                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 23                                 | 76           | 13          | 44          | 45                         | 0.075                              | 0.230                   | 963                   | 0.33            |
| 25                                 | 79           | 15          | 46          | 43                         | 0.071                              | 0.230                   | 963                   | 0.33            |
| 25                                 | 79           | 15          | 46          | 43                         | 0.071                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 35                                 | 111          | 20          | 64          | 31                         | 0.051                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 35                                 | 111          | 20          | 64          | 31                         | 0.051                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 30                                 | 95           | 17          | 55          | 36                         | 0.059                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 37                                 | 117          | 21          | 68          | 29                         | 0.048                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 47                                 | 154          | 27          | 90          | 22                         | 0.037                              | 0.230                   | 963                   | 0.33            |
| 43                                 | 141          | 25          | 82          | 24                         | 0.040                              | 0.230                   | 963                   | 0.33            |
| 45                                 | 148          | 26          | 86          | 23                         | 0.038                              | 0.230                   | 963                   | 0.33            |
| Permanent mold casting (continued) |              |             |             |                            |                                    |                         |                       |                 |
| 54                                 | 177          | 31          | 103         | 19                         | 0.032                              | 0.210                   | 879                   | 0.33            |
| 30                                 | 90           | 52          | 57          | 35                         | 0.057                              | 0.230                   | 963                   | 0.33            |
| 33                                 | 108          | 57          | 63          | 32                         | 0.052                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| 24                                 | 79           | 14          | 46          | 43                         | 0.072                              | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |
| ...                                | ...          | ...         | ...         | ...                        | ...                                | 0.230                   | 963                   | 0.33            |

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

| Alloy                              | Temper | Density             |                   | Specific gravity | Average coefficient of thermal expansion |                                 | Approx melting range(a) |         | Thermal conductivity                           |                     |
|------------------------------------|--------|---------------------|-------------------|------------------|------------------------------------------|---------------------------------|-------------------------|---------|------------------------------------------------|---------------------|
|                                    |        | lb/in. <sup>3</sup> | g/cm <sup>3</sup> |                  | 68–212 °F, 10 <sup>−6</sup> /°F          | 20–100 °C, 10 <sup>−6</sup> /°C | °F                      | °C      | At 77 °F<br>Btu · in./h · ft <sup>2</sup> · °F | At 25 °C<br>W/m · K |
| Permanent mold casting (continued) |        |                     |                   |                  |                                          |                                 |                         |         |                                                |                     |
| 208.0                              | F      | 0.101               | 2.79              | 2.79             | 12.4                                     | 22.3                            | 970–1160                | 520–630 | 865                                            | 125                 |
|                                    | T6     | 0.101               | 2.79              | 2.79             | 12.4                                     | 22.3                            | 970–1160                | 520–630 | ...                                            | ...                 |
|                                    | T7     | 0.101               | 2.79              | 2.79             | 12.4                                     | 22.3                            | 970–1160                | 520–630 | ...                                            | ...                 |
| 213.0                              | F      | 0.110               |                   |                  |                                          |                                 | 970–1160                | 520–630 | ...                                            | ...                 |
| 222.0                              | F      | 0.107               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | 925                                            | 133                 |
|                                    | T551   | 0.107               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | ...                                            | ...                 |
|                                    | T52    | 0.107               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | ...                                            | ...                 |
|                                    | T61    | 0.107               | 2.95              | 2.95             | 12.3                                     | 22.1                            | 970–1160                | 520–630 | 895                                            | 129                 |
| 238.0                              | F      | 0.110               | 2.95              | 2.95             | 11.9                                     | 21.4                            | 945–1110                | 510–600 | 720                                            | 104                 |
| 242.0                              | T571   | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 925                                            | 133                 |
|                                    | T61    | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 925                                            | 133                 |
|                                    | T77    | 0.102               | 2.81              | 2.81             | 12.6                                     | 22.7                            | 990–1175                | 525–635 | 1040                                           | 150                 |
| A249.0                             | T63    | ...                 | ...               | ...              | ...                                      | ...                             | ...                     | ...     | ...                                            | ...                 |
| 296.0                              | T4     | 0.101               | 2.80              | 2.80             | 12.2                                     | 22.0                            | 970–1170                | 520–630 | 925                                            | 133                 |
|                                    | T6     | 0.101               | 2.80              | 2.80             | 12.2                                     | 22.0                            | 970–1170                | 520–630 | 925                                            | 133                 |
|                                    | T7     | 0.101               | 2.80              | 2.80             | 12.2                                     | 22.0                            | 970–1170                | 520–630 | ...                                            | ...                 |
| 308.0                              | F      | 0.101               | 2.79              | 2.79             | 11.9                                     | 21.4                            | 970–1135                | 520–615 | 1010                                           | 145                 |
| 319.0                              | F      | 0.101               | 2.79              | 2.79             | 11.9                                     | 21.4                            | 960–1120                | 520–605 | 780                                            | 112                 |
|                                    | T6     | 0.101               | 2.79              | 2.79             | 11.9                                     | 21.4                            | 960–1120                | 520–605 | ...                                            | ...                 |
| 324.0                              | F      | 0.096               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1010–1120               | 545–605 | 1070                                           | 154                 |
|                                    | T5     | 0.096               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1010–1120               | 545–605 | ...                                            | ...                 |
|                                    | T62    | 0.096               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1010–1120               | 545–605 | ...                                            | ...                 |
| 328.0                              | F      | 0.098               | 2.70              | 2.70             | 11.9                                     | 21.4                            | 1025–1105               | 520–600 | 840                                            | 121                 |
|                                    | T6     | 0.098               | 2.70              | 2.70             | 11.9                                     | 21.4                            | 1025–1105               | 520–600 | ...                                            | ...                 |
| 332.0                              | T5     | 0.100               | 2.76              | 2.76             | 11.5                                     | 20.7                            | 970–1080                | 525–585 | 720                                            | 104                 |
| 333.0                              | F      | 0.100               | 2.77              | 2.77             | 11.4                                     | 20.5                            | 960–1085                | 520–585 | 720                                            | 104                 |
|                                    | T5     | 0.100               | 2.77              | 2.77             | 11.4                                     | 20.5                            | 960–1085                | 520–585 | 810                                            | 117                 |
|                                    | T6     | 0.100               | 2.77              | 2.77             | 11.4                                     | 20.5                            | 960–1085                | 520–585 | 810                                            | 117                 |
|                                    | T7     | 0.100               | 2.77              | 2.77             | 11.4                                     | 20.5                            | 960–1085                | 520–585 | 955                                            | 138                 |
| 336.0                              | T551   | 0.098               | 2.72              | 2.72             | 11.0                                     | 19.8                            | 1000–1050               | 540–570 | 810                                            | 117                 |
|                                    | T65    | 0.098               | 2.72              | 2.72             | 11.0                                     | 19.8                            | 1000–1050               | 540–570 | ...                                            | ...                 |
| 354.0                              | T61    | 0.098               | 2.71              | 2.71             | 11.6                                     | 20.9                            | 1000–1105               | 540–600 | 866                                            | 125                 |
|                                    | T62    | 0.098               | 2.71              | 2.71             | 11.6                                     | 20.9                            | 1000–1105               | 540–600 | ...                                            | ...                 |
| 355.0                              | F      | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 |                                                |                     |
|                                    | T51    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1155                                           | 166                 |
|                                    | T6     | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1040                                           | 150                 |
|                                    | T61    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1010                                           | 145                 |
|                                    | T62    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1010                                           | 145                 |
|                                    | T7     | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1125                                           | 162                 |
|                                    | T71    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1040                                           | 150                 |
| C355.0                             | T6     | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | ...                                            | ...                 |
|                                    | T61    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | 1010                                           | 145                 |
|                                    | T62    | 0.098               | 2.71              | 2.71             | 12.4                                     | 22.3                            | 1015–1150               | 550–620 | ...                                            | ...                 |
| 356.0                              | F      | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 |                                                |                     |
|                                    | T51    | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1155                                           | 166                 |
|                                    | T6     | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1040                                           | 150                 |
|                                    | T7     | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1110                                           | 160                 |
|                                    | T71    | 0.097               | 2.68              | 2.68             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
| A356.0                             | F      | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
|                                    | T51    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |
|                                    | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1040                                           | 150                 |
|                                    | T61    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | ...                                            | ...                 |

(continued)

(a) Based on nominal composition of each alloy in thicknesses of 1/4 in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

| Electrical conductivity(h)         |                 |                |                |                            |                                    |                         |                       |                    |
|------------------------------------|-----------------|----------------|----------------|----------------------------|------------------------------------|-------------------------|-----------------------|--------------------|
| At 68 °F                           |                 | At 25 °C       |                | Electrical resistivity     |                                    | Specific heat           |                       |                    |
| Volume<br>%IACS                    | Weight<br>%IACS | Volume<br>MS/m | Weight<br>MS/m | At 68 °F<br>Ohm-Cir.mil/ft | At 20 °C<br>Ohm-mm <sup>2</sup> /m | At 68 °F<br>Btu/lb · °F | At 20 °C<br>J/kg · °C | Poisson's<br>ratio |
| Permanent mold casting (continued) |                 |                |                |                            |                                    |                         |                       |                    |
| 31                                 | 102             | 18             | 59             | 34                         | 0.056                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 34                                 | 112             | 20             | 65             | 31                         | 0.051                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 33                                 | 108             | 19             | 63             | 32                         | 0.052                              | 0.230                   | 963                   | 0.33               |
| 25                                 | 82              | 15             | 48             | 42                         | 0.069                              | 0.230                   | 963                   | 0.33               |
| 34                                 | 112             | 20             | 65             | 31                         | 0.051                              | 0.230                   | 963                   | 0.33               |
| 33                                 | 108             | 19             | 63             | 32                         | 0.052                              | 0.230                   | 963                   | 0.33               |
| 38                                 | 125             | 22             | 73             | 27                         | 0.045                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 33                                 | 108             | 19             | 63             | 32                         | 0.052                              | 0.230                   | 963                   | 0.33               |
| 33                                 | 108             | 19             | 63             | 32                         | 0.052                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 37                                 | 122             | 21             | 71             | 28                         | 0.047                              | 0.230                   | 963                   | 0.33               |
| 27                                 | 89              | 16             | 52             | 39                         | 0.064                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 34                                 | 112             | 20             | 65             | 31                         | 0.051                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 30                                 | 99              | 17             | 57             | 35                         | 0.057                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 26                                 | 85              | 15             | 50             | 40                         | 0.066                              | 0.230                   | 963                   | 0.33               |
| 26                                 | 85              | 15             | 50             | 40                         | 0.066                              | 0.230                   | 963                   | 0.33               |
| 29                                 | 95              | 17             | 55             | 36                         | 0.059                              | 0.230                   | 963                   | 0.33               |
| 29                                 | 95              | 17             | 55             | 36                         | 0.059                              | 0.230                   | 963                   | 0.33               |
| 35                                 | 115             | 20             | 67             | 30                         | 0.049                              | 0.230                   | 963                   | 0.33               |
| 29                                 | 95              | 17             | 55             | 36                         | 0.059                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 32                                 | 105             | 19             | 61             | 33                         | 0.054                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 43                                 | 141             | 25             | 82             | 24                         | 0.040                              | 0.230                   | 963                   | 0.33               |
| 39                                 | 128             | 23             | 74             | 27                         | 0.044                              | 0.230                   | 963                   | 0.33               |
| 37                                 | 122             | 21             | 71             | 28                         | 0.047                              | 0.230                   | 963                   | 0.33               |
| 38                                 | 125             | 22             | 73             | 27                         | 0.045                              | 0.230                   | 963                   | 0.33               |
| 42                                 | 138             | 24             | 80             | 25                         | 0.041                              | 0.230                   | 963                   | 0.33               |
| 39                                 | 128             | 23             | 74             | 27                         | 0.044                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 43                                 | 141             | 25             | 82             | 24                         | 0.040                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 43                                 | 141             | 25             | 82             | 24                         | 0.040                              | 0.230                   | 963                   | 0.33               |
| 41                                 | 135             | 24             | 78             | 25                         | 0.042                              | 0.230                   | 963                   | 0.33               |
| 42                                 | 138             | 24             | 80             | 25                         | 0.041                              | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| ...                                | ...             | ...            | ...            | ...                        | ...                                | 0.230                   | 963                   | 0.33               |
| 39                                 | 128             | 23             | 74             | 27                         | 0.044                              | 0.230                   | 963                   | 0.33               |

(continued)

(a) Based on nominal composition of each alloy in thicknesses of ¼ in. (6 mm) or greater. (b) %IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

Table 8.2 (continued)

| Alloy                              | Temper | Density             |                   | Specific gravity | Average coefficient of thermal expansion |                                 | Approx melting range(a) |         | Thermal conductivity               |          |
|------------------------------------|--------|---------------------|-------------------|------------------|------------------------------------------|---------------------------------|-------------------------|---------|------------------------------------|----------|
|                                    |        | lb/in. <sup>3</sup> | g/cm <sup>3</sup> |                  | 68–212 °F, 10 <sup>−6</sup> /°F          | 20–100 °C, 10 <sup>−6</sup> /°C | °F                      | °C      | At 77 °F                           | At 25 °C |
|                                    |        |                     |                   |                  |                                          |                                 |                         |         | Btu · in./h · ft <sup>2</sup> · °F | W/m · K  |
| Permanent mold casting (continued) |        |                     |                   |                  |                                          |                                 |                         |         |                                    |          |
| 357.0                              | F      | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1040                               | 150      |
|                                    | T51    | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 |                                    |          |
|                                    | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 |                                    |          |
|                                    | T7     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 |                                    |          |
| A357.0                             | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1100                               | 158      |
|                                    | T6     | 0.097               | 2.67              | 2.67             | 11.9                                     | 21.4                            | 1035–1135               | 560–615 | 1100                               | 158      |
| 359.0                              | T6     | 0.097               | 2.67              | 2.67             | 11.6                                     | 20.9                            | 1045–1115               | 565–605 | 955                                | 138      |
|                                    | T61    | 0.097               | 2.67              | 2.67             | 11.6                                     | 20.9                            | 1045–1115               | 565–605 | ...                                | ...      |
|                                    | T62    | 0.097               | 2.67              | 2.67             | 11.6                                     | 20.9                            | 1045–1115               | 565–605 | ...                                | ...      |
| 443.0                              | O      | 0.097               | 2.69              | 2.69             | 12.3                                     | 22.1                            | 1065–1170               | 575–630 | 1125                               | 162      |
|                                    | F      | 0.097               | 2.69              | 2.69             | 12.3                                     | 22.1                            | 1065–1170               | 575–630 | 1010                               | 145      |
| B443.0                             | F      | 0.097               | 2.69              | 2.69             | 12.3                                     | 22.1                            | 1065–1170               | 575–630 | 1010                               | 145      |
| A444.0                             | F      | 0.097               | 2.68              | 2.68             | 12.1                                     | 21.8                            | 1070–1170               | 575–630 | 1100                               | 158      |
|                                    | T4     | 0.097               | 2.68              | 2.68             | 12.1                                     | 21.8                            | 1070–1170               | 575–630 |                                    |          |
| 513.0                              | F      | 0.097               | 2.68              | 2.68             | 13.4                                     | 24.1                            | 1075–1180               | 580–640 | 925                                | 133      |
| 711.0                              | F      | 0.103               | 2.84              | 2.84             | 13.1                                     | 23.6                            | 1110–1190               | 600–645 | 1100                               | 158      |
| 850.0                              | T5     | 0.104               | 2.88              | 2.88             | 13.0                                     | 23.4                            | 435–1200                | 225–650 | 1290                               | 186      |
| 851.0                              | T5     | 0.103               | 2.83              | 2.83             | 12.6                                     | 22.7                            | 440–1165                | 230–630 | 1155                               | 166      |
|                                    | T6     | 0.103               | 2.83              | 2.83             | 12.6                                     | 22.7                            | 440–1165                | 230–630 | ...                                | ...      |
| 852.0                              | T5     | 0.104               | 2.88              | 2.88             | 12.9                                     | 23.2                            | 400–1175                | 210–635 | 1215                               | 175      |
| Die casting                        |        |                     |                   |                  |                                          |                                 |                         |         |                                    |          |
| 360.0                              | F      | 0.095               | 2.63              | 2.63             | 11.6                                     | 21.0                            | 1035–1105               | 557–596 | 785                                | 113      |
| A360.0                             | F      | 0.095               | 2.63              | 2.63             | 11.6                                     | 21.0                            | 1035–1105               | 557–596 | 785                                | 113      |
| 380.0                              | F      | 0.099               | 2.74              | 2.74             | 12.2                                     | 22.2                            | 1000–1100               | 540–595 | 667                                | 96       |
| A380.0                             | F      | 0.098               | 2.71              | 2.71             | 12.1                                     | 21.8                            | 1000–1100               | 540–595 | 667                                | 96       |
| 383.0                              | F      | 0.099               | 2.74              | 2.74             | 11.7                                     | 21.1                            | 960–1080                | 516–582 | 667                                | 96       |
| 384.0                              | F      | 0.102               | 2.82              | 2.82             | 11.6                                     | 21.0                            | 960–1080                | 516–582 | 667                                | 96       |
| 390.0                              | F      | ...                 | ...               | ...              | ...                                      | ...                             | ...                     | ...     | ...                                | ...      |
| B390.0                             | F      | 0.098               | 2.73              | 2.73             | 10.0                                     | 18.0                            | 950–1200                | 510–650 | 930                                | 134      |
| 392.0                              | F      | ...                 | ...               | ...              | ...                                      | ...                             | ...                     | ...     | ...                                | ...      |
| 413.0                              | F      | 0.096               | 2.66              | 2.66             | 11.3                                     | 20.4                            | 1065–1080               | 574–582 | 840                                | 121      |
| A413.0                             | F      | 0.096               | 2.66              | 2.66             | 11.9                                     | 21.6                            | 1065–1080               | 574–582 | 840                                | 121      |
| C443.0                             | F      | 0.097               | 2.69              | 2.69             | 12.2                                     | 22.0                            | 1065–1170               | 574–632 | 985                                | 142      |
| 518.0                              | F      | 0.093               | 2.57              | 2.57             | 13.4                                     | 24.1                            | 995–1150                | 535–621 | 667                                | 96       |

(a) Based on nominal composition of each alloy in thicknesses of 1/4 in. (6 mm) or greater. (b) %ACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9



Table 8.2 (continued)

| Electrical conductivity(b)         |              |             |             |                         |                    |                      |                    |                 |
|------------------------------------|--------------|-------------|-------------|-------------------------|--------------------|----------------------|--------------------|-----------------|
| At 68 °F                           |              | At 25 °C    |             | Electrical resistivity  |                    | Specific heat        |                    | Poisson's ratio |
| Volume %IACS                       | Weight %IACS | Volume MS/m | Weight MS/m | At 68 °F Ohm-Cir.mil/ft | At 20 °C Ohm-mm²/m | At 68 °F Btu/lb · °F | At 20 °C J/kg · °C |                 |
|                                    |              |             |             |                         |                    |                      |                    |                 |
| Permanent mold casting (continued) |              |             |             |                         |                    |                      |                    |                 |
| 39                                 | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 39                                 | 128          | 23          | 74          | 27                      | 0.044              | 0.230                | 963                | 0.33            |
| 35                                 | 115          | 20          | 67          | 30                      | 0.049              | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 42                                 | 138          | 24          | 80          | 25                      | 0.041              | 0.230                | 963                | 0.33            |
| 37                                 | 122          | 21          | 71          | 28                      | 0.047              | 0.230                | 963                |                 |
| 37                                 | 122          | 21          | 71          | 28                      | 0.047              | 0.230                | 963                | 0.33            |
| 41                                 | 135          | 24          | 78          | 25                      | 0.042              | 0.230                | 963                | 0.33            |
| 41                                 | 135          | 24          | 78          | 25                      | 0.042              | 0.230                | 963                | 0.33            |
| 34                                 | 112          | 20          | 65          | 31                      | 0.051              | 0.230                | 963                | 0.33            |
| 40                                 | 127          | 23          | 74          | 27                      | 0.045              | 0.230                | 963                | 0.33            |
| 47                                 | 154          | 27          | 90          | 22                      | 0.037              | 0.230                | 963                | 0.33            |
| 43                                 | 141          | 25          | 82          | 24                      | 0.040              | 0.230                | 963                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | 0.230                | 963                | 0.33            |
| 45                                 | 148          | 26          | 86          | 23                      | 0.038              | 0.230                | 963                | 0.33            |
| Die casting (continued)            |              |             |             |                         |                    |                      |                    |                 |
| 30                                 | 99           | 17          | 57          | 35                      | 0.057              | 0.230                | 963                | 0.33            |
| 29                                 | 95           | 17          | 55          | 36                      | 0.059              | 0.230                | 963                | 0.33            |
| 27                                 | 89           | 16          | 52          | 39                      | 0.064              | 0.230                | 963                | 0.33            |
| 23                                 | 76           | 13          | 44          | 45                      | 0.075              | 0.230                | 963                | 0.33            |
| 23                                 | 76           | 13          | 44          | 45                      | 0.075              | 0.230                | 963                | 0.33            |
| 22                                 | 72           | 13          | 42          | 47                      | 0.078              | ...                  | ...                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | ...                  | ...                | 0.33            |
| 27                                 | 89           | 16          | 52          | 39                      | 0.064              | ...                  | ...                | 0.33            |
| ...                                | ...          | ...         | ...         | ...                     | ...                | ...                  | ...                | 0.33            |
| 31                                 | 102          | 18          | 59          | 34                      | 0.056              | 0.230                | 963                | 0.33            |
| 31                                 | 102          | 18          | 59          | 34                      | 0.056              | 0.230                | 963                | 0.33            |
| 37                                 | 122          | 21          | 71          | 28                      | 0.047              | 0.230                | 963                | 0.33            |
| 24                                 | 79           | 14          | 46          | 43                      | 0.072              | ...                  | ...                | 0.33            |

(a) Based on nominal composition of each alloy in thicknesses of 1/4 in. (6 mm) or greater. (b) % IACS, percentage of International Annealed Copper Standard. (c) Coefficient of friction, 0.4. (d) Coefficient of friction, 0.3. Source: Ref 3, 4, 6, 8, 9

**Table 8.3** Alloy constants for calculation of coefficients of thermal expansion for some aluminum casting alloys over various temperature ranges

| Alloy  | Alloy constant <i>C</i> | Alloy  | Alloy constant <i>C</i> | Alloy | Alloy constant <i>C</i> |
|--------|-------------------------|--------|-------------------------|-------|-------------------------|
| 208.0  | 0.950                   | 356.0  | 0.910                   | 511.0 | 1.005                   |
| 240.0  | 0.990                   | A356.0 | 0.910                   | 513.0 | 1.020                   |
| 242.0  | 0.955                   | 357.0  | 0.920                   | 514.0 | 1.020                   |
| 295.0  | 0.970                   | A357.0 | 0.920                   | 518.0 | 1.015                   |
| 308.0  | 0.910                   | 359.0  | 0.900                   | 520.0 | 1.040                   |
| 319.0  | 0.905                   | 360.0  | 0.890                   | 710.0 | 1.020                   |
| 332.0  | 0.875                   | A360.0 | 0.900                   | 711.0 | 1.000                   |
| 333.0  | 0.880                   | 380.0  | 0.885                   | 712.0 | 1.010                   |
| 336.0  | 0.845                   | A380   | 0.895                   | 850.0 | 0.990                   |
| 354.0  | 0.895                   | 413.0  | 0.860                   | 851.0 | 0.965                   |
| 355.0  | 0.950                   | C443.0 | 0.945                   | 852.0 | 0.985                   |
| C355.0 | 0.950                   | A444.0 | 0.920                   | ...   | ...                     |

Equations of linear thermal expansion:

- $L_{t(0 \text{ to } -320 \text{ }^{\circ}\text{F})} = L_0[1 + C(11.74t - 0.00125t^2 - 0.0000248t^3) 10^{-6}]$
- $L_{t(0 \text{ to } 1000 \text{ }^{\circ}\text{F})} = L_0[1 + C(12.19t + 0.003115t^2) 10^{-6}]$
- $L_{t(-76 \text{ to } 212 \text{ }^{\circ}\text{F})} = L_0[1 + C(12.08t + 0.003765t^2) 10^{-6}]$

$L_0$  = Length at 0 °F  
 $L_t$  = Length at temperature,  $t$  °F, within the range indicated  
*C* = Alloy constant

Constants established from determinations made on alloys in the annealed (O temper) condition. With heat treatable alloys, the application of the above equations and alloy constants is limited to temperatures below 600 °F (315 °C); for such alloys, the alloy constants are approximately 0.015 higher in the heat treated condition and should be applied to temperatures that do not exceed those used in the final aging treatments. For 7xx.x and 8xx.x casting alloys, application is restricted to 400 °F (200 °C). Source: Ref 10

**Table 8.4** Effect of elements in and out of solution on resistivity

| Element   | Maximum solubility in aluminum, % | Average increase in resistivity per wt%(a), μΩ/cm |                    |
|-----------|-----------------------------------|---------------------------------------------------|--------------------|
|           |                                   | In solution                                       | Out of solution(b) |
| Chromium  | 0.77                              | 4                                                 | 0.18               |
| Copper    | 5.65                              | 0.344                                             | 0.03               |
| Iron      | 0.052                             | 2.56                                              | 0.058              |
| Lithium   | 4                                 | 3.31                                              | 0.68               |
| Magnesium | 14.9                              | 0.54(c)                                           | 0.22(c)            |
| Manganese | 1.82                              | 2.94                                              | 0.34               |
| Nickel    | 0.05                              | 0.81                                              | 0.061              |
| Silicon   | 1.65                              | 1.02                                              | 0.088              |
| Titanium  | 1                                 | 2.88                                              | 0.12               |
| Vanadium  | 0.5                               | 3.58                                              | 0.28               |
| Zinc      | 82.8                              | 0.094(d)                                          | 0.023(d)           |
| Zirconium | 0.28                              | 1.74                                              | 0.044              |

(a) Add increase to the base resistivity for high-purity aluminum: 2.65 μΩ-cm at 20 °C (68 °F) or 2.71 μΩ-cm at 25 °C (77 °F). (b) Limited to about twice the concentration given for the maximum solid solubility, except as noted. (c) Limited to approximately 10%. (d) Limited to approximately 20%

**Table 8.5** Densities and elastic moduli of aluminum and aluminum alloying elements

| Alloying element | Density             |                   | Elastic modulus     |       |
|------------------|---------------------|-------------------|---------------------|-------|
|                  | lb/in. <sup>2</sup> | g/cm <sup>3</sup> | 10 <sup>6</sup> psi | GPa   |
| Aluminum         | 0.0971              | 2.699             | 10.0                | 69    |
| Chromium         | 0.260               | 7.19              | 36.0                | 248   |
| Copper           | 0.324               | 8.96              | 16.0                | 128   |
| Iron             | 0.284               | 7.87              | 28.5                | 208   |
| Magnesium        | 0.0628              | 1.74              | 6.5(a)              | 44(a) |
| Manganese        | 0.268               | 7.43              | 23.0                | 159   |
| Nickel           | 0.322               | 8.90              | 30.0                | 207   |
| Silicon          | 0.084               | 2.33              | 16.0                | 110   |
| Tin              | 0.264               | 7.30              | 6.0                 | 44    |
| Titanium         | 0.164               | 4.54              | 16.8                | 120   |
| Zinc             | 0.258               | 7.13              | 10(b)               | 69(b) |
| Zirconium        | 0.23                | 6.5               | 11.0                | 49    |

(a) Effect of magnesium is equivalent to approximately 11.0 × 10<sup>6</sup> psi or 75 GPa. (b) The modulus of zinc is not well defined; these values are lower limit estimates.

ture, especially in the intermediate temperature range. Elongations increase with increasing time and/or temperature.

Of the alloys for which data are presented, 201.0-T7 clearly has the superior strengths at elevated temperatures. In fact all of the 2xx.0 alloys hold up rather well at temperatures up to about 400 °F (205 °C) compared to alloys of the other series. It is the influence of the copper content providing the high-temperature resistance of the 2xx.0 series.

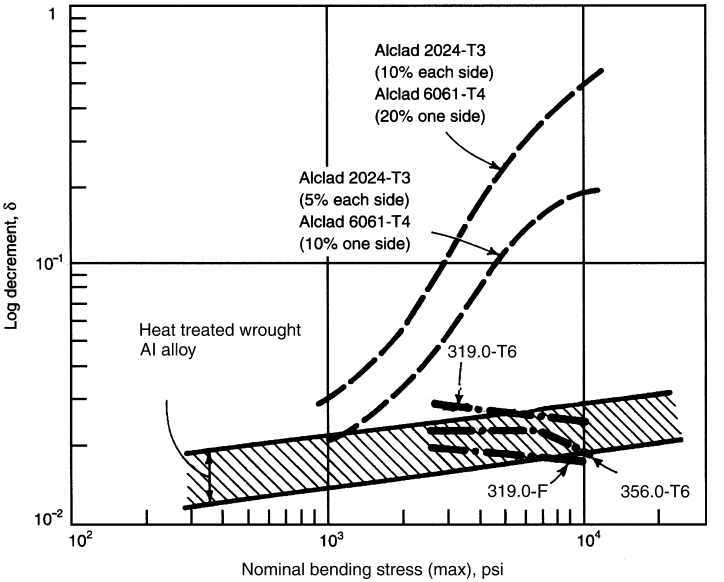


**Fig. 8.1** Damping characteristics of 319.0 and 356.0 casting alloys compared with those of wrought alloys, including clad 2024. Source: Ref 11

**Table 8.6 Typical mechanical properties of aluminum alloy castings at room temperature (engineering units)**

Values are representative of separately cast test bars, not of specimens taken from commercial castings.

| Alloy        | Temper | Tension                      |                              |                                    | Hardness(b),<br>HB | Shear<br>ultimate<br>strength,<br>ksi | Fatigue<br>ultimate<br>limit(c),<br>ksi | Modulus<br>of<br>elasticity(d),<br>10 <sup>6</sup> psi |
|--------------|--------|------------------------------|------------------------------|------------------------------------|--------------------|---------------------------------------|-----------------------------------------|--------------------------------------------------------|
|              |        | Ultimate<br>strength,<br>ksi | Yield<br>strength(a),<br>ksi | Elongation<br>in 2 in. or 4D,<br>% |                    |                                       |                                         |                                                        |
| Sand casting |        |                              |                              |                                    |                    |                                       |                                         |                                                        |
| 201.0        | T6     | 65                           | 55                           | 8                                  | 130                | ...                                   | ...                                     | ...                                                    |
|              | T7     | 68                           | 60                           | 6                                  | ...                | ...                                   | 14                                      | ...                                                    |
|              | T43    | 60                           | 37                           | 17                                 | ...                | ...                                   | ...                                     | ...                                                    |
| 204.0        | T4     | 45                           | 28                           | 6                                  | ...                | ...                                   | ...                                     | ...                                                    |
| A206.0       | T4     | 51                           | 36                           | 7                                  | ...                | 40                                    | ...                                     | ...                                                    |
| 208.0        | F      | 21                           | 14                           | 3                                  | ...                | 17                                    | 11                                      | ...                                                    |
| 213.0        | F      | 24                           | 15                           | 2                                  | 70                 | 20                                    | 9                                       | ...                                                    |
| 222.0        | O      | 27                           | 20                           | 1                                  | 80                 | 21                                    | 9.5                                     | 10.7                                                   |
|              | T61    | 41                           | 40                           | <0.5                               | 115                | 32                                    | 8.5                                     |                                                        |
| 224.0        | T72    | 55                           | 40                           | 10                                 | 123                | 35                                    | 9                                       | 10.5                                                   |
| 240.0        | F      | 34                           | 28                           | 1                                  | 90                 | ...                                   | ...                                     | ...                                                    |
| 242.0        | F      | 31                           | 20                           | 1                                  | ...                | ...                                   | ...                                     | 10.3                                                   |
|              | O      | 27                           | 18                           | 1                                  | 70                 | 21                                    | 8                                       | 10.3                                                   |
|              | T571   | 32                           | 30                           | 1                                  | 85                 | 26                                    | 11                                      | 10.3                                                   |
|              | T61    | 32                           | 20                           | ...                                | 90–120             | ...                                   | ...                                     | 10.3                                                   |
|              | T77    | 30                           | 23                           | 2                                  | 75                 | 24                                    | 10.5                                    | 10.3                                                   |
|              |        |                              |                              |                                    |                    |                                       |                                         |                                                        |
| A242.0       | T75    | 31                           | ...                          | 2                                  | ...                | ...                                   | ...                                     | ...                                                    |
| 295.0        | T4     | 32                           | 16                           | 9                                  | 80                 | 26                                    | 7                                       | 10.0                                                   |
|              | T6     | 36                           | 24                           | 5                                  | 75                 | 30                                    | 7.5                                     | 10.0                                                   |
|              | T62    | 41                           | 32                           | 2                                  | 90                 | 33                                    | 8                                       | 10.0                                                   |
|              | T7     | 29                           | 16                           | 3                                  | 55–85              | ...                                   | ...                                     | 10.0                                                   |
| 319.0        | F      | 27                           | 18                           | 2                                  | 70                 | 22                                    | 10                                      | 10.7                                                   |
|              | T5     | 30                           | 26                           | 2                                  | 80                 | 24                                    | 11                                      | 10.7                                                   |
|              | T6     | 36                           | 24                           | 2                                  | 80                 | 29                                    | 11                                      | 10.7                                                   |
| 328.0        | F      | 25                           | 14                           | 1                                  | 45–75              | ...                                   | ...                                     | ...                                                    |
|              | T6     | 34                           | 21                           | 1                                  | 65–95              | ...                                   | ...                                     | ...                                                    |
| 354.0        | T62    | 55                           | 45                           | 3                                  | ...                | ...                                   | ...                                     | ...                                                    |
| 355.0        | F      | 23                           | 12                           | 3                                  | ...                | ...                                   | ...                                     | 10.2                                                   |
|              | T51    | 28                           | 23                           | 2                                  | 65                 | 22                                    | 8                                       | 10.2                                                   |
|              | T6     | 35                           | 25                           | 3                                  | 80                 | 28                                    | 9                                       | 10.2                                                   |
|              | T61    | 35                           | 35                           | 1                                  | 90                 | 31                                    | 9.5                                     | 10.2                                                   |
|              | T7     | 38                           | 26                           | 1                                  | 85                 | 28                                    | 10                                      | 10.2                                                   |
|              | T71    | 35                           | 29                           | 2                                  | 75                 | 26                                    | 10                                      | 10.2                                                   |
| C355.0       | T6     | 39                           | 29                           | 5                                  | 85                 | ...                                   | ...                                     | ...                                                    |
| 356.0        | F      | 24                           | 18                           | 6                                  | ...                | ...                                   | ...                                     | 10.5                                                   |
|              | T51    | 25                           | 20                           | 2                                  | 60                 | 20                                    | 8                                       | 10.5                                                   |
|              | T6     | 33                           | 24                           | 4                                  | 70                 | 26                                    | 8.5                                     | 10.5                                                   |
|              | T7     | 34                           | 30                           | 2                                  | 75                 | 24                                    | 9                                       | 10.5                                                   |
|              | T71    | 28                           | 21                           | 4                                  | 60                 | 20                                    | 8.5                                     | 10.5                                                   |
| A356.0       | F      | 23                           | 12                           | 6                                  | ...                | ...                                   | ...                                     | 10.5                                                   |
|              | T51    | 26                           | 18                           | 3                                  | ...                | ...                                   | ...                                     | 10.5                                                   |
|              | T6     | 40                           | 30                           | 6                                  | 75                 | ...                                   | ...                                     | 10.5                                                   |
|              | T71    | 30                           | 20                           | 3                                  | ...                | ...                                   | ...                                     | 10.5                                                   |
| 357.0        | F      | 25                           | 13                           | 5                                  | ...                | ...                                   | ...                                     | ...                                                    |
|              | T51    | 26                           | 17                           | 3                                  | ...                | ...                                   | ...                                     | ...                                                    |
|              | T6     | 50                           | 43                           | 2                                  | ...                | ...                                   | ...                                     | ...                                                    |
|              | T7     | 40                           | 34                           | 3                                  | 60                 | ...                                   | ...                                     | ...                                                    |
| A357.0       | T6     | 46                           | 36                           | 3                                  | 85                 | 40                                    | 12                                      | ...                                                    |
| 359.0        | T62    | 50                           | 42                           | 5                                  | ...                | ...                                   | 16                                      | ...                                                    |
| A390.0       | F      | 26                           | 26                           | <1.0                               | 100                | ...                                   | ...                                     | ...                                                    |
|              | T5     | 26                           | 26                           | <1.0                               | 100                | ...                                   | ...                                     | ...                                                    |
|              | T6     | 40                           | 40                           | <1.0                               | 140                | ...                                   | 13                                      | ...                                                    |

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.6 (continued)

| Alloy                    | Temper | Tension                      |                              |                                    | Hardness(b),<br>HB | Shear<br>ultimate<br>strength,<br>ksi | Fatigue<br>ultimate<br>limit(c),<br>ksi | Modulus<br>of<br>elasticity(d),<br>10 <sup>6</sup> psi |
|--------------------------|--------|------------------------------|------------------------------|------------------------------------|--------------------|---------------------------------------|-----------------------------------------|--------------------------------------------------------|
|                          |        | Ultimate<br>strength,<br>ksi | Yield<br>strength(a),<br>ksi | Elongation<br>in 2 in. or 4D,<br>% |                    |                                       |                                         |                                                        |
| Sand casting (continued) |        |                              |                              |                                    |                    |                                       |                                         |                                                        |
|                          | T7     | 36                           | 36                           | <1.0                               | 115                | ...                                   | ...                                     | ...                                                    |
| 443.0                    | F      | 19                           | 8                            | 8                                  | 40                 | 14                                    | 8                                       | 10.3                                                   |
| B443.0                   | F      | 17                           | 6                            | 3                                  | 25–55              | ...                                   | ...                                     | ...                                                    |
| A444.0                   | F      | 21                           | 9                            | 9                                  | 44                 | ...                                   | ...                                     | ...                                                    |
|                          | T4     | 23                           | 9                            | 12                                 | 45                 | ...                                   | ...                                     | ...                                                    |
| 511.0                    | F      | 21                           | 12                           | 3                                  | 50                 | 17                                    | 8                                       | ...                                                    |
| 512.0                    | F      | 20                           | 13                           | 2                                  | 50                 | 17                                    | 9                                       | ...                                                    |
| 514.0                    | F      | 25                           | 12                           | 9                                  | 50                 | 20                                    | 7                                       | ...                                                    |
| 520.0                    | T4     | 48                           | 26                           | 16                                 | 75                 | 34                                    | 8                                       | ...                                                    |
| 535.0                    | F      | 35                           | 18                           | 9                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
|                          | T5     | 35                           | 18                           | 9                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
| A535.0                   | F      | 36                           | 18                           | 9                                  | 65                 | ...                                   | ...                                     | ...                                                    |
| 707.0                    | T5     | 33                           | 22                           | 2                                  | 70–100             | ...                                   | ...                                     | ...                                                    |
|                          | T7     | 37                           | 30                           | 1                                  | 65–95              | ...                                   | ...                                     | ...                                                    |
| 710.0                    | F      | 32                           | 20                           | 2                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
|                          | T5     | 32                           | 20                           | 2                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
| 712.0                    | F      | 34                           | 25                           | 4                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
|                          | T5     | 34                           | 25                           | 4                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
| 713.0                    | F      | 32                           | 22                           | 3                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
|                          | T5     | 32                           | 22                           | 3                                  | 60–90              | ...                                   | ...                                     | ...                                                    |
| 771.0                    | T5     | 32                           | 27                           | 3                                  | 70–100             | ...                                   | ...                                     | ...                                                    |
|                          | T52    | 36                           | 30                           | 2                                  | 70–100             | ...                                   | ...                                     | ...                                                    |
|                          | T53    | 36                           | 27                           | 2                                  | ...                | ...                                   | ...                                     | ...                                                    |
|                          | T6     | 42                           | 35                           | 5                                  | 75–105             | ...                                   | ...                                     | ...                                                    |
|                          | T71    | 48                           | 45                           | 2                                  | 105–135            | ...                                   | ...                                     | ...                                                    |
| 850.0                    | T5     | 20                           | 11                           | 8                                  | 45                 | 14                                    | ...                                     | 10.3                                                   |
| 851.0                    | T5     | 20                           | 11                           | 5                                  | 45                 | 14                                    | ...                                     | 10.3                                                   |
| 852.0                    | T5     | 27                           | 22                           | 2                                  | 65                 | 18                                    | 10                                      | 10.3                                                   |
| Permanent mold casting   |        |                              |                              |                                    |                    |                                       |                                         |                                                        |
| 201.0                    | T6     | 65                           | 55                           | 8                                  | 130                | ...                                   | ...                                     | ...                                                    |
|                          | T7     | 68                           | 60                           | 6                                  | ...                | ...                                   | 14                                      | ...                                                    |
|                          | T43    | 60                           | 37                           | 17                                 | ...                | ...                                   | ...                                     | ...                                                    |
| 204.0                    | T4     | 48                           | 29                           | 8                                  | ...                | ...                                   | ...                                     | ...                                                    |
| A206.0                   | T4     | 62                           | 38                           | 17                                 | ...                | 42                                    | ...                                     | ...                                                    |
|                          | T7     | 63                           | 50                           | 12                                 | ...                | 37                                    | ...                                     | ...                                                    |
| 208.0                    | T6     | 35                           | 22                           | 2                                  | 75–105             | ...                                   | ...                                     | ...                                                    |
|                          | T7     | 33                           | 16                           | 3                                  | 65–95              | ...                                   | ...                                     | ...                                                    |
| 213.0                    | F      | 30                           | 24                           | 2                                  | 85                 | 24                                    | 9.5                                     | ...                                                    |
| 222.0                    | T551   | 37                           | 35                           | <0.5                               | 115                | 30                                    | 8.5                                     | 10.7                                                   |
|                          | T52    | 35                           | 31                           | 1                                  | 100                | 25                                    | ...                                     | 10.7                                                   |
| 238.0                    | F      | 30                           | 24                           | 2                                  | 100                | 24                                    | ...                                     | ...                                                    |
| 242.0                    | T571   | 40                           | 34                           | 1                                  | 105                | 30                                    | 10.5                                    | 10.3                                                   |
|                          | T61    | 47                           | 42                           | 1                                  | 110                | 35                                    | 10                                      | 10.3                                                   |

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5



Table 8.6 (continued)

| Alloy                              | Temper | Tension                      |                              |                                             | Hardness(b),<br>HB | Shear<br>ultimate<br>strength,<br>ksi | Fatigue<br>ultimate<br>limit(c),<br>ksi | Modulus<br>of<br>elasticity(d),<br>10 <sup>6</sup> psi |
|------------------------------------|--------|------------------------------|------------------------------|---------------------------------------------|--------------------|---------------------------------------|-----------------------------------------|--------------------------------------------------------|
|                                    |        | Ultimate<br>strength,<br>ksi | Yield<br>strength(a),<br>ksi | Elongation<br>in 2 in. or 4 <i>D</i> ,<br>% |                    |                                       |                                         |                                                        |
| Permanent mold casting (continued) |        |                              |                              |                                             |                    |                                       |                                         |                                                        |
| A249.0                             | T63    | 69                           | 60                           | 6                                           | ...                | ...                                   | ...                                     | ...                                                    |
| 296.0                              | T7     | 39                           | 20                           | 5                                           | 80                 | 30                                    | 9                                       | 10.1                                                   |
| 308.0                              | F      | 28                           | 16                           | 2                                           | 70                 | 22                                    | 13                                      | ...                                                    |
| 319.0                              | F      | 34                           | 19                           | 3                                           | 85                 | 24                                    | ...                                     | 10.7                                                   |
| 324.0                              | T6     | 40                           | 27                           | 3                                           | 95                 | ...                                   | ...                                     | 10.7                                                   |
|                                    | F      | 30                           | 16                           | 4                                           | 70                 | ...                                   | ...                                     | ...                                                    |
|                                    | T5     | 36                           | 26                           | 3                                           | 90                 | ...                                   | ...                                     | ...                                                    |
|                                    | T62    | 45                           | 39                           | 3                                           | 105                | ...                                   | ...                                     | ...                                                    |
| 332.0                              | T5     | 36                           | 28                           | 1                                           | 105                | ...                                   | ...                                     | ...                                                    |
| 328.0                              | T6     | 34                           | 21                           | 1                                           | 65–95              | ...                                   | ...                                     | ...                                                    |
| 333.0                              | F      | 34                           | 19                           | 2                                           | 90                 | 27                                    | 15                                      | ...                                                    |
|                                    | T5     | 34                           | 25                           | 1                                           | 100                | 27                                    | 12                                      | ...                                                    |
|                                    | T6     | 42                           | 30                           | 2                                           | 105                | 33                                    | 15                                      | ...                                                    |
|                                    | T7     | 37                           | 28                           | 2                                           | 90                 | 28                                    | 12                                      | ...                                                    |
| 336.0                              | T551   | 36                           | 28                           | 1                                           | 105                | 28                                    | 14                                      | ...                                                    |
|                                    | T65    | 47                           | 43                           | 1                                           | 125                | 36                                    | ...                                     | ...                                                    |
| 354.0                              | T61    | 52                           | 39                           | 6                                           | ...                | ...                                   | 19                                      | ...                                                    |
|                                    | T62    | 55                           | 45                           | 3                                           | ...                | ...                                   | ...                                     | ...                                                    |
| 355.0                              | F      | 27                           | 15                           | 4                                           | ...                | ...                                   | ...                                     | 10.2                                                   |
|                                    | T51    | 30                           | 24                           | 2                                           | 75                 | 24                                    | ...                                     | 10.2                                                   |
|                                    | T6     | 42                           | 27                           | 4                                           | 90                 | 34                                    | 10                                      | 10.2                                                   |
|                                    | T61    | 45                           | 40                           | 2                                           | 105                | 36                                    | 10                                      | 10.2                                                   |
|                                    | T7     | 40                           | 30                           | 2                                           | 85                 | 30                                    | 10                                      | 10.2                                                   |
|                                    | T71    | 36                           | 31                           | 3                                           | 85                 | 27                                    | 10                                      | 10.2                                                   |
| C355.0                             | T6     | 48                           | 28                           | 8                                           | 90                 | ...                                   | ...                                     | 10.2                                                   |
|                                    | T61    | 46                           | 34                           | 6                                           | 100                | ...                                   | ...                                     | 10.2                                                   |
|                                    | T62    | 48                           | 37                           | 5                                           | 100                | ...                                   | ...                                     | 10.2                                                   |
| 356.0                              | F      | 26                           | 18                           | 5                                           | ...                | ...                                   | ...                                     | 10.5                                                   |
|                                    | T51    | 27                           | 20                           | 2                                           | ...                | ...                                   | ...                                     | 10.5                                                   |
|                                    | T6     | 38                           | 27                           | 5                                           | 80                 | 30                                    | 13                                      | 10.5                                                   |
|                                    | T7     | 32                           | 24                           | 6                                           | 70                 | 25                                    | 11                                      | 10.5                                                   |
|                                    | T71    | 25                           | ...                          | 3                                           | 60–90              | ...                                   | ...                                     | 10.5                                                   |
| A356.0                             | F      | 27                           | 13                           | 8                                           | ...                | ...                                   | ...                                     | 10.5                                                   |
|                                    | T51    | 29                           | 20                           | 5                                           | ...                | ...                                   | ...                                     | 10.5                                                   |
|                                    | T6     | 41                           | 30                           | 12                                          | 80                 | ...                                   | ...                                     | 10.5                                                   |
| 357.0                              | F      | 28                           | 15                           | 6                                           | ...                | ...                                   | ...                                     | ...                                                    |
|                                    | T51    | 29                           | 21                           | 4                                           | ...                | ...                                   | ...                                     | ...                                                    |
|                                    | T6     | 52                           | 43                           | 5                                           | 100                | 35                                    | 13                                      | ...                                                    |
|                                    | T7     | 38                           | 30                           | 5                                           | 70                 | ...                                   | ...                                     | ...                                                    |
| A357.0                             | T6     | 52                           | 42                           | 5                                           | 100                | 35                                    | 15                                      | ...                                                    |
| 359.0                              | T61    | 48                           | 37                           | 6                                           | ...                | ...                                   | ...                                     | ...                                                    |
|                                    | T62    | 50                           | 42                           | 5                                           | ...                | ...                                   | 16                                      | ...                                                    |
| A390.0                             | F      | 29                           | 29                           | <1.0                                        | 110                | ...                                   | ...                                     | ...                                                    |
|                                    | T5     | 29                           | 29                           | <1.0                                        | 110                | ...                                   | ...                                     | ...                                                    |
|                                    | T6     | 45                           | 45                           | <1.0                                        | 145                | ...                                   | 17                                      | ...                                                    |
|                                    | T7     | 38                           | 38                           | <1.0                                        | 120                | ...                                   | 15                                      | ...                                                    |
| 443.0                              | F      | 23                           | 9                            | 10                                          | 45                 | 16                                    | 8                                       | 10.3                                                   |
| B443.0                             | F      | 21                           | 6                            | 6                                           | 30–60              | ...                                   | ...                                     | ...                                                    |
| A444.0                             | F      | 24                           | 11                           | 13                                          | 44                 | ...                                   | ...                                     | ...                                                    |
|                                    | T4     | 23                           | 10                           | 21                                          | 45                 | 16                                    | 8                                       | ...                                                    |
| 513.0                              | F      | 27                           | 16                           | 7                                           | 60                 | 22                                    | 10                                      | ...                                                    |
| 535.0                              | F      | 35                           | 18                           | 8                                           | 60–90              | ...                                   | ...                                     | ...                                                    |

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.6 (continued)

| Alloy                              | Temper | Tension                      |                              |                                             | Hardness(b),<br>HB | Shear<br>ultimate<br>strength,<br>ksi | Fatigue<br>ultimate<br>limit(c),<br>ksi | Modulus<br>of<br>elasticity(d),<br>10 <sup>6</sup> psi |
|------------------------------------|--------|------------------------------|------------------------------|---------------------------------------------|--------------------|---------------------------------------|-----------------------------------------|--------------------------------------------------------|
|                                    |        | Ultimate<br>strength,<br>ksi | Yield<br>strength(a),<br>ksi | Elongation<br>in 2 in. or 4 <i>D</i> ,<br>% |                    |                                       |                                         |                                                        |
| Permanent mold casting (continued) |        |                              |                              |                                             |                    |                                       |                                         |                                                        |
| 705.0                              | T5     | 37                           | 17                           | 10                                          | 55–75              | ...                                   | ...                                     | ...                                                    |
| 707.0                              | T7     | 45                           | 35                           | 3                                           | 80–110             | ...                                   | ...                                     | ...                                                    |
| 711.0                              | T1     | 28                           | 18                           | 7                                           | 55–85              | ...                                   | ...                                     | ...                                                    |
| 713.0                              | T5     | 32                           | 22                           | 4                                           | 60–90              |                                       |                                         |                                                        |
| 850.0                              | T5     | 23                           | 11                           | 12                                          | 45                 | 15                                    | 9                                       | 10.3                                                   |
| 851.0                              | T5     | 20                           | 11                           | 5                                           | 45                 | 14                                    | 9                                       | 10.3                                                   |
|                                    | T6     | 18                           | ...                          | 8                                           | ...                | ...                                   | ...                                     | 10.3                                                   |
| 852.0                              | T5     | 32                           | 23                           | 5                                           | 70                 | 21                                    | 11                                      | 10.3                                                   |
| Die casting                        |        |                              |                              |                                             |                    |                                       |                                         |                                                        |
| 360.0                              | F      | 44                           | 25                           | 3                                           | 75                 | 28                                    | 20                                      | 10.3                                                   |
| A360.0                             | F      | 46                           | 24                           | 4                                           | 75                 | 26                                    | 18                                      | 10.3                                                   |
| 380.0                              | F      | 46                           | 23                           | 3                                           | 80                 | 28                                    | 20                                      | 10.3                                                   |
| A380.0                             | F      | 47                           | 23                           | 4                                           | 80                 | 27                                    | 20                                      | 10.3                                                   |
| 383.0                              | F      | 45                           | 22                           | 4                                           | 75                 | ...                                   | 21                                      | 10.3                                                   |
| 384.0                              | F      | 48                           | 24                           | 3                                           | 85                 | 29                                    | 20                                      | ...                                                    |
| 390.0                              | F      | 40.5                         | 35                           | <1                                          | ...                | ...                                   | ...                                     | ...                                                    |
| B390.0                             | F      | 46                           | 36                           | <1                                          | 120                | ...                                   | 20                                      | 11.8                                                   |
| 392.0                              | F      | 42                           | 39                           | <1                                          | ...                | ...                                   | ...                                     | ...                                                    |
| 413.0                              | F      | 43                           | 21                           | 3                                           | 80                 | 25                                    | 19                                      | 10.3                                                   |
| A413.0                             | F      | 42                           | 19                           | 4                                           | 80                 | 25                                    | 19                                      | ...                                                    |
| C443.0                             | F      | 33                           | 14                           | 9                                           | 65                 | 29                                    | 17                                      | 10.3                                                   |
| 518.0                              | F      | 45                           | 28                           | 5                                           | 80                 | 29                                    | 20                                      | ...                                                    |

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 10 mm ball. (c) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (d) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

### 8.3.4 Influence of Premium Practices and Emerging Casting Technologies on Mechanical Properties

**Premium Engineered Castings.** As noted in Chapter 3, it has been recognized for many years that special care in the application of metal flow and chill practices can lead to superior properties for aluminum casting alloys, and the consistent use of such practices has led to a classification of aluminum castings known as “premium quality” or “premium engineered” castings.

The typical and minimum properties of the more widely used casting alloys developed using this technology are summarized in Tables 8.9 and 8.10, respectively (Ref 8, 15). The minimum properties shown are the design mechanical properties published in MMPDS (previously known as MIL-HDBK-5) and from AMS-A-21180 (previously MIL-A-21180). Note the several levels of control on location and quality of casting, which sometimes greatly influences the published design property.

Both aluminum industry sources and MMPDS/MIL-HDBK-5 define the minimum and/or design properties as the values which the properties of 99% of the lots of a given alloy and temper would equal or exceed, with 95% confidence.

Specification AMS-A-21180 defines the requirements for high-strength aluminum alloy castings. Mechanical properties based on the results of excised or prolongation specimens representing the actual casting rather than separately cast specimens that represent conformance to expected chemistry and heat treatment responses. In most cases, this and other specifications and standards serve only as the guide to separately negotiated requirements. With the passage of time property requirements for premium engineered castings increasingly exceeded those defined by this specification.

Plaster cast low-pressure impellers and rotors that were heavily and directionally chilled routinely exceeded even negotiated property limits. For level and conventionally poured premium engineered castings, consistently meeting mechanical testing requirements was more tenuous when guarantees for tensile properties were 15 to 25% and ductility 60 to 100% higher than the limits

**Table 8.7 Typical mechanical properties of aluminum alloy castings at room temperature (metric units)**

Values are representative of separately cast test bars, not of specimens taken from commercial castings.

| Alloy        | Temper | Tension                      |                              |                           | Hardness(b),<br>HB<br>500 kg/10 mm | Shear<br>ultimate<br>strength,<br>MPa | Fatigue<br>endurance<br>limit(b),<br>MPa | Modulus<br>of<br>elasticity(c),<br>GPa |
|--------------|--------|------------------------------|------------------------------|---------------------------|------------------------------------|---------------------------------------|------------------------------------------|----------------------------------------|
|              |        | Ultimate<br>strength,<br>MPa | Yield<br>strength(a),<br>MPa | Elongation<br>in 5D,<br>% |                                    |                                       |                                          |                                        |
| Sand casting |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| 201.0        | T6     | 450                          | 380                          | 8                         | 130                                | ...                                   | ...                                      | ...                                    |
|              | T7     | 470                          | 415                          | 6                         | ...                                | ...                                   | 95                                       | ...                                    |
|              | T43    | 415                          | 255                          | 17                        | ...                                | ...                                   | ...                                      | ...                                    |
| 204.0        | T4     | 310                          | 195                          | 6                         | ...                                | ...                                   | ...                                      | ...                                    |
| A206.0       | T4     | 350                          | 250                          | 7                         | ...                                | 275                                   | ...                                      | ...                                    |
| 208.0        | F      | 145                          | 655                          | 3                         | ...                                | 115                                   | 75                                       | ...                                    |
| 213.0        | F      | 165                          | 105                          | 2                         | 70                                 | 140                                   | 60                                       | ...                                    |
| 222.0        | O      | 185                          | 140                          | 1                         | 80                                 | 145                                   | 65                                       | 74                                     |
|              | T61    | 285                          | 275                          | <0.5                      | 115                                | 220                                   | 60                                       |                                        |
| 224.0        | T72    | 380                          | 275                          | 10                        | 123                                | 240                                   | 60                                       | 73                                     |
| 240.0        | F      | 235                          | 195                          | 1                         | 90                                 | ...                                   | ...                                      | ...                                    |
| 242.0        | F      | 145                          | 140                          | 1                         | ...                                | ...                                   | ...                                      | 71                                     |
|              | O      | 185                          | 125                          | 1                         | 70                                 | 145                                   | 55                                       | 71                                     |
|              | T571   | 220                          | 205                          | 1                         | 85                                 | 180                                   | 75                                       | 71                                     |
|              | T61    | 220                          | 140                          | ...                       | 90–120                             | ...                                   | ...                                      | 71                                     |
|              | T77    | 205                          | 160                          | 2                         | 75                                 | 165                                   | 70                                       | 71                                     |
|              |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| A242.0       | T75    | 215                          | ...                          | 2                         | ...                                | ...                                   | ...                                      | ...                                    |
| 295.0        | T4     | 220                          | 110                          | 9                         | 80                                 | 180                                   | 50                                       | 69                                     |
|              | T6     | 250                          | 165                          | 5                         | 75                                 | 205                                   | 50                                       | 69                                     |
|              | T62    | 285                          | 220                          | 2                         | 90                                 | 230                                   | 55                                       | 69                                     |
|              | T7     | 200                          | 110                          | 3                         | 55–85                              | ...                                   | ...                                      | 69                                     |
| 319.0        | F      | 185                          | 125                          | 2                         | 70                                 | 150                                   | 70                                       | 74                                     |
|              | T5     | 205                          | 180                          | 2                         | 80                                 | 165                                   | 75                                       | 74                                     |
|              | T6     | 250                          | 165                          | 2                         | 80                                 | 200                                   | 75                                       | 74                                     |
| 328.0        | F      | 170                          | 95                           | 1                         | 45–75                              | ...                                   | ...                                      | ...                                    |
|              | T6     | 235                          | 145                          | 1                         | 65–95                              | ...                                   | ...                                      | ...                                    |
| 354.0        | T62    | 380                          | 310                          | 3                         | ...                                | ...                                   | ...                                      | ...                                    |
| 355.0        | F      | 160                          | 85                           | 3                         | ...                                | ...                                   | ...                                      | 70                                     |
|              | T51    | 195                          | 160                          | 2                         | 65                                 | 150                                   | 55                                       | 70                                     |
|              | T6     | 240                          | 170                          | 3                         | 80                                 | 195                                   | 60                                       | 70                                     |
|              | T61    | 240                          | 240                          | 1                         | 90                                 | 215                                   | 65                                       | 70                                     |
|              | T7     | 260                          | 180                          | 1                         | 85                                 | 195                                   | 70                                       | 70                                     |
|              | T71    | 240                          | 200                          | 2                         | 75                                 | 180                                   | 70                                       | 70                                     |
| C355.0       | T6     | 270                          | 200                          | 5                         | 85                                 | ...                                   | ...                                      | ...                                    |
| 356.0        | F      | 165                          | 125                          | 6                         | ...                                | ...                                   | ...                                      | 73                                     |
|              | T51    | 170                          | 140                          | 2                         | 60                                 | 140                                   | 55                                       | 73                                     |
|              | T6     | 230                          | 165                          | 4                         | 70                                 | 180                                   | 60                                       | 73                                     |
|              | T7     | 235                          | 205                          | 2                         | 75                                 | 165                                   | 60                                       | 73                                     |
|              | T71    | 195                          | 145                          | 4                         | 60                                 | 140                                   | 60                                       | 73                                     |
| A356.0       | F      | 160                          | 85                           | 6                         | ...                                | ...                                   | ...                                      | 73                                     |
|              | T51    | 180                          | 125                          | 3                         | ...                                | ...                                   | ...                                      | 73                                     |
|              | T6     | 275                          | 205                          | 6                         | 75                                 | ...                                   | ...                                      | 73                                     |
|              | T71    | 205                          | 140                          | 3                         | ...                                | ...                                   | ...                                      | 73                                     |
| 357.0        | F      | 170                          | 90                           | 5                         | ...                                | ...                                   | ...                                      | ...                                    |
|              | T51    | 180                          | 115                          | 3                         | ...                                | ...                                   | ...                                      | ...                                    |
|              | T6     | 345                          | 295                          | 2                         | ...                                | ...                                   | ...                                      | ...                                    |
|              | T7     | 275                          | 235                          | 3                         | 60                                 | ...                                   | ...                                      | ...                                    |
| A357.0       | T6     | 315                          | 250                          | 3                         | 85                                 | 275                                   | 85                                       | ...                                    |
| 359.0        | T62    | 345                          | 290                          | 5                         | ...                                | ...                                   | 110                                      | ...                                    |
| A390.0       | F      | 180                          | 180                          | <1.0                      | 100                                | ...                                   | ...                                      | ...                                    |
|              | T5     | 180                          | 180                          | <1.0                      | 100                                | ...                                   | ...                                      | ...                                    |

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.7 (continued)

| Alloy                    | Temper | Tension                      |                              |                           | Hardness(b),<br>HB<br>500 kg/10 mm | Shear<br>ultimate<br>strength,<br>MPa | Fatigue<br>endurance<br>limit(b),<br>MPa | Modulus<br>of<br>elasticity(c),<br>GPa |
|--------------------------|--------|------------------------------|------------------------------|---------------------------|------------------------------------|---------------------------------------|------------------------------------------|----------------------------------------|
|                          |        | Ultimate<br>strength,<br>MPa | Yield<br>strength(a),<br>MPa | Elongation<br>in 5D,<br>% |                                    |                                       |                                          |                                        |
| Sand casting (continued) |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| 443.0                    | T6     | 275                          | 275                          | <1.0                      | 140                                | ...                                   | 90                                       | ...                                    |
|                          | T7     | 250                          | 250                          | <1.0                      | 115                                | ...                                   | ...                                      | ...                                    |
|                          | F      | 130                          | 55                           | 8                         | 40                                 | 95                                    | 55                                       | 71                                     |
| B443.0                   | F      | 115                          | 40                           | 3                         | 25–55                              | ...                                   | ...                                      | ...                                    |
| A444.0                   | F      | 145                          | 60                           | 9                         | 43,400                             | ...                                   | ...                                      | ...                                    |
|                          | T4     | 23                           | 60                           | 12                        |                                    |                                       |                                          |                                        |
| 511.0                    | F      | 145                          | 85                           | 3                         | 50                                 | 115                                   | 55                                       | ...                                    |
| 512.0                    | F      | 140                          | 90                           | 2                         | 50                                 | 115                                   | 60                                       | ...                                    |
| 514.0                    | F      | 170                          | 85                           | 9                         | 50                                 | 140                                   | 50                                       | ...                                    |
| 520.0                    | T4     | 330                          | 180                          | 16                        | 75                                 | 235                                   | 55                                       | ...                                    |
| 535.0                    | T      | 240                          | 125                          | 9                         | 60–90                              | ...                                   | ...                                      | ...                                    |
|                          | T5     | 240                          | 125                          | 9                         | 60–90                              | ...                                   | ...                                      | ...                                    |
| A535.0                   | F      | 250                          | 125                          | 9                         | 65                                 | ...                                   | ...                                      | ...                                    |
| 707.0                    | T5     | 230                          | 150                          | 2                         | 70–100                             | ...                                   | ...                                      | ...                                    |
|                          | T7     | 255                          | 205                          | 1                         | 65–95                              | ...                                   | ...                                      | ...                                    |
| 710.0                    | F      | 220                          | 140                          | 2                         | 60–90                              | ...                                   | ...                                      | ...                                    |
|                          | T5     | 220                          | 140                          | 2                         | 60–90                              | ...                                   | ...                                      | ...                                    |
| 712.0                    | F      | 235                          | 170                          | 4                         | 60–90                              | ...                                   | ...                                      | ...                                    |
|                          | T5     | 235                          | 170                          | 4                         | 60–90                              | ...                                   | ...                                      | ...                                    |
| 713.0                    | F      | 220                          | 150                          | 3                         | 60–90                              | ...                                   | ...                                      | ...                                    |
|                          | T5     | 220                          | 150                          | 3                         | 60–90                              | ...                                   | ...                                      | ...                                    |
| 771.0                    | T5     | 220                          | 185                          | 3                         | 70–100                             | ...                                   | ...                                      | ...                                    |
|                          | T52    | 250                          | 205                          | 2                         | 70–100                             | ...                                   | ...                                      | ...                                    |
|                          | T53    | 250                          | 185                          | 2                         | ...                                | ...                                   | ...                                      | ...                                    |
|                          | T6     | 290                          | 240                          | 5                         | 75–105                             | ...                                   | ...                                      | ...                                    |
|                          | T71    | 330                          | 310                          | 2                         | 105–135                            | ...                                   | ...                                      | ...                                    |
| 850.0                    | T5     | 140                          | 75                           | 8                         | 45                                 | 95                                    | ...                                      | 71                                     |
| 851.0                    | T5     | 140                          | 75                           | 5                         | 45                                 | 95                                    | ...                                      | 71                                     |
| 852.0                    | T5     | 185                          | 150                          | 2                         | 65                                 | 125                                   | 60                                       | 71                                     |
| Permanent mold casting   |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| 201.0                    | T6     | 450                          | 380                          | 8                         | 130                                | ...                                   | ...                                      | ...                                    |
|                          | T7     | 470                          | 415                          | 6                         | ...                                | ...                                   | 95                                       | ...                                    |
|                          | T43    | 415                          | 255                          | 17                        | ...                                | ...                                   | ...                                      | ...                                    |
| 204.0                    | T4     | 330                          | 200                          | 8                         | ...                                | ...                                   | ...                                      | ...                                    |
| A206.0                   | T4     | 430                          | 260                          | 17                        | ...                                | 290                                   | ...                                      | ...                                    |
|                          | T7     | 435                          | 345                          | 12                        | ...                                | 255                                   | ...                                      | ...                                    |
| 208.0                    | T6     | 240                          | 150                          | 2                         | 75–105                             | ...                                   | ...                                      | ...                                    |
|                          | T7     | 230                          | 110                          | 3                         | 65–95                              | ...                                   | ...                                      | ...                                    |
| 213.0                    | F      | 205                          | 165                          | 2                         | 85                                 | 165                                   | 65                                       | ...                                    |
| 222.0                    | T551   | 255                          | 240                          | <0.5                      | 115                                | 205                                   | 60                                       | 74                                     |
|                          | T52    | 240                          | 215                          | 1                         | 100                                | 170                                   | ...                                      | 74                                     |
| 238.0                    | F      | 205                          | 165                          | 2                         | 100                                | 165                                   | ...                                      | ...                                    |
| 242.0                    | T571   | 275                          | 235                          | 1                         | 105                                | 205                                   | 70                                       | 74                                     |
|                          | T61    | 325                          | 290                          | 1                         | 110                                | 450                                   | 70                                       | 74                                     |
| A249.0                   | T63    | 475                          | 415                          | 6                         | ...                                | ...                                   | ...                                      | ...                                    |
| 296.0                    | T7     | 270                          | 140                          | 5                         | 80                                 | 205                                   | 60                                       | 70                                     |
| 308.0                    | F      | 195                          | 110                          | 2                         | 70                                 | 150                                   | 90                                       | ...                                    |
| 319.0                    | F      | 235                          | 130                          | 3                         | 85                                 | 165                                   | ...                                      | 74                                     |
|                          | T6     | 275                          | 185                          | 3                         | 95                                 | ...                                   | ...                                      | 74                                     |

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5

Table 8.7 (continued)

| Alloy                              | Temper | Tension                      |                              |                           | Hardness(b),<br>HB<br>500 kg/10 mm | Shear<br>ultimate<br>strength,<br>MPa | Fatigue<br>endurance<br>limit(b),<br>MPa | Modulus<br>of<br>elasticity(c),<br>GPa |
|------------------------------------|--------|------------------------------|------------------------------|---------------------------|------------------------------------|---------------------------------------|------------------------------------------|----------------------------------------|
|                                    |        | Ultimate<br>strength,<br>MPa | Yield<br>strength(a),<br>MPa | Elongation<br>in 5D,<br>% |                                    |                                       |                                          |                                        |
| Permanent mold casting (continued) |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| 324.0                              | F      | 205                          | 110                          | 4                         | 70                                 | ...                                   | ...                                      | ...                                    |
|                                    | T5     | 250                          | 180                          | 3                         | 90                                 | ...                                   | ...                                      | ...                                    |
|                                    | T62    | 310                          | 270                          | 3                         | 105                                | ...                                   | ...                                      | ...                                    |
| 332.0                              | T5     | 250                          | 195                          | 1                         | 105                                | ...                                   | ...                                      | ...                                    |
| 328.0                              | T6     | 235                          | 145                          | 1                         | 65–95                              | ...                                   | ...                                      | ...                                    |
| 333.0                              | F      | 235                          | 130                          | 2                         | 90                                 | 185                                   | 105                                      | ...                                    |
|                                    | T5     | 235                          | 170                          | 1                         | 100                                | 185                                   | 85                                       | ...                                    |
|                                    | T6     | 290                          | 205                          | 2                         | 105                                | 230                                   | 105                                      | ...                                    |
|                                    | T7     | 255                          | 195                          | 2                         | 90                                 | 195                                   | 85                                       | ...                                    |
| 336.0                              | T551   | 250                          | 193                          | 1                         | 105                                | 193                                   | 95                                       | ...                                    |
|                                    | T65    | 325                          | 295                          | 1                         | 125                                | 250                                   | ...                                      | ...                                    |
| 354.0                              | T61    | 360                          | 270                          | 6                         | ...                                | ...                                   | ...                                      | ...                                    |
|                                    | T62    | 380                          | 310                          | 3                         | ...                                | ...                                   | ...                                      | ...                                    |
| 355.0                              | F      | 185                          | 105                          | 4                         | ...                                | ...                                   | ...                                      | 70                                     |
|                                    | T51    | 205                          | 165                          | 2                         | 75                                 | 165                                   | ...                                      | 70                                     |
|                                    | T6     | 290                          | 185                          | 4                         | 90                                 | 235                                   | 70                                       | 70                                     |
|                                    | T61    | 310                          | 275                          | 2                         | 105                                | 250                                   | 70                                       | 70                                     |
|                                    | T7     | 275                          | 205                          | 2                         | 85                                 | 205                                   | 70                                       | 70                                     |
|                                    | T71    | 250                          | 215                          | 3                         | 85                                 | 185                                   | 70                                       | 70                                     |
| C355.0                             | T6     | 330                          | 195                          | 8                         | 90                                 | ...                                   | ...                                      | 70                                     |
|                                    | T61    | 315                          | 235                          | 6                         | 100                                | ...                                   | ...                                      | 70                                     |
|                                    | T62    | 330                          | 255                          | 5                         | 100                                | ...                                   | ...                                      | 70                                     |
| 356.0                              | F      | 180                          | 125                          | 5                         | ...                                | ...                                   | ...                                      | 73                                     |
|                                    | T51    | 185                          | 140                          | 2                         | ...                                | ...                                   | ...                                      | 73                                     |
|                                    | T6     | 260                          | 185                          | 5                         | 80                                 | 205                                   | 90                                       | 73                                     |
|                                    | T7     | 220                          | 165                          | 6                         | 70                                 | 170                                   | 75                                       | 73                                     |
|                                    | T71    | 170                          | ...                          | 3                         | 60–90                              | ...                                   | ...                                      | 73                                     |
| A356.0                             | F      | 185                          | 90                           | 8                         | ...                                | ...                                   | ...                                      | 73                                     |
|                                    | T51    | 200                          | 140                          | 5                         | ...                                | ...                                   | ...                                      | 73                                     |
|                                    | T6     | 285                          | 205                          | 12                        | 80                                 | ...                                   | ...                                      | 73                                     |
| 357.0                              | F      | 195                          | 105                          | 6                         | ...                                | ...                                   | ...                                      | ...                                    |
|                                    | T51    | 200                          | 145                          | 4                         | ...                                | ...                                   | ...                                      | ...                                    |
|                                    | T6     | 360                          | 295                          | 5                         | 100                                | 240                                   | 90                                       | ...                                    |
|                                    | T7     | 260                          | 205                          | 5                         | 70                                 | ...                                   | ...                                      | ...                                    |
| A357.0                             | T6     | 360                          | 290                          | 5                         | 100                                | 240                                   | 105                                      | ...                                    |
| 359.0                              | T61    | 330                          | 255                          | 6                         | ...                                | ...                                   | ...                                      | ...                                    |
|                                    | T62    | 345                          | 290                          | 5                         | ...                                | ...                                   | 110                                      | ...                                    |
| A390.0                             | F      | 200                          | 200                          | <1.0                      | 110                                | ...                                   | ...                                      | ...                                    |
|                                    | T5     | 200                          | 200                          | <1.0                      | 110                                | ...                                   | ...                                      | ...                                    |
|                                    | T6     | 310                          | 310                          | <1.0                      | 145                                | ...                                   | 115                                      | ...                                    |
|                                    | T7     | 260                          | 260                          | <1.0                      | 120                                | ...                                   | 105                                      | ...                                    |
| 443.0                              | F      | 160                          | 60                           | 10                        | 45                                 | 110                                   | 55                                       | 71                                     |
| B443.0                             | F      | 145                          | 40                           | 6                         | 30–60                              | ...                                   | ...                                      | ...                                    |
| A444.0                             | F      | 165                          | 75                           | 13                        | 44                                 | ...                                   | ...                                      | ...                                    |
|                                    | T4     | 160                          | 70                           | 21                        | 45                                 | 110                                   | 55                                       | ...                                    |
| 513.0                              | F      | 185                          | 110                          | 7                         | 60                                 | 150                                   | 70                                       | ...                                    |
| 535.0                              | F      | 240                          | 125                          | 8                         | 60–90                              | ...                                   | ...                                      | ...                                    |
| 705.0                              | T5     | 255                          | 115                          | 10                        | 55–75                              | ...                                   | ...                                      | ...                                    |
| 707.0                              | T7     | 310                          | 240                          | 3                         | 80–110                             | ...                                   | ...                                      | ...                                    |
| 711.0                              | T1     | 195                          | 125                          | 7                         | 55–85                              | ...                                   | ...                                      | ...                                    |
| 713.0                              | T5     | 220                          | 150                          | 4                         | 60–90                              | ...                                   | ...                                      | ...                                    |
| 850.0                              | T5     | 160                          | 75                           | 12                        | 45                                 | 105                                   | 60                                       | 71                                     |

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3–5



Table 8.7 (continued)

| Alloy                              | Temper | Tension                      |                              |                           | Hardness(b),<br>HB<br>500 kg/10 mm | Shear<br>ultimate<br>strength,<br>MPa | Fatigue<br>endurance<br>limit(b),<br>MPa | Modulus<br>of<br>elasticity(c),<br>GPa |
|------------------------------------|--------|------------------------------|------------------------------|---------------------------|------------------------------------|---------------------------------------|------------------------------------------|----------------------------------------|
|                                    |        | Ultimate<br>strength,<br>MPa | Yield<br>strength(a),<br>MPa | Elongation<br>in 5D,<br>% |                                    |                                       |                                          |                                        |
| Permanent mold casting (continued) |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| 851.0                              | T5     | 140                          | 75                           | 5                         | 45                                 | 95                                    | 60                                       | 71                                     |
|                                    | T6     | 125                          | ...                          | 8                         | ...                                | ...                                   | ...                                      | 71                                     |
| 852.0                              | T5     | 220                          | 160                          | 5                         | 70                                 | 145                                   | 75                                       | 71                                     |
| Die casting                        |        |                              |                              |                           |                                    |                                       |                                          |                                        |
| 360.0                              | F      | 305                          | 170                          | 3                         | 75                                 | 195                                   | 140                                      | 71                                     |
| A360.0                             | F      | 315                          | 165                          | 4                         | 75                                 | 180                                   | 124                                      | 71                                     |
| 380.0                              | F      | 315                          | 160                          | 3                         | 80                                 | 195                                   | 140                                      | 71                                     |
| A380.0                             | F      | 325                          | 160                          | 4                         | 80                                 | 185                                   | 140                                      | 71                                     |
| 383.0                              | F      | 310                          | 150                          | 4                         | 75                                 | ...                                   | 145                                      | 71                                     |
| 384.0                              | F      | 330                          | 165                          | 3                         | 85                                 | 200                                   | 140                                      | ...                                    |
| 390.0                              | F      | 280                          | 240                          | <1                        | ...                                | ...                                   | ...                                      | ...                                    |
| B390.0                             | F      | 315                          | 250                          | <1                        | 120                                | ...                                   | 140                                      | 81                                     |
| 392.0                              | F      | 290                          | 270                          | <1                        | ...                                | ...                                   | ...                                      | ...                                    |
| 413.0                              | F      | 295                          | 145                          | 3                         | 80                                 | 170                                   | 130                                      | 71                                     |
| A413.0                             | F      | 290                          | 130                          | 4                         | 80                                 | 170                                   | 130                                      | ...                                    |
| C443.0                             | F      | 230                          | 95                           | 9                         | 65                                 | 200                                   | 115                                      | 71                                     |
| 518.0                              | F      | 310                          | 193                          | 5                         | 80                                 | 200                                   | 140                                      | ...                                    |

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 500,000,000 cycles of completely reversed stress using R.R. Moore type of machines and specimens. (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. Source: Ref 3-5

defined by statistical analysis, and every technique permitted by practicality and specification was used to improve conformance. Alloying impurities were reduced, soluble phase components were adjusted, heat treatment practices stretched to permissible limits, and there was unusual concentration on the metallurgical structure of critical casting areas corresponding to test specimen locations.

Aluminum rocker arm requirements include strength at modestly elevated temperatures, hardness, and cost. Alloy 333.0, developed at the same time as 319.0 as the preferred secondary general-purpose permanent mold composition, was selected for this application. Over several years, randomly selected parts were destructively tested to ensure that casting quality and properties were maintained. The power of casting process and solidification conditions was evident. Typical mechanical properties for 333.0-T6 are 42 ksi (290 MPa) tensile strength, 30 ksi (210 MPa) yield strength, and 2% elongation. What was consistently demonstrated was 60 ksi (420 MPa) tensile strength, 50 ksi (350 MPa) yield strength, and 5% elongation, easily exceeding specification requirements for all conventional high-strength alloys in use at that time and matching many wrought compositions in plate and forged form with the advantage of near-net-shape and anisotropic properties. The application of premium engineered casting practices even to conventional casting alloys provides significant rewards.

The magnitude of the improvement achievable utilizing premium quality practices may be seen by comparing the values in Tables 8.9 and 8.10 with those in Tables 8.6 to 8.8, where differences of 5 to 15 ksi (35 to 105 MPa) or more in tensile yield strength

and 3 to 4% in elongation are sometimes seen. Such differences are particularly significant when it is noted that the values for the premium quality castings are based on tests of specimens cut from the castings, whereas the published typical and minimum values for standard alloys are based on tests of separately cast tensile specimens.

**Squeeze Casting.** In recent years, broader use has been made of techniques for applying pressure to the metal while it is solidifying during the manufacture of castings. The most common and commercially most widely implemented technique is squeeze casting (see Chapter 3, Section 3.5.5).

The properties of representative castings produced by squeeze casting technology are presented in Table 8.11, as published in Ref 8 and 16, compared with the published typical properties of aluminum castings of the same alloys.

The strengths range from about the same as to about 5 ksi (35 MPa) above the typical properties for comparable sand and permanent mold castings, very significant considering that the values for the squeeze castings are based on tests of specimens cut from the castings themselves, whereas the typical values used in comparison are based on separately cast test bars. In addition, the elongations of the squeeze castings are, with only one exception, significantly higher than the published typical values.

In general, it appears that consistently better properties may be obtained by squeeze casting than by conventional casting technologies, in the absence of the application of premium casting technologies.

**Table 8.8 Minimum mechanical properties of aluminum alloy sand, permanent mold, and die castings**

Values are representative of separately cast test bars, not of specimens taken from commercial castings.

| Alloy        | Temper | Tension           |     |                   |     |                              | Compression       |     | Shear             |     | Ref      |
|--------------|--------|-------------------|-----|-------------------|-----|------------------------------|-------------------|-----|-------------------|-----|----------|
|              |        | Ultimate strength |     | Yield strength(a) |     | Elongation in 2 in. or 4D, % | yield strength(a) |     | ultimate strength |     |          |
|              |        | ksi               | MPa | ksi               | MPa |                              |                   | ksi | MPa               | ksi | MPa      |
| Sand casting |        |                   |     |                   |     |                              |                   |     |                   |     |          |
| 201.0        | T7     | 60.0              | 415 | 50.0              | 345 | 3.0                          | 51.0              | 350 | 36.0              | 250 | 6, 13(b) |
| 204.0        | T4     | 45.0              | 310 | 28.0              | 195 | 6.0                          | ...               | ... | ...               | ... | 6        |
| 208.0        | F      | 19.0              | 130 | 12.0              | 85  | 1.5                          | ...               | ... | ...               | ... | 6        |
| 222.0        | O      | 23.0              | 160 | ...               | ... | ...                          | ...               | ... | ...               | ... | 6        |
|              | T61    | 30.0              | 205 | ...               | ... | ...                          | ...               | ... | ...               | ... | 6        |
| 242.0        | O      | 23.0              | 160 | ...               | ... | ...                          | ...               | ... | ...               | ... | 6        |
|              | T571   | 29.0              | 200 | ...               | ... | ...                          | ...               | ... | ...               | ... | 6        |
|              | T61    | 32.0              | 220 | 20.0              | 140 | ...                          | ...               | ... | ...               | ... | 6        |
|              | T77    | 24.0              | 165 | 13.0              | 90  | 1.0                          | ...               | ... | ...               | ... | 6        |
| 295.0        | T4     | 29.0              | 200 | 13.0              | 90  | 6.0                          | ...               | ... | ...               | ... | 6        |
|              | T6     | 32.0              | 220 | 20.0              | 140 | 3.0                          | ...               | ... | ...               | ... | 6        |
|              | T62    | 36.0              | 250 | 28.0              | 195 | ...                          | ...               | ... | ...               | ... | 6        |
|              | T7     | 29.0              | 200 | 16.0              | 110 | 3.0                          | ...               | ... | ...               | ... | 6        |
| 319.0        | F      | 23.0              | 160 | 13.0              | 90  | 1.5                          | ...               | ... | ...               | ... | 6        |
|              | T5     | 25.0              | 170 | ...               | ... | ...                          | ...               | ... | ...               | ... | 6        |
|              | T6     | 31.0              | 215 | 20.0              | 140 | 1.5                          | ...               | ... | ...               | ... | 6        |
| 328.0        | F      | 25.0              | 170 | 14.0              | 95  | 1.0                          | ...               | ... | ...               | ... | 6        |
|              | T6     | 34.0              | 235 | 21.0              | 145 | 1.0                          | ...               | ... | ...               | ... | 6        |
| 354.0        | T6     | 47.0              | 325 | 36.0              | 250 | 3.0                          | 36.0              | 250 | 29.0              | 200 | 13(b)    |
| 355.0        | T51    | 25.0              | 170 | 18.0              | 125 | ...                          | ...               | ... | ...               | ... | 6        |
|              | T6     | 32.0              | 220 | 20.0              | 140 | 2.0                          | ...               | ... | ...               | ... | 6        |
|              | T7     | 35.0              | 240 | ...               | ... | ...                          | ...               | ... | ...               | ... | 6        |
|              | T71    | 30.0              | 205 | 22.0              | 150 | ...                          | ...               | ... | ...               | ... | 6        |
| C355.0       | T6     | 41.0              | 285 | 31.0              | 215 | 3.0                          | 31.0              | 215 | 31.0              | 215 | 13(b)    |
|              | T6     | 36.0              | 250 | 25.0              | 170 | 2.5                          | ...               | ... | ...               | ... | 6        |
| 356.0        | F      | 19.0              | 130 | ...               | ... | 2.0                          | ...               | ... | ...               | ... | 6        |
|              | T51    | 23.0              | 160 | 16.0              | 110 | ...                          | ...               | ... | ...               | ... | 6        |
|              | T6     | 22.0              | 150 | 15.0              | 105 | 0.7                          | 15.0              | 105 | 15.0              | 105 | 13(b)    |
|              | T6     | 30.0              | 205 | 20.0              | 140 | 3.0                          | ...               | ... | ...               | ... | 6        |
|              | T7     | 31.0              | 215 | 29.0              | 200 | ...                          | ...               | ... | ...               | ... | 6        |
|              | T71    | 25.0              | 170 | 18.0              | 125 | 3.0                          | ...               | ... | ...               | ... | 6        |
| A356.0       | T6     | 34.0              | 235 | 24.0              | 165 | 3.5                          | ...               | ... | ...               | ... | 6        |
|              | T6     | 38.0              | 260 | 28.0              | 195 | 5.0                          | 28.0              | 195 | 28.0              | 195 | 13(b)    |
| 357.0        | T6     | 45.0              | 310 | 35.0              | 240 | 3.0                          | 35.0              | 240 | 28.0              | 195 | 13(b)    |
| 359.0        | T6     | 45.0              | 310 | 35.0              | 240 | 4.0                          | 35.0              | 240 | 28.0              | 195 | 13(b)    |
| 443.0        | F      | 17.0              | 115 | 7.0               | 50  | 3.0                          | ...               | ... | ...               | ... | 6        |
| B443.0       | F      | 17.0              | 115 | 6.0               | 40  | 3.0                          | ...               | ... | ...               | ... | 6        |
| 512.0        | F      | 17.0              | 115 | 10.0              | 70  | ...                          | ...               | ... | ...               | ... | 6        |
| 514.0        | F      | 22.0              | 150 | 9.0               | 60  | 6.0                          | ...               | ... | ...               | ... | 6        |
| 520.0        | T4     | 42.0              | 290 | 22.0              | 150 | 12.0                         | ...               | ... | ...               | ... |          |
| 535.0        | T      | 35.0              | 240 | 18.0              | 125 | 9.0                          | ...               | ... | ...               | ... | 3        |
|              | T5     | 35.0              | 240 | 18.0              | 125 | 9.0                          | ...               | ... | ...               | ... | 3        |
| 707.0        | T5     | 33.0              | 230 | 22.0              | 150 | 2.0                          | ...               | ... | ...               | ... | 3        |
|              | T7     | 37.0              | 255 | 30.0              | 205 | 1.0                          | ...               | ... | ...               | ... | 3        |
| 710.0        | F      | 32.0              | 220 | 20.0              | 140 | 2.0                          | ...               | ... | ...               | ... | 3        |
|              | T5     | 32.0              | 220 | 20.0              | 140 | 2.0                          | ...               | ... | ...               | ... | 3        |
| 712.0        | F      | 34.0              | 235 | 25.0              | 170 | 4.0                          | ...               | ... | ...               | ... | 3        |
|              | T5     | 34.0              | 235 | 25.0              | 170 | 4.0                          | ...               | ... | ...               | ... | 3        |
| 713.0        | F      | 32.0              | 220 | 22.0              | 150 | 3.0                          | ...               | ... | ...               | ... | 3        |
|              | T5     | 32.0              | 220 | 22.0              | 150 | 3.0                          | ...               | ... | ...               | ... | 3        |

(continued)

(a) For tensile compressive yield strengths, offset = 0.2%. (b) Values for class 1 only

Table 8.8 (continued)

| Alloy                    | Temper | Tension              |     |                      |       | Elongation<br>in 2 in. or 4D,<br>% | Compression<br>yield<br>strength(a) |     | Shear<br>ultimate<br>strength |     | Ref      |
|--------------------------|--------|----------------------|-----|----------------------|-------|------------------------------------|-------------------------------------|-----|-------------------------------|-----|----------|
|                          |        | Ultimate<br>strength |     | Yield<br>strength(a) |       |                                    | ksi                                 | MPa | ksi                           | MPa |          |
|                          |        | ksi                  | MPa | ksi                  | MPa   |                                    |                                     |     |                               |     |          |
| Sand casting (continued) |        |                      |     |                      |       |                                    |                                     |     |                               |     |          |
| 771.0                    | T5     | 42.0                 | 290 | 38.0                 | 260   | 1.5                                | ...                                 | ... | ...                           | ... | 3        |
|                          | T51    | 32.0                 | 220 | 27.0                 | 185   | 3.0                                | ...                                 | ... | ...                           | ... | 3        |
|                          | T52    | 36.0                 | 250 | 30.0                 | 205   | 1.5                                | ...                                 | ... | ...                           | ... | 3        |
|                          | T53    | 36.0                 | 250 | 27.0                 | 185   | 1.5                                | ...                                 | ... | ...                           | ... | 3        |
|                          | T6     | 42.0                 | 290 | 35.0                 | 240   | 5.0                                | ...                                 | ... | ...                           | ... | 3        |
|                          | T71    | 48.0                 | 330 | 45.0                 | 310   | 2.0                                | ...                                 | ... | ...                           | ... | 6        |
| 850.0                    | T5     | 16.0                 | 110 | ...                  | ...   | 5.0                                | ...                                 | ... | ...                           | ... | 6        |
| 851.0                    | T5     | 17.0                 | 115 | ...                  | ...   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
| 852.0                    | T5     | 24.0                 | 165 | 18.0                 | 125   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| Permanent mold casting   |        |                      |     |                      |       |                                    |                                     |     |                               |     |          |
| 201.0                    | T7     | 60.0                 | 415 | 50.0                 | 345   | 3.0                                | 51.0                                | 350 | 36.0                          | 250 | 6        |
| 204.0                    | T4     | 48.0                 | 330 | 29.0                 | 200   | 8.0                                | ...                                 | ... | ...                           | ... | 6        |
| 208.0                    | T4     | 33.0                 | 230 | 15.0                 | 105   | 4.5                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T6     | 35.0                 | 240 | 22.0                 | 150   | 2.0                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T7     | 33.0                 | 230 | 16.0                 | 110   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
| 22.0                     | T551   | 30.0                 | 205 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T65    | 40.0                 | 275 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| 242.0                    | T571   | 34.0                 | 235 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T61    | 40.0                 | 275 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| 296.0                    | T7     | 35.0                 | 240 | ...                  | ...   | 2.0                                | ...                                 | ... | ...                           | ... | 6        |
| 308.0                    | F      | 24.0                 | 165 | ...                  | ...   | 2.0                                | ...                                 | ... | ...                           | ... | 6        |
| 319.0                    | F      | 28.0                 | 195 | 14.0                 | 95    | 1.5                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T6     | 34.0                 | 235 | ...                  | ...   | 2.0                                | ...                                 | ... | ...                           | ... | 6        |
| 332.0                    | T5     | 31.0                 | 215 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| 333.0                    | F      | 28.0                 | 195 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T5     | 30.0                 | 205 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T6     | 35.0                 | 240 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T7     | 31.0                 | 215 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| 336.0                    | T551   | 31.0                 | 215 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T65    | 40.0                 | 275 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| 354.0                    | T6     | 47.0                 | 325 | 36.0                 | 250   | 3.0                                | 36.0                                | 250 | 29.0                          | 200 | 13(b)    |
|                          | T61    | 48.0                 | 330 | 37.0                 | 255   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T62    | 52.0                 | 360 | 42.0                 | 290   | 2.0                                | ...                                 | ... | ...                           | ... | 6        |
| 355.0                    | T51    | 27.0                 | 185 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T6     | 27.0                 | 185 | 17.0                 | 115.0 | 0.4                                | 17.0                                | 115 | 17.0                          | 115 | 13(b)    |
|                          | T6     | 37.0                 | 255 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T62    | 42.0                 | 290 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T7     | 36.0                 | 250 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T71    | 34.0                 | 235 | 27.0                 | 185   | ...                                | ...                                 | ... | ...                           | ... | 6        |
| C355.0                   | T6     | 41.0                 | 285 | 31.0                 | 215.0 | 3.0                                | 31.0                                | 215 | 31.0                          | 215 | 13(b)    |
|                          | T61    | 40.0                 | 275 | 30.0                 | 205   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T62    |                      |     |                      |       |                                    |                                     |     |                               |     |          |
| 356.0                    | F      | 21.0                 | 145 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T51    | 25.0                 | 170 | ...                  | ...   | ...                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T6     | 25.0                 | 170 | 16.0                 | 110.0 | 0.7                                | 16.0                                | 110 | 16.0                          | 110 | 13(b)    |
|                          | T6     | 33.0                 | 230 | ...                  | ...   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T7     | 25.0                 | 170 | ...                  | ...   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
|                          | T71    | 25.0                 | 170 | ...                  | ...   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |
| A356.0                   | F      |                      |     |                      |       |                                    |                                     |     |                               |     |          |
|                          | T51    |                      |     |                      |       |                                    |                                     |     |                               |     |          |
|                          | T6     | 38.0                 | 260 | 28.0                 | 195   | 5.0                                | 28.0                                | 195 | 28.0                          | 195 | 13(b)    |
|                          | T61    | 37.0                 | 255 | 26.0                 | 180   | 5.0                                | ...                                 | ... | ...                           | ... | 6        |
| 357.0                    | T6     | 45.0                 | 310 | 35.0                 | 240   | 3.0                                | 35.0                                | 240 | 28.0                          | 195 | 6, 13(b) |
| A357.0                   | T61    | 45.0                 | 310 | 36.0                 | 250   | 3.0                                | ...                                 | ... | ...                           | ... | 6        |

(continued)

(a) For tensile compressive yield strengths, offset = 0.2%. (b) Values for class 1 only

Table 8.8 (continued)

| Alloy                              | Temper | Tension           |     |                   |     |                                       | Compression       |                   | Shear |     | Ref   |
|------------------------------------|--------|-------------------|-----|-------------------|-----|---------------------------------------|-------------------|-------------------|-------|-----|-------|
|                                    |        | Ultimate strength |     | Yield strength(a) |     | Elongation in 2 in. or 4 <i>D</i> , % | yield strength(a) | ultimate strength |       |     |       |
|                                    |        | ksi               | MPa | ksi               | MPa |                                       |                   | ksi               | MPa   |     |       |
| Permanent mold casting (continued) |        |                   |     |                   |     |                                       |                   |                   |       |     |       |
| D357.0                             | T6     | 46.0              | 315 | 39.0              | 270 | 3.0                                   | 39.0              | 270               | 29.0  | 200 | 13(b) |
| 359.0                              | T6     | 45.0              | 310 | 35.0              | 240 | 4                                     | 35.0              | 240               | 28.0  | 195 | 13(b) |
|                                    | T61    | 45.0              | 310 | 34.0              | 235 | 4.0                                   | ...               | ...               | ...   | ... | 6     |
|                                    | T62    | 47.0              | 325 | 38.0              | 260 | 3.0                                   | ...               | ...               | ...   | ... | 6     |
| 443.0                              | F      | 21.0              | 145 | 7.0               | 50  | 2.0                                   | ...               | ...               | ...   | ... | 6     |
| B443.0                             | F      | 21.0              | 145 | 6.0               | 40  | 2.5                                   | ...               | ...               | ...   | ... | 6     |
| A444.0                             | T4     | 20.0              | 140 | ...               | ... | 20.0                                  | ...               | ...               | ...   | ... | 6     |
| 513.0                              | F      | 22.0              | 150 | 12.0              | 85  | 2.5                                   | ...               | ...               | ...   | ... | 6     |
| 535.0                              | F      | 35.0              | 240 | 18.0              | 125 | 8.0                                   | ...               | ...               | ...   | ... | 6     |
| 705.0                              | T5     | 37.0              | 255 | 17.0              | 120 | 10.0                                  | ...               | ...               | ...   | ... | 6     |
| 707.0                              | T7     | 45.0              | 310 | 35.0              | 240 | 3.0                                   | ...               | ...               | ...   | ... | 6     |
| 711.0                              | T1     | 28.0              | 195 | 18.0              | 125 | 7.0                                   | ...               | ...               | ...   | ... | 6     |
| 713.0                              | T5     | 32.0              | 220 | 22.0              | 150 | 4.0                                   | ...               | ...               | ...   | ... | 6     |
| 850.0                              | T5     | 18.0              | 125 | ...               | ... | 8.0                                   | ...               | ...               | ...   | ... | 6     |
| 851.0                              | T5     | 17.0              | 115 | ...               | ... | 3.0                                   | ...               | ...               | ...   | ... | 6     |
|                                    | T6     | 18.0              | 125 | ...               | ... | 8.0                                   | ...               | ...               | ...   | ... | 6     |
| 852.0                              | T5     | 27.0              | 185 | ...               | ... | 3.0                                   | ...               | ...               | ...   | ... | 6     |
| Die casting                        |        |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 360.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| A360.0                             | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 380.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| A380.0                             | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 383.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 384.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 390.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| B390.0                             | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 392.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 413.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| A413.0                             | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| C443.0                             | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |
| 518.0                              | F      |                   |     |                   |     |                                       |                   |                   |       |     |       |

(a) For tensile compressive yield strengths, offset = 0.2%. (b) Values for class 1 only

**Semisolid casting** also holds promise for providing higher-quality aluminum alloy castings, though it has as yet been less widely implemented successfully. The properties of some representative semisolid casting are presented in Table 8.12, again with published typical values for sand and permanent mold castings.

As for squeeze castings, the strengths of the semisolid castings range from about the same as to about 5 ksi (35 MPa) above the typical properties for comparable sand and permanent mold castings. Also, as in the case for squeeze castings, this is significant considering that the values for the semisolid castings are based on tests of specimens cut from the castings themselves, whereas the

typical values used in comparison are based on separately cast test bars. The elongations of the semisolid castings are superior to the typical values for sand castings and are about the same as those for permanent mold castings.

It appears that with careful engineering of the process, some gains are possible with semisolid casting if the process can be successfully implemented on a broader scale.

**High-Integrity Die Casting.** The application of vacuum and other technologies to die casting has resulted in superior strengths and substantially higher elongations especially when combined with process features described in Chapter 3, Section 3.6.2. Figure

**Table 8.9 Typical mechanical properties of premium engineered aluminum castings**

Typical values of premium engineered casting are the same regardless of class or the area from which the specimen is cut; see Table 8.10 for minimum values.

| Alloy  | Temper | Tension           |     |                |     |                                      | Fatigue endurance limit(a) |        |
|--------|--------|-------------------|-----|----------------|-----|--------------------------------------|----------------------------|--------|
|        |        | Ultimate strength |     | Yield strength |     | Elongation<br>in 50 mm (2 in.),<br>% | ksi                        | MPa    |
|        |        | ksi               | MPa | ksi            | MPa |                                      |                            |        |
| A201.0 | T7     | 72                | 495 | 65             | 448 | 6                                    | 14                         | 97     |
| A206.0 | T7     | 65                | 445 | 59             | 405 | 6                                    | 13                         | 90     |
| 224.0  | T7     | 61                | 420 | 48             | 330 | 4                                    | 12.5                       | 86     |
| 249.0  | T7     | 68                | 470 | 59             | 407 | 6                                    | 11                         | 75     |
| 354.0  | T6     | 55                | 380 | 41             | 283 | 6                                    | 19.5(b)                    | 135(b) |
| C355.0 | T6     | 46                | 317 | 34             | 235 | 6                                    | 14                         | 97     |
| A356.0 | T6     | 41                | 283 | 30             | 207 | 10                                   | 13                         | 90     |
| A357.0 | T6     | 52                | 360 | 42             | 290 | 8                                    | 13                         | 90     |

(a) Rotating beam reversed bending ( $R = -1.0$ ) tests; endurance limit at  $5 \times 10^8$  cycles. (b) Fatigue strength for  $10^6$  cycles. Source: Ref 8

8.2 (Ref 17) illustrates the properties obtained in European applications of this technology; specific heat treatment conditions were not cited but are assumed to comprise lower solution heat treatment temperature than that of the true T6 temper.

According to Altenpohl (Ref 17), the pressure in the casting chamber must be less than 50 millibars (5 kPa) to ensure the success of the vacuum casting technique, and by its application components previously made by other casting processes, forging, and impact extrusion have been replaced.

**USCAR.** In the period from 1999 to 2001, a number of automotive components were produced and evaluated by USCAR (Ref 18) to determine the statistical levels of strength achievable with several carefully controlled casting processes, including in some cases vacuum casting and squeeze casting. In all of the USCAR activity, the test results were based on specimens cut from specific locations in actual full-size castings. A summary of the tensile properties of the castings from that study are presented in Table 8.13.

While individual castings developed interesting properties in this study, none of the practices employed consistently provided prop-

erties above the ranges of typical and minimum values for comparable sand and permanent mold castings. The principal value of the study appears to have been that the published values based on cast test bars are pretty representative of what may be expected in closely controlled high-quality commercial production, provided consistent casting practices and quality control are exercised; in such cases, it appears that the use of the reduced strength guideline (75%) may not be necessary.

## 8.4 Fatigue Properties of Aluminum Casting Alloys

Rotating beam reversed-bending fatigue data, at a stress ratio of  $-1.0$ , have long been a standard in aluminum industry publications, and extensive files of such data are available for aluminum casting alloys as presented herein. It is appropriate to recognize that such data are simply one of many indices of fatigue strength, and for specific applications, engineers may wish to consult data for other stress ratios such as 0.0,  $+0.1$ , and/or  $+0.5$ .

The fatigue properties of a rather wide range of sand and permanent mold castings (specimens per Appendix 3, Fig. A3.2) at room temperature are summarized in Table 8.14 (Ref 15).

Actual rotating beam ( $R = -1.0$ ) fatigue curves for representative lots of castings at room temperature are shown in Data Set 6, in these cases often including both smooth and notched specimens of the types in Appendix 3, Fig. A3.2. In most cases, the specimens were as-cast test bars, tested with the as-cast surface in place; in a few cases, the tests were made with specimens machined from cast parts, such as pistons. A summary of the rotating-beam fatigue strengths from these tests of individual castings (as contrasted to the "typical" values in Table 8.14) is presented in Table 8.15. Most of these individual test results are compatible with the typical values in Table 8.14.

The fatigue strengths of a number of these alloys from similar tests at elevated temperatures are presented in Table 8.16.

A close review of the data in Tables 8.14 to 8.16 indicates to the authors that these data, though developed in accordance to good engineering laboratory standards, should be used very carefully, and the differences from alloy to alloy or among tempers of a

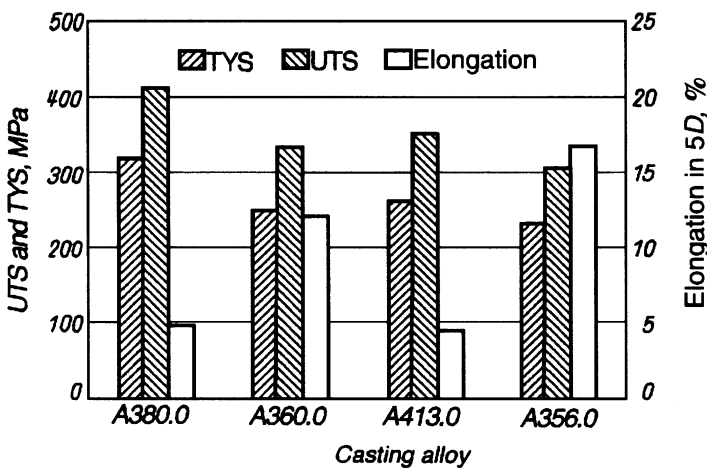


**Fig. 8.2** Average tensile properties of representative aluminum alloy castings produced by vacuum technology. UTS, ultimate tensile strength; TYS, tensile yield strength. Source: Ref 17





**Table 8.11 Tensile properties of representative squeeze-cast aluminum alloy castings**

Values are averages for an unspecified number of tests of specimens taken from commercial castings.

| Alloy  | Temper | Casting process         | Ultimate strength |     | Yield strength(a) |     | Elongation in 2 in. or 4D,<br>% | Ref |
|--------|--------|-------------------------|-------------------|-----|-------------------|-----|---------------------------------|-----|
|        |        |                         | ksi               | MPa | ksi               | MPa |                                 |     |
| A206   | T4     | Squeeze (1)             | 59.5              | 410 | 37.5              | 258 | 23.5                            | 16  |
|        |        | Squeeze (2)             | 56.5              | 390 | 34.2              | 236 | 24.0                            | 8   |
|        | T4     | Typical, sand cast      | 55                | 379 | 36                | 248 | 6.0                             | 4   |
|        | T4     | Typical, permanent mold | 62                | 428 | 38                | 262 | 17.0                            | 4   |
| 356.0  | T6     | Squeeze cast            | 44.8              | 309 | 38.5              | 265 | 3.0                             | 8   |
|        | T6     | Squeeze cast (quenched) | 46.0              | 371 | 33.6              | 232 | 11.9                            | 16  |
|        | T6     | Typical, sand cast      | 33                | 228 | 24                | 166 | 3.5                             | 4   |
|        | T6     | Typical, permanent mold | 38                | 262 | 27                | 186 | 5.0                             | 4   |
|        | T61    | Squeeze cast            | 46.0              | 371 | 33.6              | 232 | 11.9                            | 8   |
| A356.0 | T4     | Squeeze cast            | 38.4              | 265 | 25.9              | 179 | 20.0                            | 8   |
|        | T61    | Squeeze cast            | 43.5              | 300 | 35.8              | 247 | 6.6                             | 16  |
|        | T61    | Typical, permanent mold | 41.0              | 283 | 30.0              | 207 | 10.0                            | 4   |
| B356.0 | T61    | Squeeze cast            | 43.9              | 303 | 32.3              | 223 | 17.6                            | 16  |
| 357.0  | T6     | Squeeze cast            | 48.0              | 331 | 36.5              | 252 | 9.0                             | 16  |
|        | T6     | Typical, sand cast      | 50                | 345 | 43                | 297 | 2.0                             | 4   |
|        | T6     | Typical, permanent mold | 52                | 359 | 43                | 297 | 5.0                             | 4   |
| 535.0  | F      | Squeeze cast            | 45.2              | 312 | 22.1              | 152 | 34.2                            | 8   |
|        | F      | Typical, permanent mold | 40                | 280 | 20                | 140 | 13.0                            | 4   |

(a) For tensile yield strengths, offset = 0.2%.

given alloy should not necessarily be considered to consistently represent their performance in finished castings. The primary reason for this is the fact that many of the data are for cast test bars that were cast to finished specimen size, or with only polishing of the surface, and there is evidence that there are favorable residual stresses in the as-cast surface that may have misleadingly positive influence on the fatigue life and strength. Consider, for example, the data for one lot of 380.0-F cast test bars for which tests were made with as-die cast test bars and with 0.01 in. and 0.025 in. removed, shown in Data Set 6. The endurance limits for

specimens with the surface machined were lower, with the difference increasing with the greater amount of the surface machined, that is:

| Surface finish of fatigue specimen | Endurance limit |     |
|------------------------------------|-----------------|-----|
|                                    | ksi             | MPa |
| As cast                            | 21.0            | 145 |
| 0.01 in. (0.25 mm) removed         | 19.5            | 134 |
| 0.025 in. (0.64 mm) removed        | 17.5            | 121 |

**Table 8.12 Tensile properties of representative semisolid cast aluminum alloy castings**

Values are averages for an unspecified number of tests of specimens taken from commercial castings.

| Alloy  | Temper | Casting process         | Ultimate strength |     | Yield strength(a) |     | Elongation in 2 in. or 4D,<br>% | Ref |
|--------|--------|-------------------------|-------------------|-----|-------------------|-----|---------------------------------|-----|
|        |        |                         | ksi               | MPa | ksi               | MPa |                                 |     |
| 206.0  | T7     | Semisolid cast          | 56.0              | 317 | 46.0              | 317 | 6.0                             | 8   |
|        | T4     | Typical, sand cast      | 50                | 345 | 28                | 193 | 10.0                            | 4   |
|        | T7     | Typical, permanent mold | 63                | 435 | 50                | 345 | 11.7                            | 4   |
| 356.0  | T5     | Semisolid cast          | 34.0              | 234 | 25.0              | 172 | 11.0                            | 8   |
|        | T51    | Typical, sand cast      | 25                | 172 | 20                | 138 | 2.0                             | 4   |
|        | T6     | Semisolid cast          | 43.0              | 296 | 28.0              | 193 | 12.0                            | 8   |
|        | T6     | Typical, sand cast      | 33                | 228 | 24                | 164 | 3.5                             | 4   |
| A356.0 | T6     | Typical, semisolid      | 55                | 380 | 33                | 225 | 12.0                            | 16  |
|        |        | Typical, permanent mold | 41                | 280 | 30                | 205 | 10.0                            | 16  |
| 357.0  | T5     | Semisolid cast          | 43.0              | 296 | 30.0              | 207 | 11.0                            | 8   |
|        | T51    | Typical, sand cast      | 26                | 179 | 17                | 117 | 3.0                             | 4   |
|        | T6     | Semisolid cast          | 52.0              | 358 | 42.0              | 290 | 10.0                            | 8   |
|        | T6     | Typical, sand cast      | 50                | 345 | 43                | 296 | 2.0                             | 4   |
| A357.0 | T61    | Semisolid cast          | 45.9              | 316 | 35.3              | 243 | 8.4                             | 16  |
|        | T62    | Semisolid cast          | 43.5              | 300 | 35.3              | 243 | 6.6                             | 16  |
|        | T6     | Typical, sand cast      | 46                | 317 | 36                | 248 | 3.0                             | 4   |
|        | T6     | Typical, permanent mold | 50                | 345 | 40                | 276 | 10.0                            | 4   |

(a) For tensile yield strengths, offset = 0.2%.

**Table 8.13 Average and three-sigma minimum tensile properties of aluminum alloy castings from USCAR program**

Values are for specimens taken from commercial castings.

| Alloy                         | Temper | Type of casting   | Vehicle component | Average           |      |                   |                              | Three-sigma minimum  |                   |      |                |      |                              |                      |     |
|-------------------------------|--------|-------------------|-------------------|-------------------|------|-------------------|------------------------------|----------------------|-------------------|------|----------------|------|------------------------------|----------------------|-----|
|                               |        |                   |                   | Ultimate strength |      | Yield strength(a) | Elongation in 2 in. or 4D, % | Reduction of area, % | Ultimate strength |      | Yield strength |      | Elongation in 2 in. or 4D, % | Reduction of area, % |     |
|                               |        |                   |                   | ksi               | MPa  |                   |                              |                      | ksi               | MPa  | ksi            | MPa  |                              |                      |     |
| A356.0                        | T6     | Tilt mold pour(b) | Rear knuckle      | 47.6              | 328  | 36.5              | 252                          | 12.3                 | 16.7              | 45.5 | 314            | 33.3 | 230                          | 5.2                  | 8.1 |
|                               |        | Tilt mold pour(b) | Front cradle      | 41.8              | 288  | 32.1              | 221                          | 7.1                  | 9.3               | 38.7 | 267            | 29.8 | 206                          | 2.1                  | 2.5 |
|                               |        | Tilt mold pour(b) | Low control arm   | 43.5              | 300  | 29.7              | 205                          | 12.0                 | 13.3              | 39.6 | 273            | 27.5 | 190                          | 3.6                  | 4.7 |
|                               |        | Lost foam         | Transfer case     | 37.3              | 257  | 29.1              | 201                          | 6.0                  | 11.8              | 28.5 | 197            | 25.7 | 177                          | 0.0                  | 5.6 |
|                               |        | VRC/PRC           | Front knuckle     | 44.8              | 309  | 33.9              | 234                          | 10.7                 | 15.6              | 43.0 | 297            | 32.6 | 225                          | 6.5                  | 6.7 |
|                               |        | Squeeze cast      | Front knuckle     | 41.4              | 286  | 31.6              | 218                          | 9.5                  | 14.9              | 37.9 | 261            | 29.3 | 202                          | 1.8                  | 0.0 |
| Published typical and minimum |        |                   |                   |                   |      |                   |                              |                      |                   |      |                |      |                              |                      |     |
| A357.0                        | T6     | Semisolid         | Low control arm   | 40.0              | 275  | 30.0              | 205                          | 6.0                  | ...               | 38.0 | ...            | 28.0 | ...                          | 5.0                  | ... |
|                               |        |                   |                   | 48.8              | 337  | 40.5              | 279                          | 8.6                  | 10.5              | 45.6 | 315            | 37.8 | 261                          | 4.3                  | 5.3 |
| Published typical and minimum |        |                   |                   |                   |      |                   |                              |                      |                   |      |                |      |                              |                      |     |
| 365.0                         | T6     | AV die cast       | Body casting      | 52.0              | 43.0 | 43.0              | ...                          | 5.0                  | ...               | 45.0 | 310            | 36.0 | 250                          | 3.0                  | ... |
| A380.0                        | F      | HP die cast       | Trans. case       | 29.6              | 160  | 20.0              | 138                          | 19                   | ...               | 28.0 | 193            | 18.4 | 127                          | 14.0                 | ... |
|                               |        |                   |                   | 27.1              | 187  | 25.5              | 176                          | ...                  | ...               | 5.5  | 38             | 21.0 | 145                          | ...                  | ... |
|                               |        |                   |                   | 47.0              | 345  | 23.0              | 295                          | 4.0                  | ...               | ...  | ...            | ...  | ...                          | ...                  | ... |
| Published typical             |        |                   |                   |                   |      |                   |                              |                      |                   |      |                |      |                              |                      |     |

(a) For tensile yield strengths, offset = 0.2%. (b) Tilt mold pour process is a variation of permanent mold casting. Source: Ref 18

(a) For tensile yield strengths, offset = 0.2%. (b) Tilt mold pour process is a variation of permanent mold casting. Source: Ref 18

**Table 8.14 Typical rotating-beam fatigue strengths of aluminum alloy castings at room temperature**

Fatigue strengths determined from reversed-bending tests of 0.330 in. diam specimens in R.R. Moore rotating beam machines

| Alloy                  | Temper | Fatigue strength at life of |     |                        |     |                        |     |                        |     |                        |     | Endurance limit               |     |
|------------------------|--------|-----------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|-------------------------------|-----|
|                        |        | 10 <sup>4</sup> cycles      |     | 10 <sup>5</sup> cycles |     | 10 <sup>6</sup> cycles |     | 10 <sup>7</sup> cycles |     | 10 <sup>8</sup> cycles |     | at 5 × 10 <sup>8</sup> cycles |     |
|                        |        | ksi                         | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                           | MPa |
| Sand casting           |        |                             |     |                        |     |                        |     |                        |     |                        |     |                               |     |
| 204.0                  | T4     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| A206.0                 | T71    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 23.0                          | 159 |
| 208.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| 222.0                  | T2     | ...                         | ... | 14.5                   | 100 | 12.0                   | 83  | 10.5                   | 72  | 10.0                   | 69  | 9.5                           | 66  |
| 224.0                  | T7     | ...                         | ... | 27.0                   | 186 | 16.5                   | 114 | 12.5                   | 86  | 12.0                   | 83  | 12.0                          | 83  |
| A240.0                 | F      | ...                         | ... | 29.0                   | 200 | 23.0                   | 159 | 19.0                   | 131 | 18.0                   | 124 | 17.5                          | 121 |
| 242.0                  | O      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
|                        | T77    | ...                         | ... | 19.0                   | 131 | 14.0                   | 97  | 11.5                   | 79  | 10.5                   | 72  | 10.5                          | 72  |
|                        | T571   | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| 249.0                  | T7     | 47.0                        | 324 | 26.0                   | 179 | 14.5                   | 100 | 11.5                   | 79  | 11.0                   | 76  | 11.0                          | 76  |
| 295.0                  | T4     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 7.0                           | 48  |
|                        | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 7.5                           | 52  |
|                        | T62    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 308.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| 319.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
|                        | T5     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
|                        | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| 355.0                  | T51    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
|                        | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
|                        | T61    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
|                        | T7     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
|                        | T71    | ...                         | ... | 21.0                   | 145 | 15.0                   | 103 | 12.0                   | 83  | 11.0                   | 76  | 10.5                          | 72  |
|                        | T77    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
| A355.0                 | T51    | ...                         | ... | 15.5                   | 107 | 11.0                   | 76  | 9.5                    | 66  | 8.5                    | 59  | 8.0                           | 55  |
| C355.0                 | T6     | ...                         | ... | 28.0                   | 193 | 19.0                   | 131 | 16.0                   | 110 | 14.5                   | 100 | 14.0                          | 97  |
| 356.0                  | T51    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
|                        | T6     | 33.0                        | 228 | 24.5                   | 169 | 18.0                   | 124 | 14.5                   | 100 | 12.5                   | 86  | 12.0                          | 83  |
|                        | T7     | ...                         | ... | 21.0                   | 145 | 14.5                   | 100 | 10.5                   | 72  | 9.5                    | 66  | 9.5                           | 66  |
|                        | T71    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.5                           | 59  |
| 357.0                  | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
| A390.0                 | F, T5  | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
|                        | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 13.0                          | 90  |
| 443.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 511.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 514.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 7.0                           | 48  |
| 518.0                  | F      | 28.0                        | 193 | 20.0                   | 138 | 13.5                   | 93  | 10.5                   | 72  | 9.5                    | 66  | 9.0                           | 62  |
| 535.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
| B535.0                 | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
| 520.0                  | T4     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 710.0                  | F, T5  | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 713.0                  | F, T5  | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
| 850.0                  | T5     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 852.0                  | T5     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
| Permanent mold casting |        |                             |     |                        |     |                        |     |                        |     |                        |     |                               |     |
| 242.0                  | T571   | 34.0                        | 234 | 26.0                   | 179 | 20.0                   | 138 | 16.5                   | 114 | 15.5                   | 107 | 15.0                          | 103 |
|                        | T61    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.5                           | 66  |
| 296.0                  | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
| 308.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 13.0                          | 90  |
| 319.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 12.0                          | 83  |
|                        | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 12.0                          | 83  |
| 333.0                  | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 14.0                          | 97  |
|                        | T5     | ...                         | ... | 22.5                   | 155 | 18.0                   | 124 | 15.5                   | 107 | 14.5                   | 100 | 13.5                          | 93  |
|                        | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 15.0                          | 103 |
|                        | T7     | ...                         | ... | 24.0                   | 166 | 18.5                   | 128 | 15.5                   | 107 | 13.5                   | 93  | 12.5                          | 86  |
| 336.0                  | T551   | ...                         | ... | 21.0                   | 145 | 18.0                   | 124 | 16.0                   | 110 | 14.5                   | 100 | 13.5                          | 93  |
| 354.0                  | T6     | 50.0                        | 345 | 40.0                   | 276 | 31.0                   | 214 | 25.5                   | 176 | 21.0                   | 145 | 19.5                          | 134 |
|                        | T62    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 17.0                          | 117 |
| 355.0                  | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
|                        | T62    | ...                         | ... | 36.0                   | 248 | 29.0                   | 200 | 23.0                   | 159 | 18.0                   | 124 | 15.5                          | 107 |
|                        | T71    | ...                         | ... | 27.0                   | 186 | 21.0                   | 145 | 17.0                   | 117 | 14.5                   | 100 | 13.0                          | 90  |
| C355.0                 | T61    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 14.0                          | 97  |
| 356.0                  | T6     | 39.0                        | 269 | 31.0                   | 214 | 24.5                   | 169 | 19.5                   | 134 | 15.0                   | 103 | 13.0                          | 90  |
|                        | T7     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| A356.0                 | T6     | ...                         | ... | 29.0                   | 200 | 23.0                   | 159 | 17.0                   | 117 | 14.0                   | 97  | 13.0                          | 90  |
|                        | T61    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 13.0                          | 90  |
| 357.0                  | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 13.0                          | 90  |
| A357.0                 | T61    | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 15.0                          | 103 |

(continued)

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897.

English units measured to nearest 0.5 ksi; metric units rounded to nearest MPa. Source: Aluminum Association and Alcoa publications

Table 8.14 (continued)

| Alloy                              | Temper | Fatigue strength at life of |     |                        |     |                        |     |                        |     |                        |     | Endurance limit               |     |
|------------------------------------|--------|-----------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|-------------------------------|-----|
|                                    |        | 10 <sup>4</sup> cycles      |     | 10 <sup>5</sup> cycles |     | 10 <sup>6</sup> cycles |     | 10 <sup>7</sup> cycles |     | 10 <sup>8</sup> cycles |     | at 5 × 10 <sup>8</sup> cycles |     |
|                                    |        | ksi                         | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                           | MPa |
| Permanent mold casting (continued) |        |                             |     |                        |     |                        |     |                        |     |                        |     |                               |     |
| 359.0                              | T61    | 43.0                        | 297 | 34.0                   | 234 | 27.0                   | 186 | 21.5                   | 148 | 17.5                   | 121 | 16.5                          | 114 |
|                                    | T62    | ...                         | ... | 37.0                   | 255 | 28.0                   | 193 | 21.0                   | 145 | 17.0                   | 117 | 16.0                          | 110 |
| A390.0                             | T6     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 17.0                          | 117 |
|                                    | T7     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 15.0                          | 103 |
| B443.0                             | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 8.0                           | 55  |
| 513.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 10.0                          | 69  |
| 711.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| 713.0                              | T5     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
| 850.0                              | T5     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
| 851.0                              | T5     | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 9.0                           | 62  |
| 852.0                              | T5     |                             |     |                        |     |                        |     |                        |     |                        |     | 11.0                          | 76  |
| Die casting                        |        |                             |     |                        |     |                        |     |                        |     |                        |     |                               |     |
| 360.0                              | F      | ...                         | ... | 30.0                   | 207 | 25.0                   | 172 | 23.0                   | 159 | 21.0                   | 145 | 19.0                          | 131 |
| A360.0                             | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 18.0                          | 124 |
| 364.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 18.0                          | 124 |
| 380.0                              | F      | ...                         | ... | 28.0                   | 193 | 22.0                   | 152 | 20.5                   | 141 | 20.0                   | 138 | 20.0                          | 138 |
| A380.0                             | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 20.0                          | 138 |
| 384.0                              | F      | 39.0                        | 269 | 32.0                   | 221 | 26.0                   | 179 | 23.5                   | 162 | 22.0                   | 152 | 21.5                          | 148 |
| 390.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 11.0                          | 76  |
| B390.0                             | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 20.0                          | 138 |
| 413.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 19.0                          | 131 |
| A413.0                             | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 19.0                          | 131 |
| C443.0                             | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 16.0                          | 110 |
| 513.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 18.0                          | 124 |
| 515.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 19.0                          | 131 |
| 518.0                              | F      | ...                         | ... | ...                    | ... | ...                    | ... | ...                    | ... | ...                    | ... | 20.0                          | 138 |

Metric values of strength determined by multiplying strengths originally determined in English units by conversion facator of 6.897.

English units measured by nearest 0.5 ksi; metric units rounded to nearest MPa. Source: Aluminum Association and Alcoa publications

Other illustrations of such differences are found in Data Set 6, in which the fatigue results for permanent mold cast 242.0-T571 and for sand cast 355.0-T7 and -T71, for which tests were made of both as-cast test bars and of specimens taken from actual castings. In both cases, as illustrated in the table that follows, the fatigue endurance limits were significantly lower for specimens machined from the castings than for the as-cast test bars:

| Alloy and temper | Fatigue specimens            | Endurance limit |     |
|------------------|------------------------------|-----------------|-----|
|                  |                              | ksi             | MPa |
| 242.0-T571       | As-cast test bars            | 15.0            | 103 |
|                  | Machined from cast pistons   | 9.5             | 66  |
| C355.0-T7, -T71  | As-cast test bars            | 10.5            | 72  |
|                  | Machined from cast crankcase | 5.5             | 38  |

In these cases, it should be noted that the as-cast test bars and the cast parts used for each alloy were totally different lots, and so the comparisons are not perfect; however, the differences seem to support indications that there is a positive influence on fatigue life of having cast-to-shape fatigue specimens.

This, of course, also may suggest that for cast parts where the surfaces are in highly stressed regions, the design of the casting may favor having the as-cast surface intact, with the resultant positive residual stresses working in favor of improved performance. In any such considerations, care should be taken to provide for a smooth, stress-raiser-free finished surface on the as-cast part.

Ignoring such influences, for the moment, of the alloys and tempers for which data are available, those exhibiting the highest

fatigue strengths include sand cast A206.0-T71 and A240.0-F, permanent mold cast 354.0-T6, 359.0-T6, and A390.0-T6. Among the die cast alloys, there was less overall variability, but 384.0-F exhibited the highest strengths. The role of positive residual stress patterns in promoting these specific alloys is unknown, but it might be noted that all of the specimens for the die castings had as-cast surfaces, perhaps accounting for their apparently overall higher fatigue strengths. Overall, it is fair to say that with a few exceptions there is not a great amount of variability in endurance limits among the alloys, for either smooth or notched specimens.

At elevated temperatures, as at room temperature, there are not very great differences among the endurance limits of the various alloys.

It should be emphasized that all of the values in Tables 8.14 and Table 8.16 are based on tests of small specimens machined from castings, including in many (regrettably unidentified) cases, cast test bars. These values may not be representative of the performance of specific cast components. More detail on the variations that may be observed is illustrated in the following sections.

#### 8.4.1 Influence of Casting Quality on Fatigue Strength

Several studies have been reported indicating the influence of casting process and microstructure on fatigue strength.

Data from Juvinall (Ref 20), reproduced in Fig. 8.3, illustrate that in general the fatigue strengths of aluminum castings are not as high as those of wrought aluminum products (i.e., components made from plate, forgings, or extrusions). Further, indications from this



**Table 8.15 Summary of reversed-bending fatigue curves for representative lots of aluminum alloy castings**Stress ratio,  $R = -1.0$ 

| Alloy                  | Temper  | Cast part(a) | Lot ID         | Type of specimens(b) |         | Endurance limit(c), ksi |      |         |     |     |
|------------------------|---------|--------------|----------------|----------------------|---------|-------------------------|------|---------|-----|-----|
|                        |         |              |                | Smooth               | Notched | Smooth                  |      | Notched |     |     |
|                        |         |              |                |                      |         | ksi                     | MPa  | ksi     | MPa |     |
| Plaster mold casting   |         |              |                |                      |         |                         |      |         |     |     |
| 255.0                  | T62     | CTB          | D1699          | X                    | X       | 15.0                    | 103  | 7.5     | 52  |     |
| C355.0                 | T62     | CTB          | D1701          | X                    | X       | 15.0                    | 103  | 7.5     | 52  |     |
| 356.0                  | T6      | CTB          | D223A,B        | X                    | X       | 12.0                    | 83   | 8.0     | 55  |     |
| A356.0                 | T61     | CTB          | D1702          | X                    | X       | 13.0                    | 90   | 7.5     | 52  |     |
|                        | T61     | CTB          | D1703          | X                    | X       | 12.0                    | 83   | 7.0     | 48  |     |
|                        | T61     | Casting      | 206548         | X                    | X       | 8.0                     | 55   | 8.0     | 55  |     |
|                        | T61 PEC | Casting      | 206547         | X                    | X       | 11.0                    | 76   | 7.5     | 52  |     |
|                        | T62     | Casting      | 175138         | X                    | ...     | 13.0                    | 90   | ...     | ... |     |
| Sand casting           |         |              |                |                      |         |                         |      |         |     |     |
| 213.0                  | F       | CTB          | C6611          | X                    | X       | 10.0                    | 69   | 7.5     | 52  |     |
| 224.0                  | T62     | CTB          | E8419C         | X                    | X       | 12.5                    | 86   | 7.5     | 52  |     |
| 240.0                  | F       | CTB          | D23,D403       | X                    | ...     | 18.0                    | 124  | ...     | ... |     |
| 242.0                  | F       | CTB          | D424           | X                    | ...     | 13.0                    | 90   | ...     | ... |     |
|                        |         | CTB          | D2551          | X                    | X       | 17.0                    | 117  | 7.5     | 52  |     |
|                        |         | CTB          | C7043F         | X                    | X       | 10.0                    | 69   | 8.0     | 55  |     |
|                        |         | CTB          | C7043A         | X                    | X       | 12.0                    | 83   | 9.0     | 62  |     |
|                        |         | CTB          | L2567          | X                    | X       | 9.0                     | 62   | 5.5     | 38  |     |
|                        |         | CTB          | C5107          | X                    | X       | 11.5                    | 79   | 7.5     | 52  |     |
|                        |         | CTB          | L2579          | X                    | ...     | 9.5                     | 66   | ...     | ... |     |
|                        |         | CTB          | C6765B         | X                    | X       | 10.0                    | 69   | 7.0     | 48  |     |
| 249.0                  | T63     | CTB          | E8083D,E8115   | X                    | X       | 9.5                     | 66   | 6.0     | 41  |     |
| 295.0                  | T6      | CTB          | C3508          | X                    | ...     | 7.0                     | 48   | ...     | ... |     |
|                        |         | CTB          | Unknown        | X                    | ...     | 7.5                     | 52   | ...     | ... |     |
|                        |         | CTB          | L1585          | X                    | ...     | 7.0                     | 48   | ...     | ... |     |
|                        |         | CTB          | Unknown        | X                    | ...     | 7.0                     | 48   | ...     | ... |     |
|                        |         | CTB          | L1670          | ...                  | X       | ...                     | ...  | 5.0     | 34  |     |
|                        |         | CTB          | 117105         | X                    | X       | 11.5                    | 79   | 7.0     | 48  |     |
| 308.0                  | F       | CTB          | C6884E         | X                    | X       | 12.0                    | 83   | 9.0     | 62  |     |
| 319.0                  | T5      | CTB          | C6884T         | X                    | X       | 11.0                    | 76   | 8.0     | 55  |     |
|                        | T6      | CTB          | C6884K         | X                    | X       | 12.5                    | 86   | 10.0    | 69  |     |
|                        | T71     | CTB          | C6884L         | X                    | X       | 10.5                    | 72   | 8.0     | 55  |     |
|                        | T51     | CTB          | C6285M         | X                    | X       | 10.0                    | 69   | 6.0     | 41  |     |
|                        | T6      | CTB          | 5 lots         | X                    | ...     | 10.0                    | 69   | ...     | ... |     |
|                        |         |              | CTB            | 5 lots               | ...     | X                       | ...  | ...     | 9.0 | 62  |
|                        |         |              | CTB            | C3509-T61            | X       | X                       | 9.5  | 66      | 7.5 | 52  |
|                        |         |              | CTB            | C6285K               | X       | X                       | 10.5 | 72      | 7.0 | 48  |
|                        |         |              | CTB            | C6285L               | X       | X                       | 11.5 | 79      | 7.5 | 52  |
|                        |         |              | CTB            | Unknown              | X       | X                       | 10.5 | 72      | 7.0 | 48  |
|                        | A355.0  |              | Cast crankcase | 175472               | X       | ...                     | 5.5  | 38      | ... | ... |
| CTB                    |         |              | L758           | X                    | ...     | 8.5                     | 59   | ...     | ... |     |
| CTB                    |         |              | L759           | X                    | ...     | 8.5                     | 59   | ...     | ... |     |
| CTB                    |         |              | P255A          | X                    | ...     | 7.5                     | 52   | ...     | ... |     |
| B355.0                 | T6      | CTB          | L3032          | X                    | ...     | 8.5                     | 59   | ...     | ... |     |
| 356.0                  | T51     | CTB          | L3032          | ...                  | X       | ...                     | ...  | 8.5     | 59  |     |
|                        |         | CTB          | C6385D         | X                    | X       | 9.0                     | 62   | 6.5     | 45  |     |
|                        |         | CTB          | L757           | X                    | ...     | 6.5                     | 45   | ...     | ... |     |
|                        |         | CTB          | L1661          | ...                  | X       | ...                     | ...  | 6.0     | 41  |     |
|                        |         | CTB          | L1704          | X                    | ...     | 7.5                     | 52   | ...     | ... |     |
|                        |         | CTB          | C6385K         | X                    | X       | 12.0                    | 83   | 9.0     | 62  |     |
|                        |         | CTB          | C3510          | X                    | ...     | 8.5                     | 59   | ...     | ... |     |
|                        |         | CTB          | C3510          | ...                  | X       | ...                     | ...  | 6.0     | 41  |     |
|                        |         | CTB          | C3510,C6385L   | X                    | ...     | 8.0                     | 55   | ...     | ... |     |
|                        |         | CTB          | C3510,C6385L   | ...                  | X       | ...                     | ...  | 7.0     | 48  |     |
| B443                   | F       | CTB          | 117104         | X                    | X       | 8.5                     | 59   | 6.0     | 41  |     |
| 712.0                  | F       | CTB          | C8455          | X                    | X       | 9.5                     | 66   | 7.0     | 48  |     |
| A712.0                 | F       | CTB          | C8533          | X                    | X       | 10.5                    | 72   | 7.0     | 48  |     |
|                        |         | CTB          | C9004H         | X                    | X       | 7.5                     | 52   | 6.0     | 41  |     |
| 852.0                  | T5      | CTB          | C8454          | X                    | X       | 9.5                     | 66   | 6.0     | 41  |     |
| Permanent mold casting |         |              |                |                      |         |                         |      |         |     |     |
| 213.0                  | F       | CTB          | D665           | X                    | X       | 17.0                    | 117  | 7.5     | 52  |     |
| 242.0                  | T571    | CTB          | L1652          | X                    | X       | 9.5                     | 66   | 7.0     | 48  |     |
|                        |         | CTB          | C6156          | X                    | X       | 15.0                    | 103  | 7.5     | 52  |     |
|                        |         | CTB          | C9609D         | X                    | X       | 15.5                    | 107  | 9.0     | 62  |     |
|                        |         | Pistons      | 301974         | X                    | ...     | 9.5                     | 66   | ...     | ... |     |
|                        |         | VRC pistons  | 317189         | X                    | ...     | 10.0                    | 69   | ...     | ... |     |
|                        |         | CTB          | C6156          | X                    | X       | 15.0                    | 103  | 7.5     | 52  |     |

(continued)

(a) CTB, cast test bars; casting, undefined cast part other than CTB; specific part given if stated on data sheet. (b) Specimens shown in Appendix 3, Fig. A3.2(b) for notched specimen, notch-tip radius  $\leq 0.001$  in;  $K_t \geq 12$ . (c) Endurance limit at 500 million cycles. Source: Ref 19

Table 8.15 (continued)

| Alloy                              | Temper  | Cast part(a)      | Lot ID | Type of specimens(b) |     | Endurance limit(c), ksi |       |         |     |
|------------------------------------|---------|-------------------|--------|----------------------|-----|-------------------------|-------|---------|-----|
|                                    |         |                   |        |                      |     | Smooth                  |       | Notched |     |
|                                    |         |                   |        | ksi                  | MPa | ksi                     | MPa   |         |     |
| Permanent mold casting (continued) |         |                   |        |                      |     |                         |       |         |     |
| 296.0                              | T6      | CTB               | C5449  | X                    | X   | 12.0                    | 83    | 8.5     | 59  |
|                                    | T7      | CTB               | C5449  | X                    | X   | 8.0                     | 55    | 6.5     | 45  |
| 308.0                              | F       | CTB               | C8902  | X                    | X   | 13.0                    | 90    | 8.0     | 55  |
| 332.0                              | T5      | CTB               | C8281  | X                    | X   | 14.0                    | 97    | 8.0     | 55  |
| 333.0                              | F       | CTB               | C6028  | X                    | X   | 13.0                    | 90    | 8.0     | 55  |
|                                    | T5      | CTB               | C6028  | X                    | X   | 12.0                    | 83    | 8.0     | 55  |
|                                    |         |                   | D278B  | X                    | X   | 13.0                    | 90    | 7.5     | 52  |
|                                    | T6      | CTB               | C6028  | X                    | X   | 15.0                    | 103   | 10.0    | 69  |
|                                    | T7      | CTB               | C6028  | X                    | X   | 12.0                    | 83    | 9.0     | 62  |
|                                    |         |                   | C9176C | X                    | X   | 12.0                    | 83    | 8.0     | 55  |
| 336.0                              | T551    | CTB               | 105678 | X                    | X   | 13.5                    | 93    | 7.5     | 52  |
| A344.0                             | T4      | CTB               | 317644 | X                    | X   | 9.0                     | 62    | 3.5     | 24  |
| 354.0                              | T61     | CTB               | D3860  | X                    | X   | 19.0                    | 131   | 12.0    | 83  |
|                                    |         |                   | E6161  | X                    | X   | 15.0                    | 103   | 9.0     | 62  |
| 355.0                              | T51     | CTB               | C8067K | X                    | X   | 12.5                    | 86    | 7.0     | 48  |
|                                    | T6      | CTB               | C5448  | X                    | X   | 10.0                    | 69    | 8.0     | 55  |
|                                    |         |                   | C8067K | X                    | X   | 16.0                    | 110   | 10.5    | 72  |
|                                    | T62     | CTB               | C5448  | X                    | X   | 9.5                     | 66    | 6.0     | 41  |
|                                    |         |                   | C8067K | X                    | X   | 15.5                    | 107   | 7.5     | 52  |
|                                    | T7      | CTB               | C8067K | X                    | X   | 13.0                    | 90    | 8.5     | 59  |
|                                    | T71     | CTB               | C5448  | X                    | X   | 9.5                     | 66    | 6.0     | 41  |
|                                    |         |                   | C8067K | X                    | X   | 12.5                    | 86    | 8.0     | 55  |
| C355.0                             | T61     | CTB               | D2245B | X                    | X   | 12.5                    | 86    | 10.0    | 69  |
|                                    | T61 PEC | PE casting        | 206428 | X                    | X   | 12.0                    | 83    | 9.0     | 62  |
| 356.0                              | T6      | CTB               | C6235  | X                    | X   | 13.0                    | 90    | 7.5     | 52  |
|                                    | T7      | CTB               | C6235  | X                    | X   | 10.5                    | 72    | 5.0     | 34  |
| A356.0                             | T6      | CTB               | D2543  | X                    | X   | 13.5                    | 93    | 7.5     | 52  |
|                                    | T61     | Casting           | 206587 | X                    | X   | 8.0                     | 55    | 7.5     | 52  |
|                                    |         | PE casting        | 206588 | X                    | X   | 8.0                     | 55    | 7.5     | 52  |
|                                    |         | PE casting        | 206547 | X                    | X   | ND                      | ...   | ND      | ... |
| A357.0                             | T61     | CTB               | 302022 | X                    | X   | 12.5                    | 86    | 7.5     | 52  |
|                                    |         |                   | 302023 | X                    | X   | 13.5                    | 93    | 7.0     | 48  |
|                                    | T62     | Casting           | 302108 | X                    | X   | 11.0est                 | 76est | 6.0     | 41  |
| 359.0                              | T61     | CTB               | D4228  | X                    | X   | 16.0                    | 110   | 11.0    | 76  |
|                                    | T62     | CTB               | E2520A | X                    | X   | 15.0                    | 103   | 9.0     | 62  |
| B443.0                             | F       | CTB               | 118348 | X                    | X   | 7.0                     | 48    | 4.0     | 28  |
| C712.0                             | F       | CTB               | C8278  | X                    | X   | 11.0                    | 76    | 6.5     | 45  |
| 850.0                              | F       | CTB               | R8036  | X                    | ... | 9.0                     | 62    | ...     | ... |
|                                    | T101    | CTB               | 270257 | X                    | ... | 10.0                    | 69    | ...     | ... |
|                                    | T5      | CTB               | 270263 | X                    | ... | 8.5                     | 59    | ...     | ... |
| 851.0                              | T6      | CTB               | C1670  | X                    | ... | 8.5                     | 59    | ...     | ... |
| 852.0                              | T5      | CTB               | D3278  | X                    | X   | 11.5                    | 79    | 5.0     | 34  |
|                                    |         |                   | C8094  | X                    | X   | 10.5                    | 72    | 5.0     | 34  |
| Die casting                        |         |                   |        |                      |     |                         |       |         |     |
| 360.0                              | F       | CTB               | P1003  | X                    | ... | 19.0                    | 131   | ...     | ... |
| A360.0                             | F       | CTB               | P1004  | X                    | ... | 18.0                    | 124   | ...     | ... |
| 364.0                              | F       | CTB               | 206520 | X                    | ... | 15.0                    | 103   | ...     | ... |
| 380.0                              | F       | CTB               | P1005  | X                    | ... | 18.5                    | 128   | ...     | ... |
|                                    |         | CTB-as cast       | 147979 | X                    | ... | 21.0                    | 145   | ...     | ... |
|                                    |         | 0.01 in. removed  |        | X                    | ... | 19.5                    | 134   | ...     | ... |
|                                    |         | 0.025 in. removed |        | X                    | ... | 17.5                    | 121   | ...     | ... |
|                                    |         | Notches           |        | ...                  | X   | ...                     | ...   | 7.0     | 48  |
| A380.0                             | F       | CTB               | P1006  | X                    | ... | 21.5                    | 148   | ...     | ... |
| 383.0                              | F       | CTB               | P1007  | X                    | ... | 21.0                    | 145   | ...     | ... |
| 390.0                              | F       | CTB-as cast       | 317782 | X                    | X   | 19.0                    | 131   | 10.5    | 72  |
|                                    |         | CTB machined      | 317782 | X                    | X   | 19.0                    | 131   | 10.5    | 72  |
| 413.0                              | F       |                   | P998   | X                    | ... | 19.0                    | 131   | ...     | ... |
|                                    |         |                   | 317250 | X                    | X   | 13.0                    | 90    | 5.5     | 38  |
| B443.0                             | F       | CTB               | P1000  | X                    | ... | 16.5                    | 114   | ...     | ... |
| 518.0                              | F       | CTB               | 158837 | X                    | X   | 15.5                    | 107   | 6.0     | 41  |
|                                    |         |                   | P1002  | X                    | ... | 22.5                    | 155   | ...     | ... |

(a) CTB, cast test bars; casting, undefined cast part other than CTB; specific part given if stated on data sheet. (b) Specimens shown in Appendix 3, Fig. A3.2(b) for notched specimen, notch-tip radius  $\leq 0.001$  in;  $K_t \geq 12$ . (c) Endurance limit at 500 million cycles. Source: Ref 19

**Table 8.16 Typical rotating-beam fatigue strength of aluminum casting alloys at elevated temperatures**

Fatigue strengths determined from reversed-bending tests of 0.330 in. diam specimens in R.R. Moore or cantilever-beam rotating-beam machines

| Alloy                  | Temper | Test        |     | Fatigue strength at life of |     |                        |     |                        |     |                        |     |                        |     | Endurance limit<br>at $5 \times 10^8$ cycles |     |
|------------------------|--------|-------------|-----|-----------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|----------------------------------------------|-----|
|                        |        | temperature |     | 10 <sup>4</sup> cycles      |     | 10 <sup>5</sup> cycles |     | 10 <sup>6</sup> cycles |     | 10 <sup>7</sup> cycles |     | 10 <sup>8</sup> cycles |     |                                              |     |
|                        |        | °F          | °C  | ksi                         | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                                          | MPa |
| Sand casting           |        |             |     |                             |     |                        |     |                        |     |                        |     |                        |     |                                              |     |
| 222.0                  | T2     | RT          | RT  | ...                         | ... | 14.5                   | 100 | 12.0                   | 83  | 10.5                   | 72  | 10.0                   | 69  | 9.5                                          | 66  |
|                        |        | 300         | 150 | ...                         | ... | 13.0                   | 90  | 11.0                   | 76  | 9.5                    | 66  | 9.0                    | 62  | 8.0                                          | 55  |
|                        |        | 400         | 205 | ...                         | ... | 11.5                   | 79  | 9.5                    | 66  | 7.5                    | 52  | 6.0                    | 41  | 5.0                                          | 34  |
|                        |        | 500         | 260 | ...                         | ... | 10.0                   | 69  | 8.0                    | 55  | 6.0                    | 41  | 5.0                    | 34  | 4.0                                          | 28  |
| 224.0                  | T7     | RT          | RT  | ...                         | ... | 27.0                   | 186 | 16.5                   | 114 | 12.5                   | 86  | 12.0                   | 83  | 12.0                                         | 83  |
|                        |        | 400         | 205 | ...                         | ... | 22.0                   | 152 | 13.5                   | 93  | 8.5                    | 59  | 7.0                    | 48  | 7.0                                          | 48  |
|                        |        | 500         | 260 | ...                         | ... | 19.5                   | 134 | 11.5                   | 79  | 7.0                    | 48  | 6.0                    | 41  | 6.0                                          | 41  |
| A240.0                 | F      | RT          | RT  | ...                         | ... | 29.0                   | 200 | 23.0                   | 159 | 19.0                   | 131 | 18.0                   | 124 | 17.5                                         | 121 |
|                        |        | 300         | 150 | ...                         | ... | 19.0                   | 131 | 14.5                   | 100 | 13.0                   | 90  | 12.5                   | 86  | 12.5                                         | 86  |
|                        |        | 400         | 205 | ...                         | ... | 17.5                   | 121 | 13.0                   | 90  | 11.0                   | 76  | 10.5                   | 72  | 10.5                                         | 72  |
|                        |        | 500         | 260 | ...                         | ... | 16.0                   | 110 | 11.5                   | 79  | 9.0                    | 62  | 8.5                    | 59  | 8.5                                          | 59  |
|                        |        | 600         | 315 | ...                         | ... | 14.0                   | 97  | 9.5                    | 66  | 7.0                    | 48  | 5.5                    | 38  | 5.0                                          | 34  |
| 242.0                  | T77    | RT          | RT  | ...                         | ... | 19.0                   | 131 | 14.0                   | 97  | 11.5                   | 79  | 10.5                   | 72  | 10.5                                         | 72  |
|                        |        | 300         | 150 | ...                         | ... | 15.0                   | 103 | 10.5                   | 72  | 8.0                    | 55  | 7.5                    | 52  | 7.5                                          | 52  |
|                        |        | 400         | 205 | ...                         | ... | 14.0                   | 97  | 10.0                   | 69  | 7.5                    | 52  | 6.5                    | 45  | 6.5                                          | 45  |
|                        |        | 500         | 260 | ...                         | ... | 12.5                   | 86  | 9.0                    | 62  | 7.0                    | 48  | 5.5                    | 38  | 5.0                                          | 34  |
|                        |        | 600         | 315 | ...                         | ... | 11.5                   | 79  | 8.5                    | 59  | 6.0                    | 41  | 4.0                    | 28  | 3.5                                          | 24  |
| 249.0                  | T7     | RT          | RT  | 47.0                        | 324 | 26.0                   | 179 | 14.5                   | 100 | 11.5                   | 79  | 11.0                   | 76  | 11.0                                         | 76  |
|                        |        | 350         | 177 | 37.0                        | 255 | 22.0                   | 152 | 12.5                   | 86  | 10.0                   | 69  | 9.5                    | 66  | 9.5                                          | 66  |
| 355.0                  | T71    | RT          | RT  | ...                         | ... | 21.0                   | 145 | 15.0                   | 103 | 12.0                   | 83  | 11.0                   | 76  | 10.5                                         | 72  |
|                        |        | 300         | 150 | ...                         | ... | 18.0                   | 124 | 14.0                   | 97  | 11.0                   | 76  | 10.0                   | 69  | 9.5                                          | 66  |
|                        |        | 400         | 205 | ...                         | ... | 17.0                   | 117 | 13.0                   | 90  | 9.5                    | 66  | 7.5                    | 52  | 7.0                                          | 48  |
|                        |        | 500         | 260 | ...                         | ... | 14.0                   | 97  | 10.0                   | 69  | 7.0                    | 48  | 5.0                    | 34  | 4.5                                          | 31  |
| C355.0                 | T6     | RT          | RT  | ...                         | ... | 28.0                   | 193 | 19.0                   | 131 | 16.0                   | 110 | 14.5                   | 100 | 14.0                                         | 97  |
|                        |        | 300         | 150 | ...                         | ... | 27.0                   | 186 | 18.0                   | 124 | 13.5                   | 93  | 12.5                   | 86  | 12.0                                         | 83  |
|                        |        | 400         | 205 | 32.0                        | 221 | 24.0                   | 166 | 16.5                   | 114 | 12.0                   | 83  | 10.0                   | 69  | 9.0                                          | 62  |
|                        |        | 500         | 260 | 25.0                        | 172 | 18.0                   | 124 | 11.5                   | 79  | 7.5                    | 52  | 5.5                    | 38  | 5.0                                          | 34  |
|                        |        | 600         | 315 | 17.0                        | 117 | 11.5                   | 79  | 7.5                    | 52  | 5.5                    | 38  | 4.0                    | 28  | 3.5                                          | 24  |
| Permanent mold casting |        |             |     |                             |     |                        |     |                        |     |                        |     |                        |     |                                              |     |
| 242.0                  | T571   | RT          | RT  | 34.0                        | 234 | 26.0                   | 179 | 20.0                   | 138 | 16.5                   | 114 | 15.5                   | 107 | 15.0                                         | 103 |
|                        |        | 300         | 150 | ...                         | ... | 24.5                   | 169 | 20.0                   | 138 | 16.0                   | 110 | 15.0                   | 103 | 13.5                                         | 93  |
|                        |        | 400         | 205 | 25.0                        | 172 | 18.5                   | 128 | 13.0                   | 90  | 9.5                    | 66  | 8.5                    | 59  | 8.0                                          | 55  |
|                        |        | 500         | 260 | 22.0                        | 152 | 16.0                   | 110 | 11.0                   | 76  | 7.5                    | 52  | 6.0                    | 41  | 5.5                                          | 38  |
|                        |        | 600         | 315 | 18.0                        | 124 | 13.0                   | 90  | 8.5                    | 59  | 5.5                    | 38  | 4.0                    | 28  | 3.5                                          | 24  |
| 333.0                  | T5     | RT          | RT  | ...                         | ... | 22.5                   | 155 | 18.0                   | 124 | 15.5                   | 107 | 14.5                   | 100 | 13.5                                         | 93  |
|                        |        | 300         | 150 | ...                         | ... | 20.0                   | 138 | 15.5                   | 107 | 11.5                   | 79  | 10.0                   | 69  | 9.5                                          | 66  |
|                        |        | 400         | 205 | ...                         | ... | 18.0                   | 124 | 14.5                   | 100 | 10.5                   | 72  | 8.5                    | 59  | 7.5                                          | 52  |
|                        |        | 500         | 260 | ...                         | ... | 15.5                   | 107 | 12.0                   | 83  | 8.5                    | 59  | 6.5                    | 45  | 6.0                                          | 41  |
|                        |        | 600         | 315 | ...                         | ... | 12.0                   | 83  | 9.0                    | 62  | 6.5                    | 45  | 5.0                    | 34  | 4.5                                          | 31  |
|                        | T7     | RT          | RT  | ...                         | ... | 24.0                   | 166 | 18.5                   | 128 | 15.5                   | 107 | 13.5                   | 93  | 12.5                                         | 86  |
|                        |        | 300         | 150 | ...                         | ... | 22.0                   | 152 | 17.0                   | 117 | 12.5                   | 86  | 10.0                   | 69  | 9.5                                          | 66  |
|                        |        | 400         | 205 | ...                         | ... | 19.5                   | 134 | 14.0                   | 97  | 9.5                    | 66  | 7.5                    | 52  | 6.5                                          | 45  |
|                        |        | 500         | 260 | ...                         | ... | 17.0                   | 117 | 12.5                   | 86  | 8.5                    | 59  | 6.0                    | 41  | 5.5                                          | 38  |
|                        |        | 600         | 315 | ...                         | ... | 11.5                   | 79  | 8.5                    | 59  | 6.0                    | 41  | 4.0                    | 28  | 3.5                                          | 24  |
| 336.0                  | T551   | RT          | RT  | ...                         | ... | 21.0                   | 145 | 18.0                   | 124 | 16.0                   | 110 | 14.5                   | 100 | 13.5                                         | 93  |
|                        |        | 300         | 150 | ...                         | ... | 19.5                   | 134 | 15.0                   | 103 | 13.0                   | 90  | 11.0                   | 76  | 15.5                                         | 107 |
|                        |        | 400         | 205 | ...                         | ... | 16.0                   | 110 | 12.5                   | 86  | 10.0                   | 69  | 8.5                    | 59  | 8.0                                          | 55  |
|                        |        | 500         | 260 | ...                         | ... | 15.0                   | 103 | 10.5                   | 72  | 8.0                    | 55  | 7.0                    | 48  | 6.5                                          | 45  |
| 354.0                  | T6     | RT          | RT  | 50.0                        | 345 | 40.0                   | 276 | 31.0                   | 214 | 25.5                   | 176 | 21.0                   | 145 | 19.5                                         | 134 |
|                        |        | 300         | 150 | ...                         | ... | 37.0                   | 255 | 29.0                   | 200 | 21.5                   | 148 | 16.5                   | 114 | 15.5                                         | 107 |
|                        |        | 400         | 205 | ...                         | ... | 31.0                   | 214 | 22.0                   | 152 | 15.0                   | 103 | 10.0                   | 69  | 8.5                                          | 59  |
|                        |        | 500         | 260 | 28.0                        | 193 | 20.5                   | 141 | 14.0                   | 97  | 9.0                    | 62  | 6.0                    | 41  | 5.5                                          | 38  |
|                        |        | 600         | 315 | 14.0                        | 97  | 11.0                   | 76  | 8.0                    | 55  | 6.0                    | 41  | 4.5                    | 31  | 4.0                                          | 28  |
| 355.0                  | T62    | RT          | RT  | ...                         | ... | 36.0                   | 248 | 29.0                   | 200 | 23.0                   | 159 | 18.0                   | 124 | 15.5                                         | 107 |
|                        |        | 300         | 150 | ...                         | ... | ...                    | 0   | 21.0                   | 145 | 16.0                   | 110 | 12.0                   | 83  | ...                                          | ... |
|                        |        | 400         | 205 | ...                         | ... | 23.0                   | 159 | 17.5                   | 121 | 12.5                   | 86  | 9.0                    | 62  | ...                                          | ... |
|                        |        | 600         | 315 | ...                         | ... | 10.5                   | 72  | 7.0                    | 48  | 5.0                    | 34  | 3.5                    | 24  | ...                                          | ... |

(continued)

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897. RT, room temperature. Source: Aluminum Association and Alcoa publications

Table 8.16 (continued)

| Alloy                              | Temper | Test temperature |     | Fatigue strength at life of |     |                        |     |                        |     |                        |     |                        |     | Endurance limit at $5 \times 10^8$ cycles |     |
|------------------------------------|--------|------------------|-----|-----------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|------------------------|-----|-------------------------------------------|-----|
|                                    |        | °F               | °C  | 10 <sup>4</sup> cycles      |     | 10 <sup>5</sup> cycles |     | 10 <sup>6</sup> cycles |     | 10 <sup>7</sup> cycles |     | 10 <sup>8</sup> cycles |     |                                           |     |
|                                    |        |                  |     | ksi                         | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                    | MPa | ksi                                       | MPa |
| Permanent mold casting (continued) |        |                  |     |                             |     |                        |     |                        |     |                        |     |                        |     |                                           |     |
| 355.0                              | T71    | RT               | RT  | ...                         | ... | 27.0                   | 186 | 21.0                   | 145 | 17.0                   | 117 | 14.5                   | 100 | 13.0                                      | 90  |
|                                    |        | 300              | 150 | ...                         | ... | 25.0                   | 172 | 19.5                   | 134 | 15.0                   | 103 | 11.0                   | 76  | 10.0                                      | 69  |
|                                    |        | 400              | 205 | ...                         | ... | 21.0                   | 145 | 16.0                   | 110 | 12.0                   | 83  | 8.5                    | 59  | 8.0                                       | 55  |
|                                    |        | 600              | 315 | ...                         | ... | 10.0                   | 69  | 8.0                    | 55  | 5.5                    | 38  | 3.0                    | 21  | 2.5                                       | 17  |
| 359.0                              | T61    | RT               | RT  | 43.0                        | 297 | 34.0                   | 234 | 27.0                   | 186 | 21.5                   | 148 | 17.5                   | 121 | 16.5                                      | 114 |
|                                    |        | 300              | 150 | 41.0                        | 283 | 31.0                   | 214 | 23.5                   | 162 | 18.5                   | 128 | 14.0                   | 97  | 12.5                                      | 86  |
|                                    |        | 400              | 205 | 34.0                        | 234 | 26.0                   | 179 | 18.0                   | 124 | 11.5                   | 79  | 6.0                    | 41  | 4.0                                       | 28  |
| Die casting                        |        |                  |     |                             |     |                        |     |                        |     |                        |     |                        |     |                                           |     |
| 380.0                              | F      | RT               | RT  | ...                         | ... | 28.0                   | 193 | 22.0                   | 152 | 20.5                   | 141 | 20.0                   | 138 | 20.0                                      | 138 |
|                                    |        | 300              | 150 | ...                         | ... | 18.5                   | 128 | 15.0                   | 103 | 13.0                   | 90  | 11.0                   | 76  | 10.0                                      | 69  |
|                                    |        | 400              | 205 | ...                         | ... | 15.0                   | 103 | 11.0                   | 76  | 8.5                    | 59  | 7.5                    | 52  | 7.0                                       | 48  |
|                                    |        | 500              | 260 | ...                         | ... | 12.5                   | 86  | 9.0                    | 62  | 6.5                    | 45  | 5.5                    | 38  | 5.0                                       | 34  |

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897. RT, room temperature. Source: Aluminum Association and Alcoa publications

summary are that the fatigue properties of permanent mold cast aluminum alloys may be expected to be superior to those of sand castings, the lowest band.

Further indication that the fatigue strengths of cast aluminum components may be expected to be inferior to those of wrought aluminum products are borne out by flexural fatigue ( $R = 0.0$ ) tests of 220.0-T4 and 356.0-T6 sand cast beams, 218.0-F and 380.0-F die cast beams, and 6061-T6 wrought beams (Ref 21), shown in Fig. 8.4. The band of data for the cast beams falls consistently below the curve for 6061-T6.

Such generalized views of the differences in fatigue lives of cast and wrought aluminum alloys probably overlook the more basic fact that casting quality itself is the most important factor in determining fatigue life (just as it is for strength and toughness). Data reported by Promisel (Ref 22), reproduced in Fig. 8.5, demonstrate that the degree of porosity of 295.0 (regrettably not documented as to temper, but probably T6) has a direct bearing on fatigue strength; for the eight different degrees of porosity for which data

are presented, fatigue strength rather consistently increases as the degree of porosity is decreased, that is, as casting quality increases.

While there are few data to demonstrate it, it is also therefore reasonable to expect that improvements in casting practices that lead to better soundness and minimal porosity, such as premium quality casting, squeeze casting, and semisolid casting, will result in improved fatigue properties. One indication of that is found in the work of Williams and Fisher (Ref 23), shown in Fig. 8.6, who found that the axial-stress fatigue strengths of A356.0-T6 squeeze castings consistently performed better than conventionally chill cast A356.0-T6 castings.

Further evidence of the effect of defects and discontinuities is illustrated by the work on hot isostatic pressing by Boileau and Wang discussed in Chapter 6.

#### 8.4.2 Influence of Stress Raisers on Fatigue Strength of Aluminum Castings

As with wrought aluminum alloys, stress raisers such as notches or holes significantly reduce the fatigue strengths of aluminum castings. Data were presented in Section 8.3.4, under "Premium Engineered Castings," to show that fatigue strength decreases with increasing porosity, and notches represent an even more severe stress concentration. The  $S$ - $N$  curves in Data Set 6, the results of which are summarized in Table 8.15, provide examples of the effects of severe machined notches (with theoretical stress concentration factors,  $K_t > 12$ ) on fatigue strengths of representative casting alloys; in these cases, the notched specimen endurance limits are one-third to one-half those for the smooth specimens.

Sharp et al. (Ref 21) (Fig. 8.7) have shown that the sharp notch fatigue strengths of 355.0-T6 aluminum castings are about the same as, perhaps even slightly superior to, those of 6070-T6 and 7005-T53 wrought products. The significance of this is that, despite the smooth-specimen superiority of wrought products over castings, when real design discontinuities are present the fatigue prop-

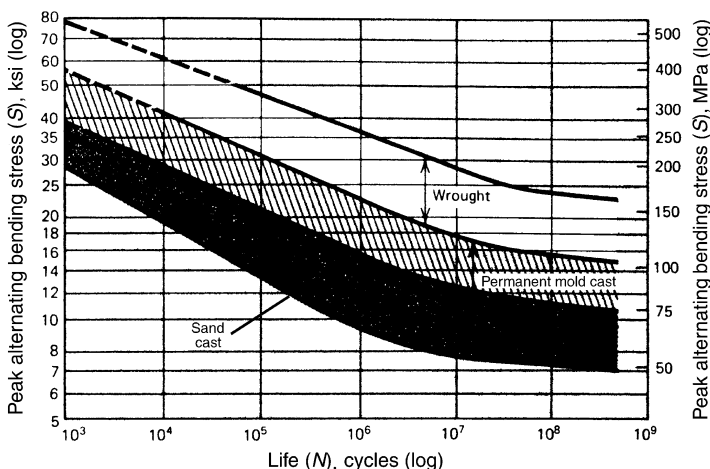


Fig. 8.3 Alternating bending stress fatigue curves for wrought and cast aluminum alloys. Source: Ref 20

erties of the various products may not differ significantly, and improving fatigue performance may be more a problem of reducing component stress concentrators and in the selection of an alloy or product form.

8.4.3 Fatigue Strengths of Welded Aluminum Castings

Few data are available to document the fatigue strengths of weldments in aluminum castings, but Sharp et al. (Ref 21) present

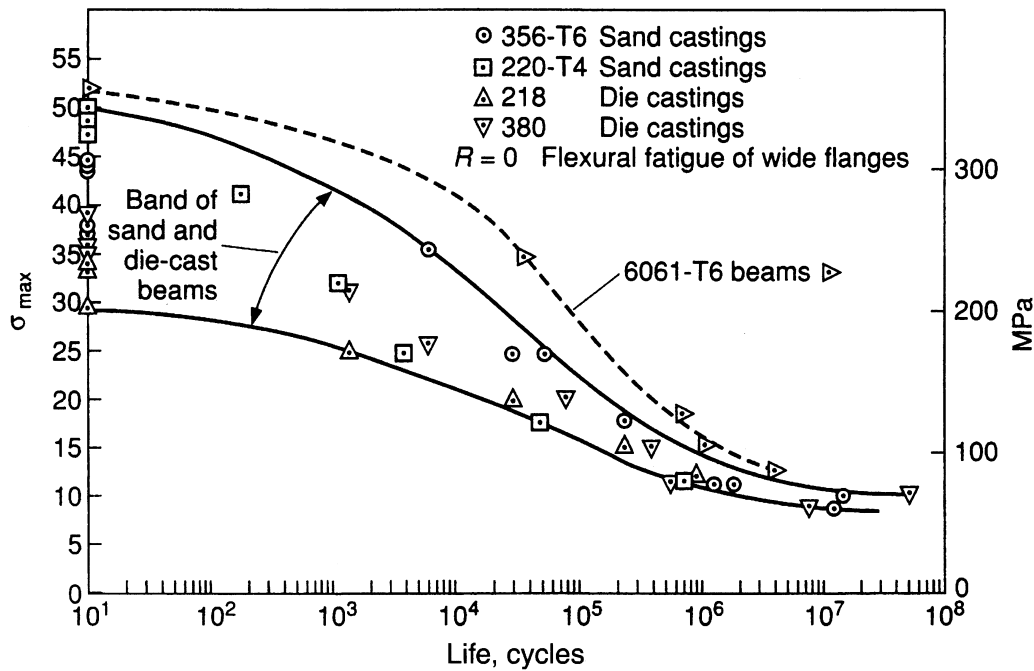


Fig. 8.4 Flexural fatigue properties ( $R = 0$ ) of aluminum alloy beams produced from wrought and cast aluminum alloys. Source: Ref 20

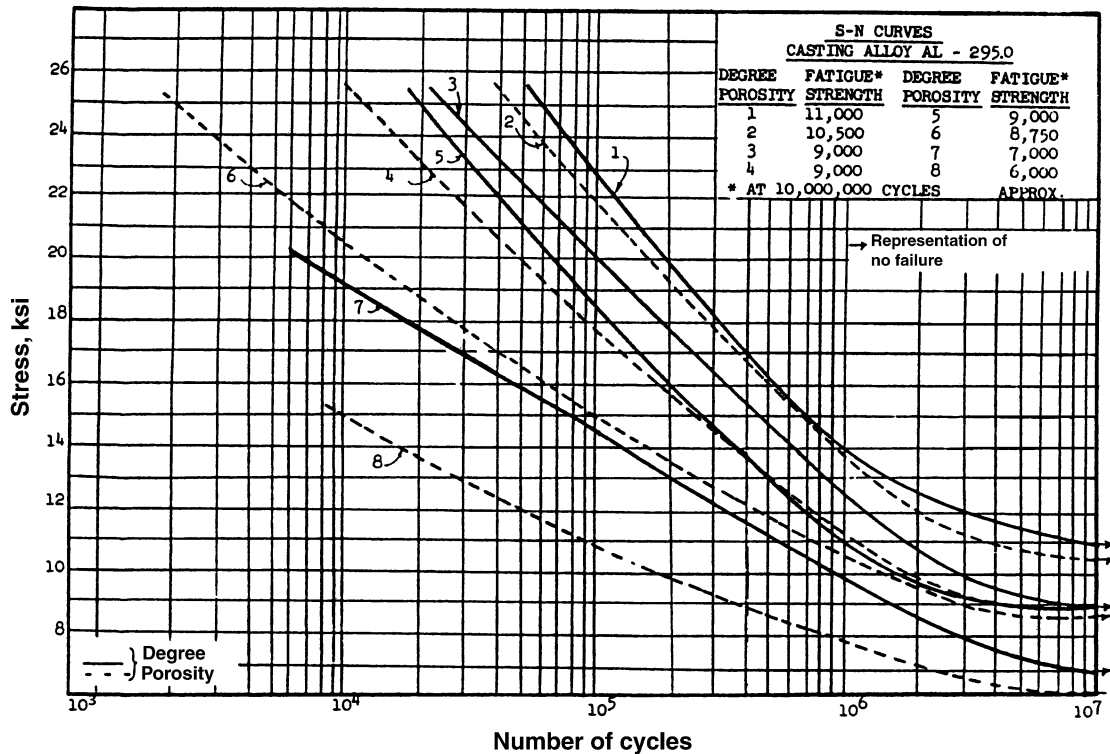


Fig. 8.5 Fatigue properties of 295.0 aluminum alloy castings with various degrees of porosity. Source: Ref 22



the results of axial-stress ( $R = 0.0$ ) fatigue tests of 355.0-T6 casting welded together with 355.0 as filler metal and also 355.0-T6 welded to 5456-H321 with 4043 as filler metal, as in Fig. 8.8. There was no significant difference in fatigue strength of the two weld combinations, nor was there any significant effect of removing the weld bead or leaving it intact.

#### 8.4.4 Design Fatigue Strengths for Aluminum Castings

MMPDS/MIL-HDBK-5H (Ref 15) includes strain-life fatigue curves for use in design of aluminum aircraft. For aluminum alloy castings, a curve is shown only for A201.0-T7, and those data are reproduced in Fig. 8.9. No other fatigue data for aluminum castings are presented.

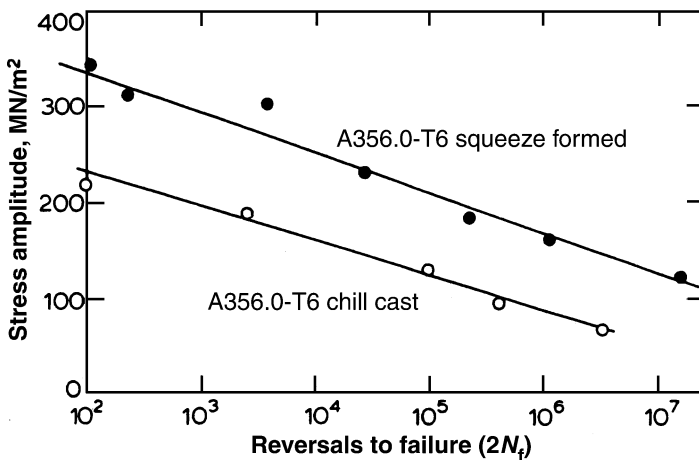


Fig. 8.6 Fatigue properties of conventionally cast and squeeze cast aluminum alloy A356.0-T6. Source: Ref 23

## 8.5 Fracture Resistance of Aluminum Alloys

Notch toughness, tear resistance, and plane-strain fracture toughness have been the primary measures used to assess the toughness of aluminum alloy castings (Ref 24). Because of the difficulty in getting valid fracture toughness tests from castings, more data are available for notch toughness and tear resistance, but representative data for all three are presented and discussed in the sections that follow.

### 8.5.1 Notch Toughness and Notch Sensitivity

One of the earliest approaches to the evaluation of the fracture characteristics of aluminum alloys was via tensile tests of specimens containing various types of stress raisers (Ref 24). The results from these tests were analyzed in terms of the theoretical stress-concentration factors. This approach, however, has not always been very useful in design, since the same theoretical stress concentration factors can be obtained with a great variety of different geometrical notch and specimen configurations, each of which has a unique influence on the numerical results of the tests; if design is the goal, the notched specimen must mirror the stress conditions in the component, including its stress raisers.

Therefore, the results of tensile tests of notched specimens have been used primarily to qualitatively merit rate aluminum alloys with respect to their notch toughness, that is, their ability to plastically deform locally in the presence of stress raisers and thus redistribute the stress. The notch tensile strength itself is of small value for this rating; the relationship of the notch tensile strength to the tensile properties is much more meaningful.

For many years, the criterion most often used from notch tensile test results was the notch-strength ratio, the ratio of the notch tensile strength to the tensile strength of the material. However, this ratio tells little about the relative abilities of alloys to deform

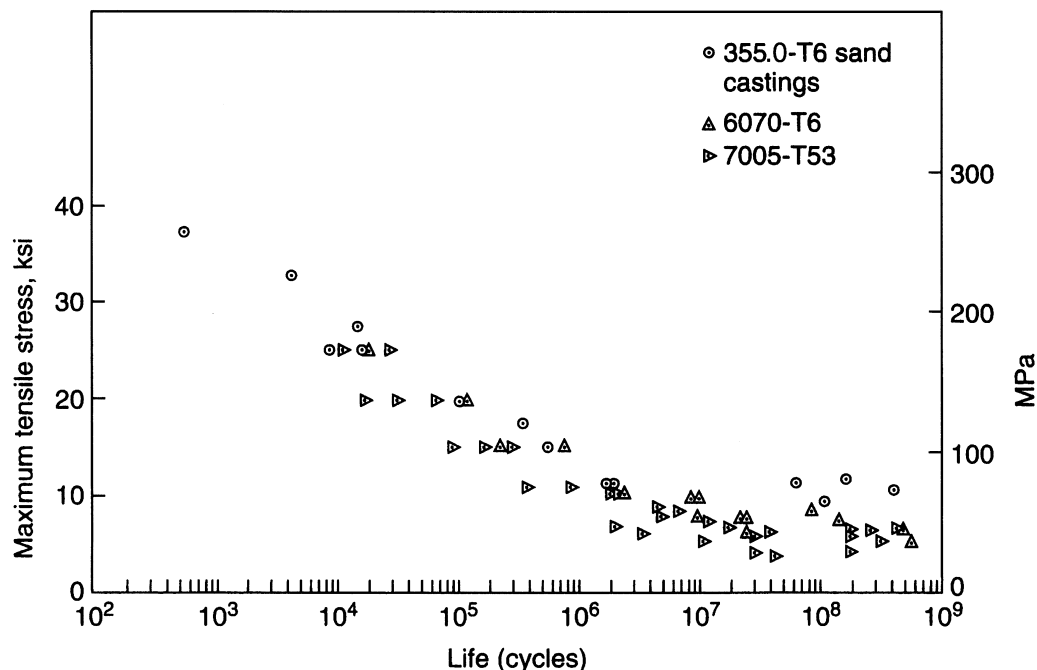


Fig. 8.7 Rotating beam ( $R = -1.0$ ) fatigue properties of notched specimens from wrought and cast aluminum alloys. Source: Ref 21

plastically in the presence of stress raisers. In fact, for different notch geometries, it can indicate contradictory ratings (Ref 24). There are instances, of course, when the notch-strength ratio is useful, for example, when a measure of tensile efficiency of a specific structural member is required, or when the ultimate strength is the primary data taken for the smooth specimens, as in fatigue tests or stress rupture tests.

A more meaningful indication of the inherent ability of a material to plastically deform locally in the presence of a severe stress raiser is provided by the notch-yield ratio—the ratio of the notch tensile strength to the tensile yield strength (Ref 24). The yield strength, although arbitrarily defined, is a measure of the lowest stress at which appreciable plastic deformation occurs in a tensile test. Therefore, the relationship of the notch tensile strength to the yield

strength tells more about the behavior of the material in the presence of a stress raiser than the ratio of the notch tensile strength to the tensile strength. If the notch tensile strength is appreciably above the yield strength (regardless of its relation to the tensile strength), the material has exhibited an ability to deform locally in the presence of the stress raiser.

If the notch tensile strength is appreciably below the yield strength, the fracture must have taken place without very much plastic deformation. For a specific notch design, this may or may not provide much specific design information, but as a relative measure of how several alloys behave in that situation, it is quite useful. Further indication of this fact is the experimental result that the notch-yield ratio provides rather consistent ratings of many alloys and tempers for a wide variety of notch geometries, and the ratings are consistent with those from fracture parameters, as described later.

While a number of different designs of notch have been used by different investigators, very sharp 60° V-notches provide the greatest discrimination among different alloys. In addition, such notches come close to representing the most severe unintentional stress raiser that is likely to exist in a structure: a crack. ASTM standards for notch tensile testing (Ref 25) call for notch-tip radii equal to or less than 0.0005 in. (0.013 mm), easily maintained in machining aluminum specimens (though quality assurance measurements are recommended).

**Notch Toughness at Room Temperature.** The specific design of notch for which data for a wide variety of casting alloys are available is shown in Appendix 3, Fig. A3.5. Representative data for various aluminum casting alloys with this design of specimen are given in Table 8.17 (Ref 24). Data for welds in various aluminum casting alloys are presented in Table 8.18. In all cases, the data were generated in accordance with ASTM E 602 (Ref 25).

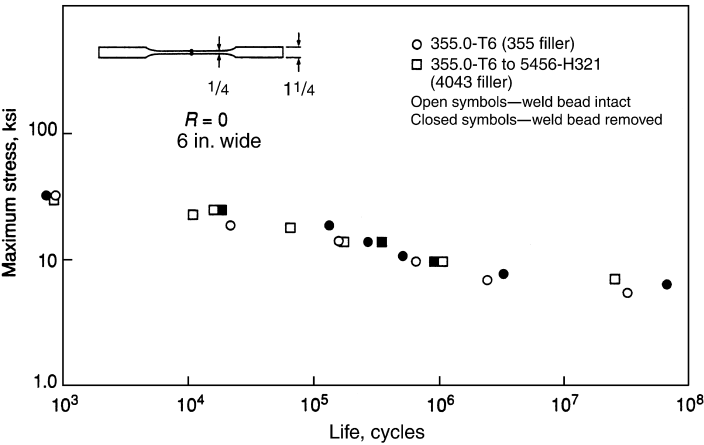


Fig. 8.8 Axial-stress ( $R = 0$ ) fatigue properties of welded aluminum alloy castings. Source: Ref 21

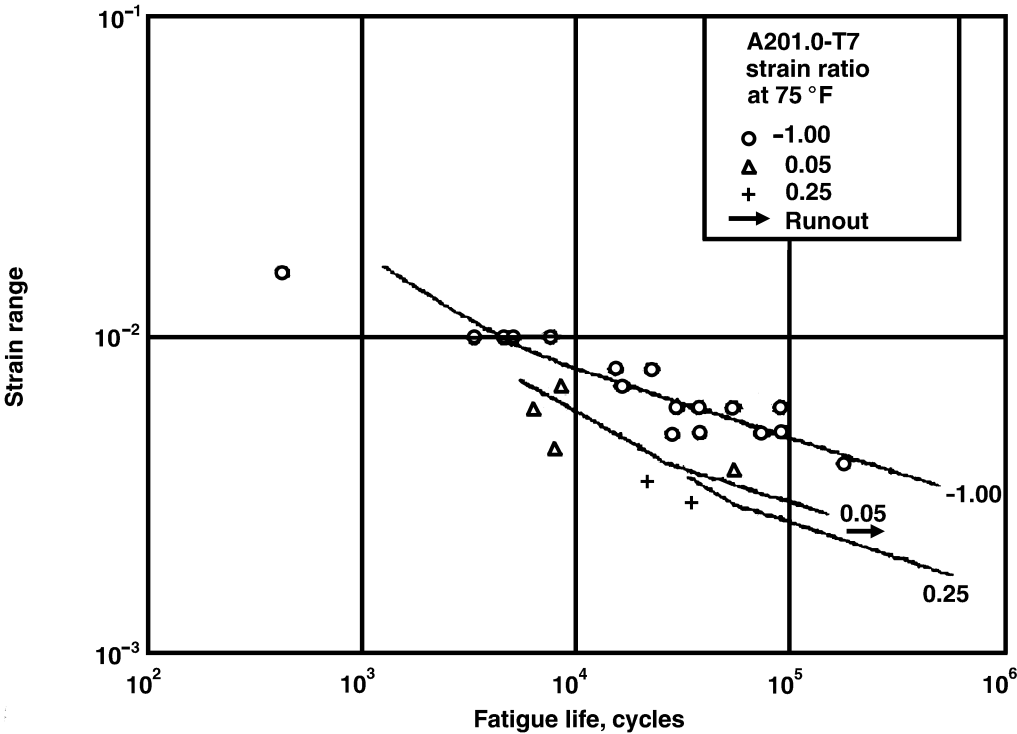


Fig. 8.9 Best-fit fatigue curves for aluminum alloy A201-T7 at various strain rates at 75 °F (24 °C). Source: Ref 14

**Table 8.17 Representative notch toughness tests of cast aluminum alloys at room temperature**

Specimens per Appendix 3, Fig. A3.5; each line is the average of two tests of a single lot of material.

| Alloy and temper           | Ultimate tensile strength |     | Tensile yield strength(a) |     | Elongation in 2 in., % | Reduction of area, % | Notch tensile strength |      | NTS/TS | NTS/YS |
|----------------------------|---------------------------|-----|---------------------------|-----|------------------------|----------------------|------------------------|------|--------|--------|
|                            | ksi                       | MPa | ksi                       | MPa |                        |                      | ksi                    | MPa  |        |        |
| Sand casting               |                           |     |                           |     |                        |                      |                        |      |        |        |
| 240.0-F                    | 33.8                      | 233 | 26.0                      | 179 | 1.4                    | 2                    | 22.5                   | 155  | 0.67   | 0.87   |
| 242.0-T77                  | 29.8                      | 206 | 20.4                      | 141 | 2.1                    | 4                    | 27.4                   | 189  | 0.92   | 1.34   |
| 295.0-T6                   | 42.0                      | 290 | 27.1                      | 187 | 6.4                    | 10                   | 47.4                   | 327  | 1.13   | 1.75   |
| 308.0-F                    | 25.0                      | 172 | 18.5                      | 128 | 1.8                    | 2                    | 22.1                   | 152  | 0.88   | 1.19   |
| X335.0-T6                  | 37.3                      | 257 | 23.4                      | 161 | 8.6                    | 12                   | 38.2                   | 263  | 1.02   | 1.63   |
|                            | 35.3                      | 243 | 22.6                      | 156 |                        |                      | 37.4                   | 258  | 1.06   | 1.65   |
| Average                    | 36.3                      | 250 | 23.0                      | 159 |                        |                      | 37.8                   | 261  | 1.04   | 1.64   |
| 356.0-T4                   | 31.1                      | 214 | 19.8                      | 137 | 4.4                    | 6                    | 31.6                   | 218  | 1.02   | 1.60   |
|                            | 29.4                      | 203 | 17.6                      | 121 |                        |                      | 31.3                   | 216  | 1.07   | 1.78   |
| Average                    | 30.2                      | 208 | 18.7                      | 129 |                        |                      | 31.4                   | 217  | 1.04   | 1.69   |
| 356.0-T6                   | 38.6                      | 266 | 32.6                      | 225 | 2.2                    | 3                    | 37.4                   | 258  | 0.97   | 1.15   |
| 356.0-T7                   | 37.8                      | 261 | 33.7                      | 232 | 1.6                    | 2                    | 34.5                   | 238  | 0.91   | 1.02   |
| 356.0-T71                  | 28.8                      | 199 | 20.2                      | 139 | 5.0                    | ...                  | 32.0                   | 221  | 1.11   | 1.59   |
|                            | 31.9                      | 220 | 24.2                      | 167 | 38.2                   |                      | 263                    | 1.20 | 1.58   |        |
|                            | 29.4                      | 203 | 20.7                      | 143 | 30.6                   |                      | 211                    | 1.04 | 1.46   |        |
| Average                    | 30.0                      | 207 | 21.7                      | 150 |                        |                      | 33.6                   | 232  | 1.12   | 1.54   |
| A356.0-T61                 | 41.6                      | 287 | 30.2                      | 208 | 8.8                    | 10                   | 51.4                   | 355  | 1.23   | 1.70   |
| A356.0-T7                  | 37.1                      | 256 | 30.5                      | 210 | 4.4                    | 7                    | 44.9                   | 310  | 1.21   | 1.47   |
|                            | 37.6                      | 259 | 33.2                      | 229 |                        |                      | 38.2                   | 263  | 1.02   | 1.15   |
| Average                    | 37.4                      | 258 | 31.8                      | 219 |                        |                      | 41.6                   | 287  | 1.12   | 1.31   |
| 520.0-F                    | 34.2                      | 236 | 31.6                      | 218 | 2.1                    | 2                    | 38.4                   | 265  | 1.12   | 1.22   |
| B535.0-F                   | 41.2                      | 284 | 21.2                      | 146 | 12.9                   | 13                   | 43.8                   | 302  | 1.06   | 2.06   |
|                            | 42.6                      | 294 | 21.0                      | 145 |                        |                      | 44.9                   | 310  | 1.05   | 2.14   |
| Average                    | 41.9                      | 289 | 21.1                      | 146 |                        |                      | 44.4                   | 306  | 1.06   | 2.10   |
| A612.0-F                   | 43.1                      | 297 | 34.8                      | 240 | 3.2                    | 7                    | 45.5                   | 314  | 1.05   | 1.31   |
| Permanent mold casting     |                           |     |                           |     |                        |                      |                        |      |        |        |
| X335.0-T61                 | 40.8                      | 281 | 28.4                      | 196 | 8.5                    | 13                   | 45.7                   | 315  | 1.12   | 1.61   |
|                            | 35.6                      | 246 | 25.6                      | 177 | 3.5                    | 4                    | 40.4                   | 279  | 1.14   | 1.58   |
| Average                    | 38.2                      | 263 | 23.8                      | 164 | 6.0                    |                      | 42.3                   | 297  | 1.13   | 1.60   |
| 354.0-T62                  | 50.1                      | 346 | 45.5                      | 314 | 1.1                    | 3                    | 54.2                   | 374  | 1.08   | 1.19   |
|                            | 47.8                      | 330 | 44.3                      | 306 | 0.9                    | 2                    | 51.2                   | 353  | 1.07   | 1.16   |
| Average                    | 49.0                      | 340 | 44.9                      | 310 | 1.0                    | 2                    | 52.7                   | 364  | 1.08   | 1.18   |
| C355.0-T7                  | 37.0                      | 255 | 31.0                      | 214 | 2.1                    | 4                    | 43.4                   | 299  | 1.17   | 1.40   |
|                            | 41.0                      | 283 | 30.4                      | 210 | 2.5                    | 6                    | 41.8                   | 288  | 1.02   | 1.38   |
| Average                    | 39.0                      | 269 | 30.7                      | 212 | 2.3                    | 5                    | 42.5                   | 294  | 1.10   | 1.39   |
| 356.0-T6                   | 35.8                      | 247 | 31.1                      | 214 | 1.4                    | 3                    | 4.3                    | 30   | 1.17   | 1.38   |
| 356.0-T7                   | 28.4                      | 196 | 21.4                      | 148 | 4.3                    | 6                    | 35.3                   | 243  | 1.24   | 1.65   |
|                            | 29.6                      | 204 | 22.0                      | 152 | 3.2                    | 6                    | 34.3                   | 237  | 1.16   | 1.56   |
| Average                    | 29.8                      | 206 | 22.0                      | 152 | 5.0                    | 8                    | 34.8                   | 240  | 1.20   | 1.60   |
| A356.0-T61                 | 39.4                      | 272 | 30.8                      | 212 | 4.3                    | 7                    | 47.8                   | 330  | 1.21   | 1.55   |
|                            | 41.7                      | 288 | 30.4                      | 210 | 7.5                    | 8                    | 45.4                   | 313  | 1.22   | 1.75   |
| Average                    | 40.6                      | 280 | 30.6                      | 211 | 5.9                    | 8                    | 46.6                   | 322  | 1.22   | 1.65   |
| A356.0-T62                 | 40.9                      | 282 | 36.7                      | 253 | 2.1                    | 6                    | 46.2                   | 319  | 1.13   | 1.26   |
|                            | 43.6                      | 301 | 36.3                      | 250 | 3.9                    | ...                  | 43.8                   | 302  | 1.00   | 1.21   |
| Average                    | 42.2                      | 291 | 36.5                      | 252 | 3.0                    | 6                    | 45.0                   | 310  | 1.06   | 1.24   |
| A356.0-T7                  | 28.2                      | 194 | 21.4                      | 148 | 5.3                    | 9                    | 36.9                   | 254  | 1.31   | 1.72   |
| 359.0-T62                  | 46.2                      | 319 | 43.2                      | 298 | 1.2                    | 3                    | 49.7                   | 343  | 1.08   | 1.15   |
|                            | 47.4                      | 327 | 43.1                      | 297 | 1.6                    | 4                    | 42.9                   | 296  | 0.91   | 1.00   |
| Average                    | 34.7                      | 239 | 43.2                      | 298 | 1.4                    | 4                    | 46.3                   | 324  | 1.00   | 1.08   |
| A444.0-F                   | 23.2                      | 160 | 9.7                       | 67  | 22.2                   | 37                   | 28.6                   | 197  | 1.23   | 2.96   |
|                            | 22.5                      | 155 | 9.6                       | 66  | 15.7                   | 21                   | 27.8                   | 192  | 1.25   | 2.90   |
| Average                    | 22.8                      | 157 | 9.6                       | 66  | 19.0                   |                      | 28.2                   | 194  | 1.24   | 2.96   |
| A444.0-T4                  | 23.0                      | 159 | 8.0                       | 55  | 24.4                   | 36                   | 30.8                   | 212  | 1.39   | 3.72   |
| Premium engineered casting |                           |     |                           |     |                        |                      |                        |      |        |        |
| A201.0-T7                  | 63.8                      | 440 | 58.1                      | 401 | 7.0                    | 10                   | 79.6                   | 549  | 1.25   | 1.37   |
| 224.0-T7                   | 54.1                      | 373 | 41.0                      | 283 | 6.6                    | 9                    | 64.5                   | 445  | 1.19   | 1.57   |
|                            | 54.2                      | 374 | 38.6                      | 266 | 6.6                    | 9                    | 65.9                   | 455  | 1.22   | 1.71   |
| Average                    | 54.2                      | 374 | 39.8                      | 274 | 6.6                    | 9                    | 65.0                   | 448  | 1.20   | 1.64   |

(continued)

NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For tensile yield strength, offset = 0.2%.

Table 8.17 (continued)

| Alloy and temper                       | Ultimate tensile strength |     | Tensile yield strength(a) |     | Elongation in 2 in., % | Reduction of area, % | Notch tensile strength |     | NTS/TS | NTS/YS |
|----------------------------------------|---------------------------|-----|---------------------------|-----|------------------------|----------------------|------------------------|-----|--------|--------|
|                                        | ksi                       | MPa | ksi                       | MPa |                        |                      | ksi                    | MPa |        |        |
| Premium engineered casting (continued) |                           |     |                           |     |                        |                      |                        |     |        |        |
| 249.0-T7                               | 57.6                      | 397 | 49.2                      | 339 | 7.4                    | 11                   | 69.3                   | 478 | 1.20   | 1.41   |
| 354.0-T6                               | 48.0                      | 331 | 43.0                      | 297 | 1.2                    | 1                    | 45.4                   | 313 | 0.95   | 1.06   |
| C355.0-T6                              | 43.6                      | 301 | 40.8                      | 281 | 1.0                    | 1                    | 43.4                   | 299 | 1.00   | 1.06   |
| C355.0-T61                             | 43.6                      | 301 | 30.3                      | 209 | 6.4                    | 9                    | 52.6                   | 363 | 1.21   | 1.74   |
| A356.0-T6                              | 41.6                      | 287 | 30.2                      | 208 | 8.8                    | 10                   | 51.4                   | 355 | 1.23   | 1.70   |
| A357.0-T6                              | 52.0                      | 359 | 43.2                      | 298 | 4.5                    | 6                    | 48.4                   | 334 | 0.93   | 1.12   |
| A357.0-T61                             | 51.2                      | 353 | 40.0                      | 276 | 11.4                   | 13                   | 56.2                   | 388 | 1.10   | 1.41   |
| A357.0-T62                             | 53.9                      | 372 | 46.4                      | 320 | 5.3                    | 7                    | 59.4                   | 410 | 1.10   | 1.28   |

NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For tensile yield strength, offset = 0.2%.

Relative rankings of the casting alloys are presented in the bar graphs in Fig. 8.10, segregated by sand castings (Fig. 8.10a), permanent mold castings (Fig. 8.10b), and premium-strength castings (Fig. 8.10c).

Alloy A444.0-F permanent mold castings, with the lowest yield strength of the entire group, ranks highest. Otherwise, for the respective groups, 295.0-T6 and B535.0-F rank highest among sand cast alloys; A356.0-T6 and -T71 rank highest among permanent mold castings; and 224.0-T7, A356.0-T6, and C355.0-T61 rank highest among the premium-strength castings. Among the higher-strength casting alloys, the premium quality castings (that is, sand castings made with special care to provide high metal chill rates in highly stressed regions) rate well, and A356.0-T6 consistently has higher toughness than does 356.0-T6, the positive effect of its higher purity (i.e., lower content of impurities such as iron).

Looking at the relationship between notch-yield ratio (NYR) and tensile yield strength also provides interesting information for castings (Fig. 8.11), most notably the relationship of their performance to that of wrought alloys.

Alloys A444.0-F and B535.0-F have among the best combinations of strength and notch toughness, as do the premium-strength castings in the T61, T62, and T7 tempers; they fall in or near lower edge of the band for wrought alloy data. However, the other sand and permanent mold cast alloys fall below the wrought alloy band; of the latter groups, the permanent mold castings generally exhibit the best performance.

Relative rankings for welds in aluminum alloy castings based on notch-yield ratio (Table 8.18) are shown in Fig. 8.12.

Welds in A444.0-F have the highest notch-yield ratios by a considerable margin, not surprising with their low strength. Alloys 354.0-T62 and C355.0-T6 are within a fairly narrow range, with C355.0-T6 welds being slightly superior.

Once again, looking at the data on the basis of NYR versus tensile yield strength (TYS) as in Fig. 8.13 reveals additional information.

For the two higher-strength alloys, 354.0-T62 and C355.0-T6, there is also an indication that welds made with 5356 and 5556 filler alloys have somewhat better combinations of strength and tough-

Table 8.18 Representative notch toughness test results of welds in cast aluminum alloys at room temperature

Specimens per Appendix 3, Fig. A3.5; each line represents the average of duplicate tests on one lot of material. Joint efficiencies based on typical values for parent alloys. No postweld thermal treatment

| Alloy and temper combination | Filler alloy | Ultimate tensile strength |     | Tensile yield strength(a) |     | Elongation in 2 in., % | Reduction of area, % | Joint strength efficiency, % | Location of fracture(b) | Notch tensile strength |     | NTS/TS | NTS/YS |
|------------------------------|--------------|---------------------------|-----|---------------------------|-----|------------------------|----------------------|------------------------------|-------------------------|------------------------|-----|--------|--------|
|                              |              | ksi                       | MPa | ksi                       | MPa |                        |                      |                              |                         | ksi                    | MPa |        |        |
| A444.0-F to A444.0-F         | 4043         | 23.8                      | 164 | 9.5                       | 66  | 12.1                   | 22                   | 100                          | B                       | 27.5                   | 190 | 1.15   | 2.90   |
| A444.0-F to 6061-T6          | 4043         | 24.0                      | 166 | 11.4                      | 79  | 5.7                    | 23                   | 100                          | B                       | 29.3                   | 202 | 1.22   | 2.51   |
| A444.0-F to 5456-H321        | 5556         | 24.1                      | 166 | 12.2                      | 84  | 12.1                   | 27                   | 100                          | B                       | 29.5                   | 203 | 1.22   | 2.42   |
| 354.0-T62 to 354.0-T6        | 4043         | 37.8                      | 261 | 21.5                      | 148 | 6.4                    | 10                   | 76                           | A                       | 32.0                   | 221 | 0.85   | 1.48   |
| 354.0-T62 to 6061-T6         | 4043         | 30.8                      | 212 | 19.0                      | 131 | 9.3                    | 39                   | 62                           | C                       | 28.7                   | 198 | 0.93   | 1.51   |
| 354.0-T62 to 5456-H321       | 5556         | 37.7                      | 260 | 24.6                      | 170 | 3.6                    | 5                    | 75                           | A                       | 37.7                   | 260 | 1.00   | 1.53   |
| C355.0-T61 to 6061-T6        | 4043         | 28.9                      | 199 | 19.3                      | 133 | 7.1                    | 32                   | 66                           | C                       | 34.5                   | 238 | 1.19   | 1.79   |
| C355.0-T61 to 5456-H321      | 5556         | 35.4                      | 244 | 24.4                      | 168 | 3.6                    | 5                    | 81                           | A                       | 40.5                   | 279 | 1.15   | 1.66   |

NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For joint yield strength, offset = 0.2%, over a 2 in. gage length. (b) Location of fracture of unnotched specimens: A, through weld; B, 1/2 to 2 1/2 in. from weld; C, edge of weld

ness than do welds made with 4043; this is also consistent with the case for wrought alloys. In low-strength, high-toughness alloy A444.0-F, choice of filler alloy made little difference.

The notch toughness of most welds as measured by NYR is generally somewhat less than that for parent metal of the same strength, the principal exceptions being welds made with the 5xxx series filler alloys. Many data for 4043 welds fall well below the

band for wrought alloys; a notable exception is when the 4043 weld in 6061-T6 was heat treated and aged after welding.

**Notch Toughness at Subzero Temperatures.** The results of notch tensile tests of several aluminum casting alloys at subzero temperatures are presented in Table 8.19. Data from these tests are plotted in Fig. 8.14 as a function of test temperature for sand cast alloys at subzero temperatures (Fig. 8.14a and b), permanent mold cast alloys (Fig. 8.14c), and premium-strength sand cast alloys (Fig. 8.14d).

From Fig. 8.14, it can be seen that the 3xx.0 and 4xx.0 casting alloys rather consistently retain most or all of their toughness at subzero temperatures, even to  $-423^{\circ}\text{F}$  ( $-253^{\circ}\text{C}$ ) and  $-452^{\circ}\text{F}$  ( $-269^{\circ}\text{C}$ ). Alloy A444.0-F (Fig. 8.14c), with its relatively low yield strength, showed an exceptionally high NYR, at or above 2.5, even at  $-320^{\circ}\text{F}$  ( $-196^{\circ}\text{C}$ ). From the notch tensile data in Fig. 8.14(d), it is also clear that A356.0-T61 performed quite well even at  $-452^{\circ}\text{F}$  ( $-269^{\circ}\text{C}$ ). Other casting alloys, notably the 2xx.0 and 5xx.0 series, generally show a consistent and more rapidly decreasing toughness with decrease in temperature.

When the notch-yield ratios for cast alloys are viewed on the basis of yield strength level (Fig 8.15), A444.0-F exhibits exceptionally high toughness and, among the higher-strength alloys, the premium-strength cast alloys have the most consistently superior strength-toughness combination, similar to the case at room temperature.

The performance of the permanent mold castings is generally nearly as good as the premium-strength castings and, in fact, B535.0

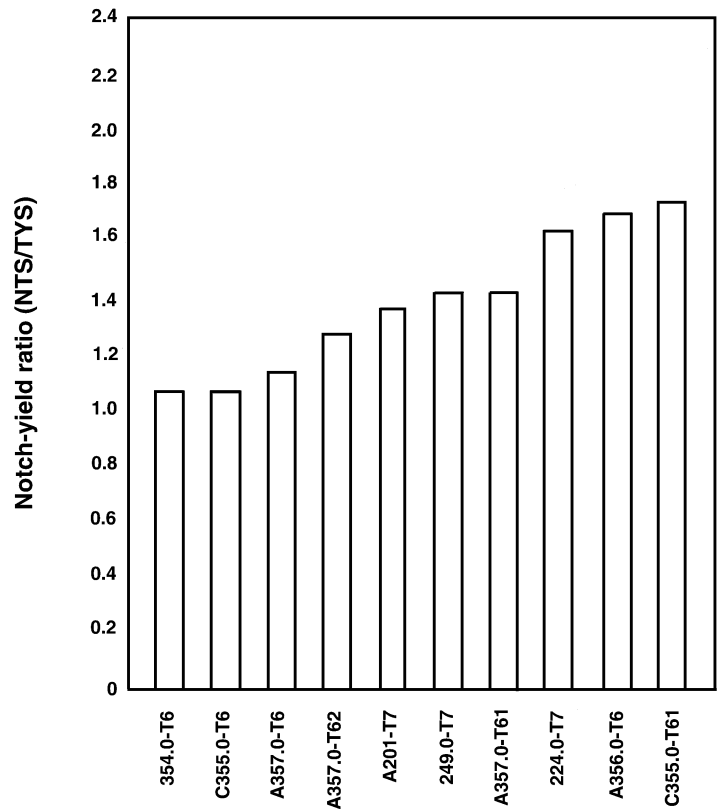
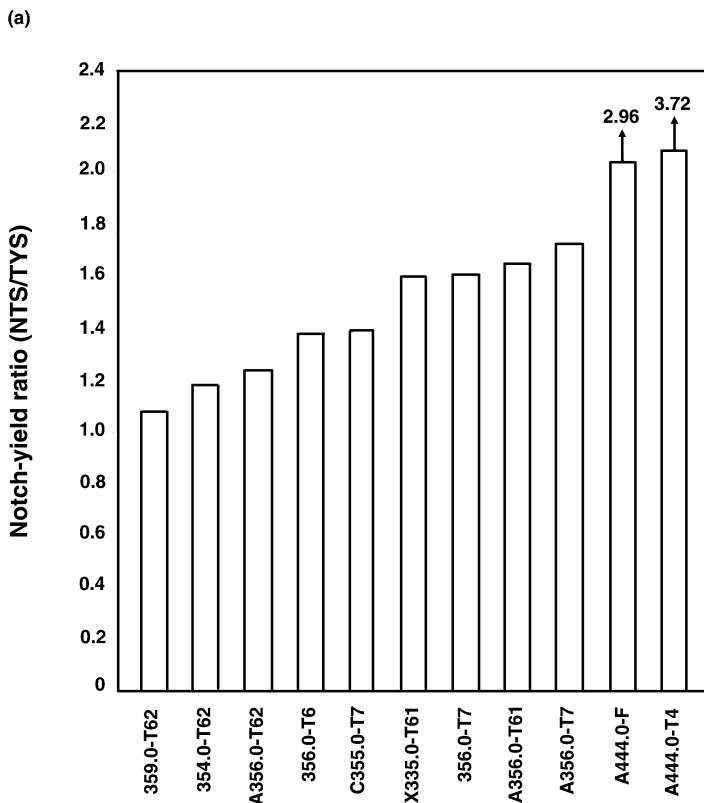
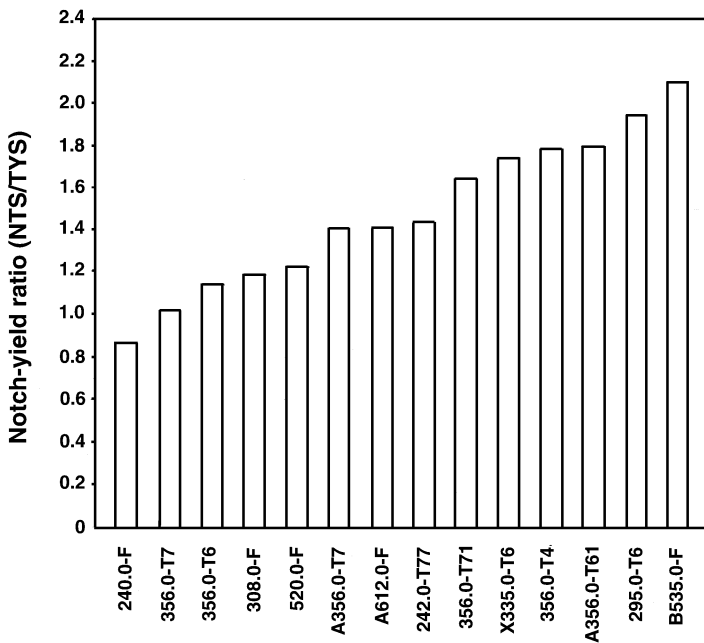


**Fig. 8.10** Relative rankings of notch toughness of aluminum casting alloys based upon notch-yield ratio. (a) Sand castings. (b) Permanent mold castings. (c) Premium engineered castings



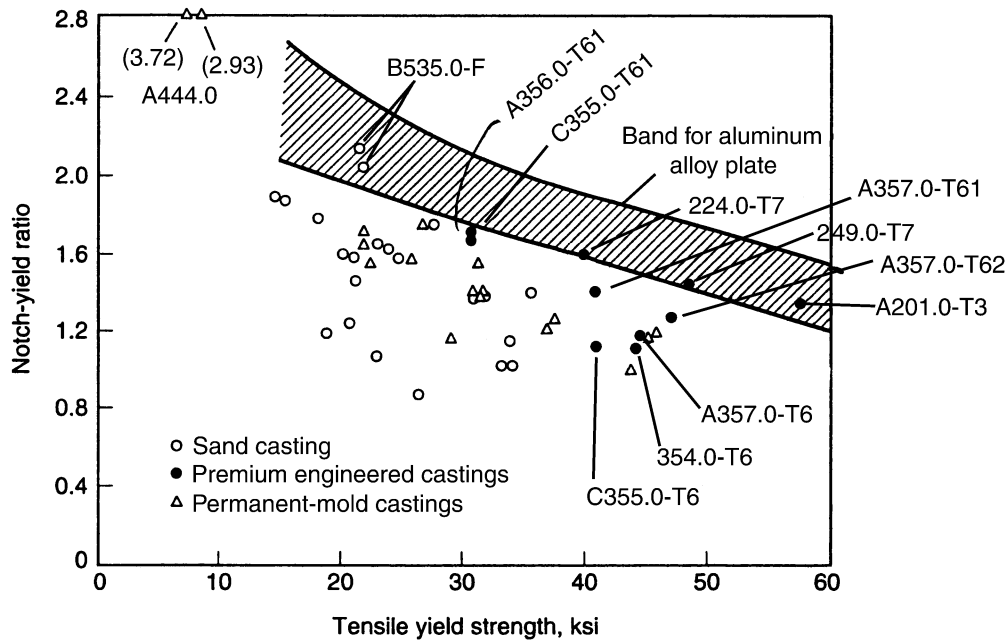


Fig. 8.11 Notch-yield ratio versus tensile yield strength for selected aluminum alloy castings

and A356.0 permanent mold castings essentially match the performance of the premium-strength castings. The conventionally cast sand castings rather consistently exhibit the poorest performance.

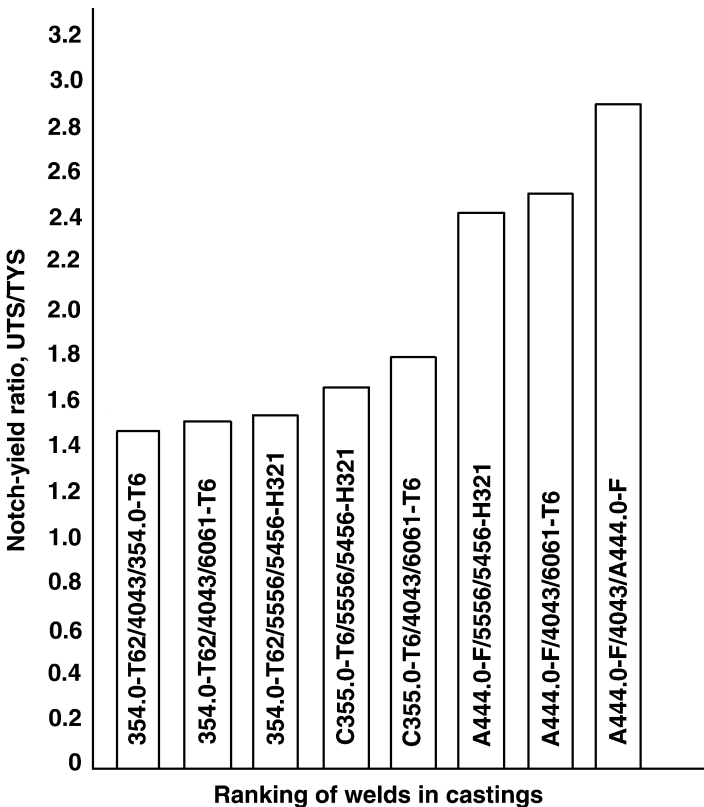


Fig. 8.12 Rankings of notch toughness of welds in aluminum casting alloys based upon notch-yield ratio for combinations of casting alloys and filler alloys (middle number)

When selecting cast alloys for cryogenic service, it seems especially important to pay careful attention to the casting process as well as the alloy itself; high-quality casting processes yield superior combinations of strength and toughness.

Data for welds in cast alloys at subzero temperatures are presented in Table 8.20, and the NYRs are plotted as a function of temperature in Fig. 8.16.

Both 4043 and 5556 welds exhibited NYRs about the same at temperatures down to  $-320^{\circ}\text{F}$  ( $-196^{\circ}\text{C}$ ) as at room temperature. At lower temperatures, both filler alloys exhibited some significant reduction, but in all cases, NYRs were above 1.0, even at  $-452^{\circ}\text{F}$  ( $-269^{\circ}\text{C}$ ).

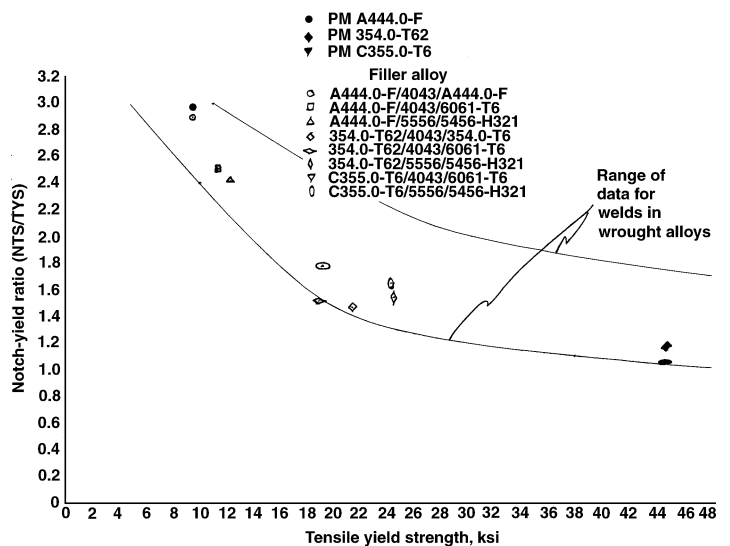


Fig. 8.13 Notch-yield ratio versus tensile yield strength for welds in aluminum alloy castings for combinations of casting alloys and filler alloys (middle number)

**Table 8.19** Representative notch toughness test results of cast aluminum alloys at subzero temperatures

Tests of single specimen per Appendix 3, Fig. A3.5 at each temperature

| Alloy and temper       | Test temperature, °F | Ultimate tensile strength |     | Tensile yield strength(a) |        | Elongation in 2 in., % | Reduction of area, % | Notch tensile strength |     | NTS/TS | NTS/YS |
|------------------------|----------------------|---------------------------|-----|---------------------------|--------|------------------------|----------------------|------------------------|-----|--------|--------|
|                        |                      | psi                       | MPa | psi                       | MPa    |                        |                      | psi                    | MPa |        |        |
| Sand casting           |                      |                           |     |                           |        |                        |                      |                        |     |        |        |
| 208.0-F                | RT                   | 25.0                      | 172 | 18.5                      | 128    | 1.8                    | 2                    | 25.2                   | 174 | 1.01   | 1.36   |
|                        | -112                 | 26.2                      | 181 | 21.7                      | 150    | 2.0(b)                 | 0(b)                 | 21.6                   | 149 | 0.82   | 1.00   |
|                        | -320                 | 30.6                      | 211 | 30.2                      | 208    | 1.3                    | 0                    | 21.7                   | 150 | 0.71   | 0.72   |
| 240.0-F                | RT                   | 33.8                      | 233 | 26.0                      | 179    | 1.4                    | 2                    | 29.9                   | 206 | 0.88   | 1.15   |
|                        | -112                 | 32.8                      | 226 | 22.7                      | 157    | (c)                    | (c)                  | 19.4                   | 134 | <0.58  | 0.75   |
|                        | -320                 | 36.8                      | 254 | 32.4                      | 223    | (c)                    | (c)                  | 17.4                   | 120 | <0.47  | 0.54   |
| 242.0-T77              | RT                   | 29.8                      | 206 | 20.4                      | 141    | 2.1                    | 4                    | 29.0                   | 200 | 0.97   | 1.42   |
|                        | -112                 | 32.8                      | 226 | 22.7                      | 157    | (c)                    | (c)                  | 26.0                   | 179 | <0.81  | 1.17   |
|                        | -320                 | 32.8                      | 226 | 26.8                      | 185    | (c)                    | (c)                  | 27.7                   | 191 | <0.84  | 1.03   |
| 295.0-T6               | RT                   | 42.0                      | 290 | 27.1                      | 187    | 6.4                    | 10                   | 43.5                   | 300 | 1.04   | 1.60   |
|                        | -112                 | 45.5                      | 314 | 32.0                      | 221    | 6.0                    | 5                    | 58.0                   | 400 | 1.08   | 1.45   |
|                        | -320                 | 53.7                      | 370 | 39.9                      | 275    | 5.0                    | 5                    | 58.0                   | 400 | 1.08   | 1.45   |
| X335.0-T6              | RT                   | 37.3                      | 257 | 23.4                      | 161    | 8.6                    | 12                   | 38.2                   | 263 | 1.02   | 1.63   |
|                        | -112                 | 42.3                      | 292 | 27.4                      | 189    | 8.0                    | 10                   | 43.0                   | 297 | 1.02   | 1.57   |
|                        | -320                 | 51.6                      | 356 | 32.1                      | 221    | 7.6                    | 10                   | 45.6                   | 315 | 0.88   | 1.42   |
| 356.0-T4               | RT                   | 31.1                      | 214 | 19.8                      | 137    | 4.4                    | 6                    | 31.6                   | 218 | 1.02   | 1.60   |
|                        | -112                 | 36.6                      | 252 | 23.4                      | 161    | 4.4                    | 6                    | 37.6                   | 259 | 1.04   | 1.61   |
|                        | -320                 | 40.8                      | 281 | 27.2                      | 188    | 2.7                    | 3                    | 42.2                   | 291 | 1.04   | 1.55   |
| 356.0-T6               | RT                   | 38.6                      | 266 | 32.6                      | 225    | 2.2                    | 3                    | 37.4                   | 258 | 0.97   | 1.15   |
|                        | -112                 | 43.1                      | 297 | 35.8                      | 247    | 2.7                    | 2                    | 40.0                   | 276 | 0.93   | 1.12   |
|                        | -320                 | 47.5                      | 328 | 39.2                      | 270    | 2.7                    | 2                    | 44.0                   | 303 | 0.93   | 1.13   |
| 356.0-T7               | RT                   | 37.8                      | 261 | 33.7                      | 232    | 1.6                    | 2                    | 34.5                   | 238 | 0.91   | 1.02   |
|                        | -112                 | 41.4                      | 286 | 34.4                      | 237    | 2.0                    | 2                    | 38.8                   | 268 | 0.94   | 1.13   |
|                        | -320                 | 45.1                      | 311 | 38.8                      | 268    | 1.3                    | 0                    | 43.1                   | 297 | 0.96   | 1.11   |
| 356.0-T71              | RT                   | 28.8                      | 199 | 20.2                      | 139    | 5.0                    | ...                  | 32.0                   | 221 | 1.11   | 1.59   |
|                        | -112                 | 32.2                      | 222 | 22.2                      | 153    | 4.4                    | 5                    | 29.6                   | 204 | 0.92   | 1.34   |
|                        | -320                 | 37.4                      | 258 | 25.3                      | 174    | 3.0                    | 2                    | 34.4                   | 237 | 0.92   | 1.36   |
| A356.0-T61             | RT                   | 41.6                      | 287 | 30.2                      | 208    | 8.8                    | 10                   | 51.4                   | 355 | 1.23   | 1.70   |
|                        | -112                 | 48.2                      | 332 | 34.8                      | 240    | 8.9                    | 10                   | 55.2                   | 381 | 1.15   | 1.59   |
|                        | -320                 | 51.7                      | 357 | 38.0                      | 262    | 4.0                    | 4                    | 59.8                   | 412 | 1.15   | 1.57   |
|                        | -452                 | 66.0                      | 455 | 48.0                      | 331    | 7.1                    | 9                    | 71.9                   | 496 | 1.09   | 1.50   |
| A356.0-T7              | RT                   | 37.1                      | 256 | 30.5                      | 210    | 4.4                    | 7                    | 44.9                   | 310 | 1.21   | 1.47   |
|                        | -112                 | 40.0                      | 276 | 31.7                      | 219    | 4.4                    | 5                    | 41.0                   | 283 | 1.02   | 1.29   |
|                        | -320                 | 45.6                      | 315 | 35.2                      | 243    | 3.4                    | 4                    | 44.0                   | 303 | 0.96   | 1.25   |
| B535.0-F               | RT                   | 41.2                      | 284 | 21.2                      | 146    | 12.9                   | 13                   | 43.8                   | 302 | 1.06   | 2.07   |
|                        | -112                 | 41.6                      | 287 | 22.3                      | 154    | 10.0                   | 11                   | 42.4                   | 292 | 1.06   | 1.90   |
|                        | -320                 | 37.3                      | 257 | 25.5                      | 176    | 3.7                    | 5                    | 35.5                   | 245 | 0.95   | 1.39   |
|                        | -423                 | 30.8                      | 212 | 28.1                      | 194    | 0.8                    | 1                    | 20.0                   | 138 | 0.65   | 0.71   |
| 520.0-F                | RT                   | 34.2                      | 236 | 31.6                      | 218    | 2.1                    | 2                    | 38.4                   | 265 | 1.12   | 1.22   |
|                        | -112                 | 41.6                      | 287 | 37.4                      | 258    | 1.3                    | 1                    | 27.9                   | 192 | 0.79   | 0.75   |
|                        | -320                 | 39.6                      | 273 | 39.6(d)                   | 273(d) | 0.7                    | 0                    | 27.2                   | 188 | 0.69   | 0.69   |
| A612.0-F               | RT                   | 43.1                      | 297 | 34.8                      | 240    | 3.2                    | 7                    | 45.5                   | 314 | 1.05   | 1.31   |
|                        | -112                 | 45.5                      | 314 | 41.0                      | 283    | 2.7                    | 2                    | 50.8                   | 350 | 1.12   | 1.24   |
|                        | -320                 | 53.2                      | 367 | 49.0                      | 338    | 2.4                    | 3                    | 51.0                   | 352 | 0.96   | 1.04   |
| Permanent mold casting |                      |                           |     |                           |        |                        |                      |                        |     |        |        |
| X335.0-T61             | RT                   | 40.8                      | 281 | 28.4                      | 196    | 8.5                    | 13                   | 45.7                   | 315 | 1.12   | 1.61   |
|                        | -112                 | 40.1                      | 277 | 29.2                      | 201    | 4.6                    | 7                    | 47.2                   | 326 | 1.18   | 1.62   |
|                        | -320                 | 45.7                      | 315 | 31.0                      | 214    | 5.3                    | 5                    | 53.4                   | 368 | 1.18   | 1.72   |
|                        | -423                 | 54.0                      | 372 | 35.8                      | 247    | 5.0                    | ...                  | 58.3                   | 402 | 1.08   | 1.63   |
| 354.0-T62              | RT                   | 50.1                      | 346 | 45.5                      | 314    | 1.1                    | 3                    | 54.2                   | 374 | 1.08   | 1.19   |
|                        | -112                 | 54.4                      | 375 | 45.6                      | 315    | 1.3                    | 2                    | 53.2                   | 367 | 0.98   | 1.17   |
|                        | -320                 | 61.0                      | 421 | 48.7                      | 336    | 1.3                    | 2                    | 56.4                   | 389 | 0.92   | 1.16   |
|                        | -423                 | 60.2                      | 415 | 56.1                      | 387    | 0.8                    | 1                    | 57.2                   | 395 | 0.95   | 1.02   |
| 356.0-T6               | RT                   | 36.8                      | 254 | 31.1                      | 214    | 1.0                    | ...                  | 43.0                   | 297 | 1.17   | 1.38   |
|                        | -112                 | 42.0                      | 290 | 34.1                      | 235    | 3.7                    | 5                    | 41.4                   | 286 | 0.98   | 1.21   |
|                        | -320                 | 45.7                      | 315 | 36.5                      | 252    | 3.2                    | 4                    | 45.0                   | 310 | 0.98   | 1.23   |

(continued)

RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For yield strength, offset = 0.2%. (b) Broke outside middle third. (c) Broke in threads. (d) Broke before reaching 0.2%

Table 8.19 (continued)

| Alloy and temper                                                                                                                                                                                                         | Test temperature, °F | Ultimate tensile strength |     | Tensile yield strength(a) |       | Elongation in 2 in., % | Reduction of area, % | Notch tensile strength |     | NTS/TS | NTS/YS |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|---------------------------|-----|---------------------------|-------|------------------------|----------------------|------------------------|-----|--------|--------|
|                                                                                                                                                                                                                          |                      | psi                       | MPa | psi                       | MPa   |                        |                      | psi                    | MPa |        |        |
| Permanent mold casting (continued)                                                                                                                                                                                       |                      |                           |     |                           |       |                        |                      |                        |     |        |        |
| 356.0-T7                                                                                                                                                                                                                 | RT                   | 28.4                      | 196 | 21.4                      | 148   | 4.3                    | 7                    | 35.3                   | 243 | 1.24   | 1.65   |
|                                                                                                                                                                                                                          | −112                 | 32.6                      | 225 | 24.3                      | 168   | 3.7                    | 5                    | 37.2                   | 257 | 1.14   | 1.53   |
|                                                                                                                                                                                                                          | −320                 | 37.3                      | 257 | 25.6                      | 177   | 3.0                    | 4                    | 39.9                   | 275 | 1.07   | 1.56   |
| A356.0-T61                                                                                                                                                                                                               | RT                   | 39.4                      | 272 | 30.8                      | 212   | 4.3                    | 6                    | 47.8                   | 330 | 1.21   | 1.55   |
|                                                                                                                                                                                                                          | −112                 | 41.9                      | 289 | 32.6                      | 225   | 3.7                    | 6                    | 47.7                   | 329 | 1.14   | 1.46   |
|                                                                                                                                                                                                                          | −320                 | 49.4                      | 341 | 35.8                      | 247   | 4.4                    | 6                    | 52.6                   | 363 | 1.07   | 1.47   |
| A356.0-T62                                                                                                                                                                                                               | RT                   | 40.9                      | 282 | 36.7                      | 253   | 2.1                    | 6                    | 46.2                   | 319 | 1.13   | 1.26   |
|                                                                                                                                                                                                                          | −112                 | 45.2                      | 312 | 39.6                      | 273   | 3.0                    | 5                    | 49.8                   | 343 | 1.10   | 1.26   |
|                                                                                                                                                                                                                          | −320                 | 48.6                      | 335 | 41.4                      | 286   | 3.0                    | 5                    | 57.9                   | 399 | 1.19   | 1.40   |
|                                                                                                                                                                                                                          | −423                 | 5.5                       | 38  | 45.3                      | 312   | 3.5                    | 3                    | 63.3                   | 437 | 1.15   | 1.40   |
| A356.0-T7                                                                                                                                                                                                                | RT                   | 28.2                      | 194 | 21.4                      | 148   | 5.3                    | 9                    | 36.9                   | 254 | 1.31   | 1.72   |
|                                                                                                                                                                                                                          | −112                 | 35.4                      | 244 | 25.8                      | 178   | 5.7                    | 8                    | 43.9                   | 303 | 1.24   | 1.70   |
|                                                                                                                                                                                                                          | −320                 | 42.7                      | 295 | 28.5                      | 197   | 6.4                    | 7                    | 47.1                   | 325 | 1.10   | 1.65   |
| 359.0-T62                                                                                                                                                                                                                | RT                   | 46.2                      | 319 | 43.2                      | 298   | 1.2                    | 3                    | 49.7                   | 343 | 1.08   | 1.15   |
|                                                                                                                                                                                                                          | −112                 | 52.4                      | 361 | 47.3                      | 326   | 2.0                    | 4                    | 49.8                   | 343 | 0.95   | 1.05   |
|                                                                                                                                                                                                                          | −320                 | 57.7                      | 398 | 49.5                      | 341   | 1.6                    | 4                    | 49.8                   | 343 | 0.86   | 1.01   |
| A444.0-F                                                                                                                                                                                                                 | RT                   | 23.2                      | 160 | 9.7                       | 67    | 22.2                   | 37                   | 28.6                   | 197 | 1.23   | 2.95   |
|                                                                                                                                                                                                                          | −112                 | 26.2                      | 181 | 10.0                      | 69    | 19.7                   | 24                   | 30.4                   | 210 | 1.16   | 3.04   |
|                                                                                                                                                                                                                          | −320                 | 37.6                      | 259 | 12.1(b)                   | 83(d) | 13.3(b)                | 12(b)                | 32.0                   | 221 | 0.85   | 2.64   |
| Premium engineered casting                                                                                                                                                                                               |                      |                           |     |                           |       |                        |                      |                        |     |        |        |
| C355.0-T61                                                                                                                                                                                                               | RT                   | 43.6                      | 301 | 30.3                      | 209   | 6.4                    | 8                    | 52.6                   | 363 | 1.21   | 1.74   |
|                                                                                                                                                                                                                          | −112                 | 48.4                      | 334 | 33.2                      | 229   | 7.5                    | 8                    | 56.6                   | 390 | 1.17   | 1.7    |
|                                                                                                                                                                                                                          | −320                 | 54.4                      | 375 | 39.4                      | 272   | 5.4                    | 6                    | 62.7                   | 432 | 1.15   | 1.59   |
| A356.0-T61                                                                                                                                                                                                               | RT                   | 41.6                      | 287 | 30.2                      | 208   | 8.8                    | 10                   | 51.4                   | 355 | 1.23   | 1.7    |
|                                                                                                                                                                                                                          | −112                 | 48.2                      | 332 | 34.8                      | 240   | 8.9                    | 10                   | 55.2                   | 381 | 1.15   | 1.59   |
|                                                                                                                                                                                                                          | −320                 | 51.7                      | 357 | 38.0                      | 262   | 4.0                    | 4                    | 59.8                   | 412 | 1.15   | 1.57   |
| A357.0-T61                                                                                                                                                                                                               | RT                   | 51.2                      | 353 | 40.0                      | 276   | 11.4                   | 13                   | 56.2                   | 388 | 1.10   | 1.41   |
|                                                                                                                                                                                                                          | −112                 | 54.4                      | 375 | 43.4                      | 299   | 4.0                    | 5                    | 58.2                   | 401 | 1.08   | 1.35   |
|                                                                                                                                                                                                                          | −320                 | 61.5                      | 424 | 47.0                      | 324   | 4.0                    | 4                    | 59.4                   | 410 | 0.96   | 1.27   |
| A357.0-T62                                                                                                                                                                                                               | RT                   | 51.2                      | 353 | 44.4                      | 306   | 2.5                    | 4                    | 55.4                   | 382 | 1.08   | 1.25   |
|                                                                                                                                                                                                                          | −112                 | 53.1                      | 366 | 46.7                      | 322   | 2.1                    | 3                    | 55.2                   | 381 | 1.04   | 1.18   |
|                                                                                                                                                                                                                          | −320                 | 62.2                      | 429 | 49.3                      | 340   | 2.5                    | 4                    | 59.7                   | 412 | 0.96   | 1.21   |
| RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For yield strength, offset = 0.2%. (b) Broke outside middle third. (c) Broke in threads. (d) Broke before reaching 0.2% |                      |                           |     |                           |       |                        |                      |                        |     |        |        |

RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For yield strength, offset = 0.2%. (b) Broke outside middle third. (c) Broke in threads. (d) Broke before reaching 0.2%

Viewing the data for welds at –320 °F (–196 °C) on the basis of NYR versus joint yield strength (JYS), as in Fig. 8.17, C355.0-T6 welded with either 4043 or 5456 exhibits a fair level of toughness for its high strength level.

All of the welds fall within the range of data for unwelded castings of the same alloys, reinforcing the point that even at temperatures as low as –320 °F (–196 °C) there is no deterioration in the strength-toughness combination associated with the welds. At the lowest temperature for which data were obtained (–452 °F, or –270 °C), A444.0-F welded with 4043 stands out and, of the higher strength alloys, C355.0-T61 welded with 5456 exhibits the highest toughness for its strength level.

### 8.5.2 Tear Resistance

A tear test of the type described in ASTM B 871 (Ref 26) was developed at Alcoa Laboratories to more discriminantly evaluate the fracture characteristics of the aluminum alloys in various tempers (Ref 24). As shown in Fig. 8.18, values of the energies

required to initiate and propagate cracks in small sharply edge-notched specimens (Appendix 3, Fig. A3.6) are determined from measurements of the appropriate areas under the autographic load-deformation curves developed during the tests. The unit propagation energy is equal to the energy required to propagate the crack divided by the initial net area of the specimen, and it is the primary criterion of tear resistance obtained from the tear test.

The unit propagation energy, more than data from notch tensile tests, provides a measure of that combination of strength and ductility that permits a material to resist crack growth under either elastic or plastic stresses. The “tear strength,” the maximum nominal direct-and-bending stress developed by the tear specimen, is also calculated, and the ratio of this tear strength to the yield strength provides a measure of notch toughness; it is referred to as the tear-yield ratio.

The usefulness of the data from this test is not dependent on the development of rapid crack propagation or fracture at elastic stresses. Therefore, the test can be used for all aluminum alloys, even very ductile, tough alloys.

While the results of tear tests are not greatly dependent on specimen thickness in the range from about 0.063 in. (1.6 mm) to about 0.125 in. (3.2 mm), all test results reported herein were obtained on specimens  $0.100 \pm 0.005$  in. ( $2.5 \pm 0.13$  mm) in thickness. Other dimensions were maintained within the tolerances in Appendix 3, Fig A3.6. It is also appropriate to note that tear test results may be dependent on testing machine characteristics. All of the results reported herein were obtained on 50,000 lbf ( $2.2 \times 10^5$  N) Tinius Olsen hydraulic testing machines.

Representative data are shown in Table 8.21 for a variety of cast aluminum alloys with 0.100 in. (2.5 mm) thick specimens machined from  $\frac{1}{2}$  to 1 in. (12 to 25 mm) thick cast slabs.

Ratings of the cast alloys and tempers based on the values of unit propagation energy are shown in Fig. 8.19, and the relationship between unit propagation energy (UPE) to TYS is shown in Fig. 8.20. The relationship between UPE to TYS for wrought aluminum alloys is shown as a band for comparison.

While it is obvious that low-strength alloys A444.0 and B535.0 have exceptionally high tear resistance compared to the other cast alloys as defined by UPE, Fig. 8.20 also reveals that:

- Sand cast alloy B535.0-F has tear resistance in the same range as wrought alloy plate of the same strength level and a much better combination of UPE and TYS than most other casting alloys.

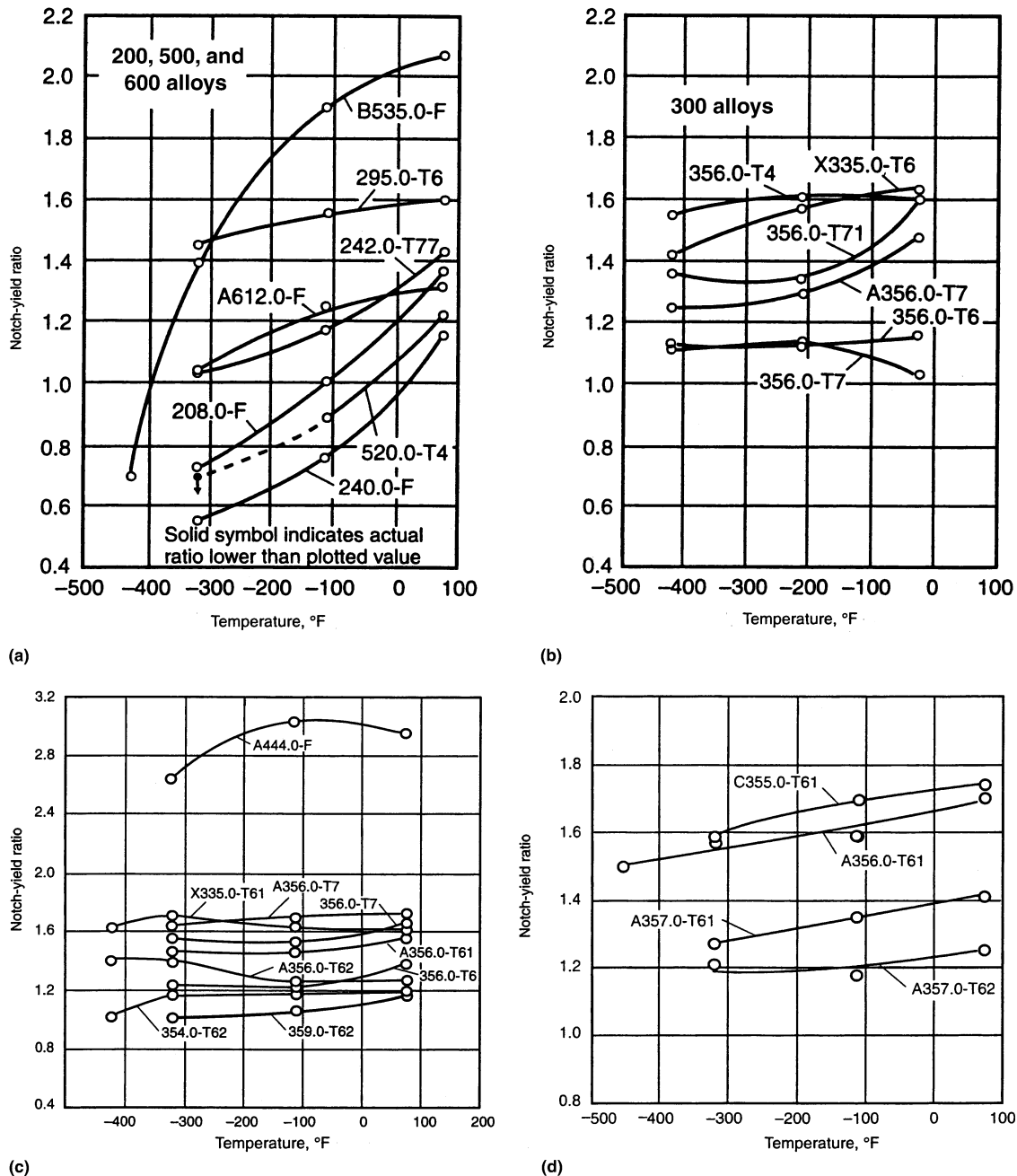


**Fig. 8.14** Notch-yield ratio as a function of temperature for aluminum alloy castings. (a) Sand castings, 2xx.0, 5xx.0, and 6xx.0 alloys. (b) Sand castings, 3xx.0 alloys. (c) Permanent mold castings. (d) Premium engineered castings

- Among the higher-strength castings, the premium engineered castings consistently have among the best combinations of UPE and TYS, especially at relatively high strength levels.
- Permanent mold cast alloys generally fall in the intermediate range, with the notable exceptions that 354.0-T62 and 359.0-T62 essentially match the performance of the premium-strength cast alloys (and, in fact, could be considered premium engineered castings based on AMS-A-21180).
- With the exception of B535.0-F, sand castings generally have among the poorest combination of strength and toughness.

Representative tear test data for welds in cast aluminum alloys are shown in Table 8.22. Ratings of the welded cast alloys and tempers based on the values of unit propagation energy are shown in Fig. 8.21.

For welds in cast alloys, the tear resistance of welds made with 5xxx filler alloys are generally appreciably higher than those of welds made with high-silicon 4043 filler alloy. As in the case with notch toughness data, there are a few exceptions, notably in joints between 6061-T6 plate and 356.0-T6 or -T7 sand castings; in these cases, the high silicon in the 3xx.0 castings may be overwhelming

the inherent high toughness of the 5xxx type filler alloys (although this was not reflected in the A356.0/6061 joints made with 5556).

An analysis of welds in castings based on UPE versus TYS is not available because joint yield strengths were not reported and a plot cannot be made. However, a scan of the data in Table 8.22 illustrates that 4043 welds in castings and 5556 welds in high-silicon castings generally provide lower toughness than other combinations of filler and parent alloys.

In general, one can conclude that for applications where high toughness is critical for joining aluminum castings, 5xxx filler alloys would be recommended, and 4043 filler alloy should be avoided except perhaps in the case of high-silicon casting alloys.

### 8.5.3 Fracture Toughness

The results of plane-strain fracture toughness tests of several aluminum castings are given in Table 8.23 (Ref 19, 24). The specimens used were of the design shown in Appendix 3, Fig. A3.7.

Background on the development and application of fracture mechanics to design is presented in Ref 24 and the other references cited therein. Very briefly summarized, it was through the work of A.A. Griffith, G.R. Irwin, and ASTM Committee E-24 on Fracture

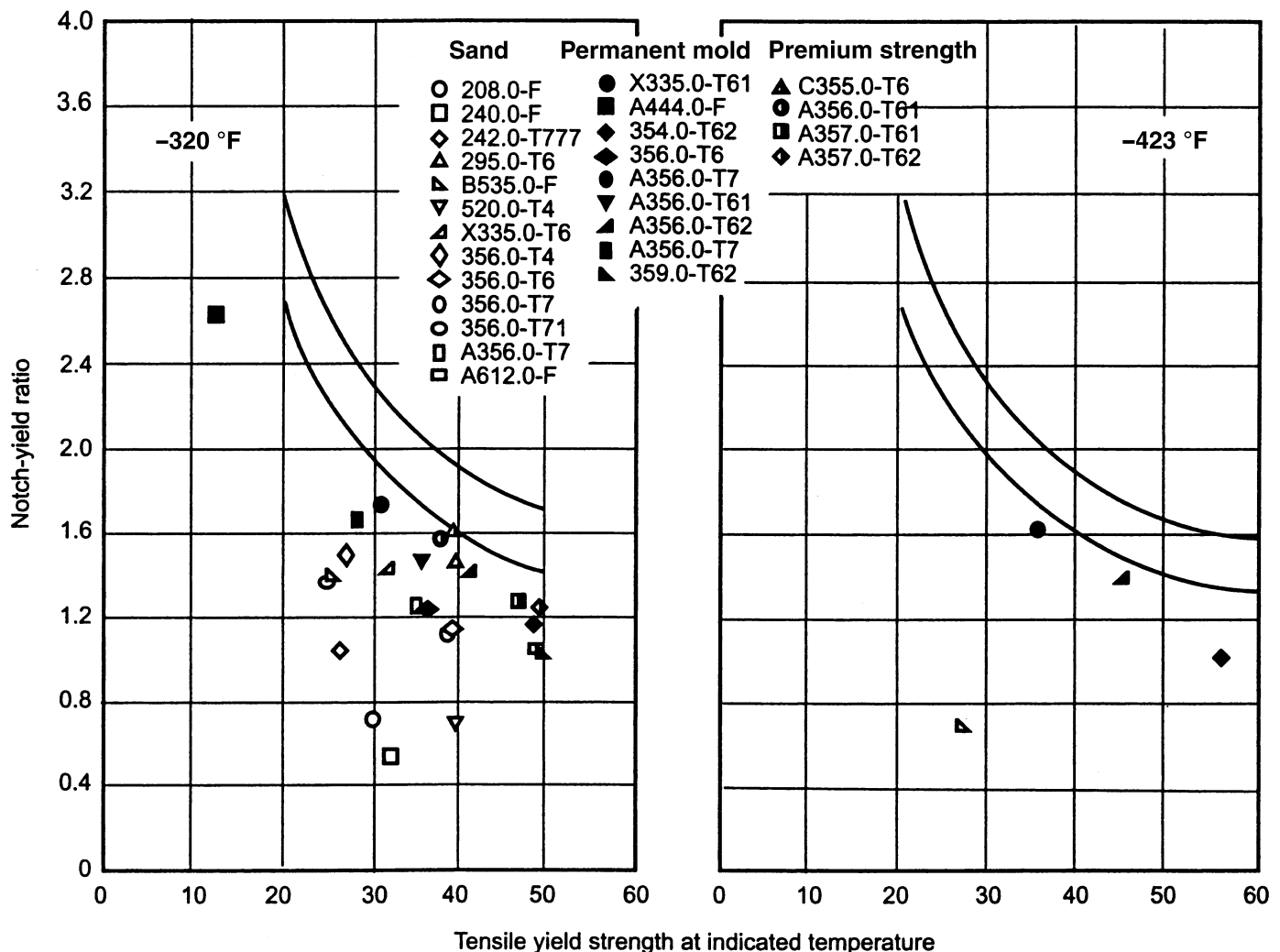


Fig. 8.15 Notch-yield ratio versus tensile yield strength for aluminum casting alloys at -320 °F (-196 °C) and -423 °F (-253 °C)



**Table 8.20 Notch toughness tests of representative welds in aluminum alloy sand castings at subzero temperatures**

Specimens per Appendix 3, Fig. A3.5; each line represents the average of duplicate tests on one lot of material. Joint efficiencies based on typical values for parent alloys. No postweld thermal treatment

| Alloy and temper combination | Filler alloy | Test temperature, °F | Ultimate tensile strength |     | Tensile yield strength(a) |     | Elongation in 2 in., % | Reduction of area, % | Jointmb;0 strength efficiency, % | Location of fracture(b) | Notch tensile strength |     | NTS/TS | NTS/YS |
|------------------------------|--------------|----------------------|---------------------------|-----|---------------------------|-----|------------------------|----------------------|----------------------------------|-------------------------|------------------------|-----|--------|--------|
|                              |              |                      | ksi                       | MPa | ksi                       | MPa |                        |                      |                                  |                         | ksi                    | MPa |        |        |
| A444.0-F to A444.0-F         | 4043         | RT                   | 23.8                      | 164 | 9.5                       | 66  | 12.1                   | 22                   | 100                              | B                       | 27.5                   | 190 | 1.15   | 2.90   |
|                              |              | -112                 | 26.1                      | 180 | 10.0                      | 69  | 14.3                   | 26                   | 100                              | B                       | 31.7                   | 219 | 1.21   | 3.17   |
|                              |              | -320                 | 33.5                      | 231 | 11.5                      | 79  | 6.4                    | 9                    | 89                               | B                       | 38.1                   | 263 | 1.14   | 3.31   |
|                              |              | -452                 | 48.6                      | 335 | 18.0                      | 124 | 10.0                   | 13                   | (c)                              | A                       | 40.4                   | 279 | 0.83   | 2.24   |
| A444.0-F to 6061-T6          | 4043         | RT                   | 24.0                      | 166 | 11.4                      | 79  | 5.7                    | 23                   | 100                              | B                       | 29.3                   | 202 | 1.22   | 2.51   |
|                              |              | -320                 | 34.7                      | 239 | 14.8                      | 102 | 7.1                    | 9                    | 92                               | B                       | 34.1                   | 235 | 0.98   | 2.30   |
|                              |              | -452                 | 45.5                      | 314 | 28.5                      | 197 | 7.1                    | 8                    | (c)                              | B                       | 36.9                   | 254 | 0.81   | 1.29   |
|                              |              |                      |                           |     |                           |     |                        |                      |                                  |                         |                        |     |        |        |
| A444.0-F to 5456-H321        | 5556         | RT                   | 24.1                      | 166 | 12.2                      | 84  | 12.1                   | 27                   | 100                              | B                       | 29.5                   | 203 | 1.22   | 2.42   |
|                              |              | -112                 | 27.0                      | 186 | 15.0                      | 103 | 5.0                    | 14                   | 100                              | B                       | 31.1                   | 214 | 1.15   | 2.08   |
|                              |              | -320                 | 33.4                      | 230 | 16.1                      | 111 | 5.7                    | 8                    | 89                               | C                       | 34.3                   | 237 | 1.03   | 2.13   |
|                              |              | -452                 | 37.2                      | 257 | 25.4                      | 175 | 4.3                    | 7                    | (c)                              | C                       | 36.4                   | 251 | 0.98   | 1.43   |
| 354.0-T62 to 354.0-T6        | 4043         | RT                   | 37.8                      | 261 | 21.5                      | 148 | 6.4                    | 10                   | 76                               | A                       | 32.0                   | 221 | 0.85   | 1.48   |
|                              |              | -112                 | 40.4                      | 279 | 22.9                      | 158 | 5.7                    | 11                   | 74                               | A                       | 33.0                   | 228 | 0.82   | 1.44   |
|                              |              | -320                 | 48.9                      | 337 | 24.1                      | 166 | 5.0                    | 8                    | 84                               | A                       | 36.9                   | 254 | 0.76   | 1.53   |
|                              |              | -452                 | 55.0                      | 379 | 38.3                      | 264 | 4.3                    | 7                    | (c)                              | A                       | 42.3                   | 292 | 0.72   | 1.05   |
| 354.0-T62 to 6061-T6         | 4043         | RT                   | 30.8                      | 212 | 19.0                      | 131 | 9.3                    | 39                   | 62                               | C                       | 28.7                   | 198 | 0.93   | 1.51   |
|                              |              | -112                 | 35.8                      | 247 | 21.8                      | 150 | 7.1                    | 7                    | 66                               | A                       | 31.5                   | 217 | 0.88   | 1.44   |
|                              |              | -320                 | 43.1                      | 297 | 23.0                      | 159 | 5.0                    | 7                    | 71                               | A                       | 34.7                   | 239 | 0.81   | 1.51   |
|                              |              | -452                 | 45.9                      | 317 | 35.7                      | 246 | 2.9                    | 4                    | (c)                              | A                       | 37.4                   | 258 | 0.82   | 1.05   |
| 354.0-T62 to 5456-H321       | 5556         | RT                   | 37.7                      | 260 | 24.6                      | 170 | 3.6                    | 5                    | 75                               | A                       | 37.7                   | 260 | 1.00   | 1.53   |
|                              |              | -112                 | 42.1                      | 290 | 27.1                      | 187 | 3.6                    | 6                    | 77                               | A                       | 35.7                   | 246 | 0.85   | 1.42   |
|                              |              | -320                 | 47.6                      | 328 | 30.4                      | 210 | 3.6                    | 5                    | 78                               | A                       | 39.5                   | 272 | 0.83   | 1.30   |
|                              |              | -452                 | 47.7                      | 329 | 37.6                      | 259 | 2.9                    | 3                    | (c)                              | A                       | 41.3                   | 285 | 0.87   | 1.10   |
| C355.0-T61 to 6061-T6        | 4043         | RT                   | 28.9                      | 199 | 19.3                      | 133 | 7.1                    | 32                   | 66                               | C                       | 34.5                   | 238 | 1.19   | 1.79   |
|                              |              | -320                 | 44.4                      | 306 | 23.3                      | 161 | 7.9                    | 19                   | 82                               | A                       | 38.9                   | 268 | 0.88   | 1.67   |
|                              |              | -452                 | 52.3                      | 361 | 38.6                      | 266 | 6.4                    | 8                    | (c)                              | A                       | 40.4                   | 279 | 0.78   | 1.05   |
|                              |              |                      |                           |     |                           |     |                        |                      |                                  |                         |                        |     |        |        |
| C355.0-T61 to 5456-H321      | 5556         | RT                   | 35.4                      | 244 | 24.4                      | 168 | 3.6                    | 5                    | 81                               | A                       | 40.5                   | 279 | 1.15   | 1.66   |
|                              |              | -320                 | 45.6                      | 315 | 29.3                      | 202 | 4.3                    | 7                    | 84                               | C                       | 45.0                   | 310 | 0.99   | 1.54   |
|                              |              | -452                 | 48.3                      | 333 | 40.8                      | 281 | 2.9                    | 5                    | (c)                              | C                       | 45.5                   | 314 | 0.94   | 1.12   |
|                              |              |                      |                           |     |                           |     |                        |                      |                                  |                         |                        |     |        |        |

RT, room temperature; NTS, notch tensile strength; TS, tensile strength; YS, yield strength. (a) For joint yield strength, offset = 0.2%, over a 2 in. gage length. (b) Location of fracture of unnotched specimens; A, through weld; B, ½ to 2½ in. from weld; C, edge of weld. (c) No parent metal tests for comparison

Testing of High-Strength Metallic Materials (now ASTM Committee E-9) that about nineteen ASTM Standard Test Methods, including E 399 (Ref 27) were generated for the determination of fracture toughness parameters that relate the load-carrying capacity of structural members stressed in tension to the size of cracks, flaws, or design discontinuities that may be present in the stress field, shown in Fig. 8.22.

These parameters, primarily the stress-intensity factor,  $K$ , and the strain energy release rate,  $G$ , are more useful to the designer than those measures of toughness that provide only a relative merit rating of materials, such as notch tensile and tear tests.  $K$  and  $G$  characterize the potential fracture conditions in terms that permit structural designers to design resistance to unstable crack growth and catastrophic fracture into a structure, even with materials that are relatively low in toughness, including those sometimes described as brittle.

Since most castings are relatively thick and irregular in shape, this discussion focuses on the values of critical stress-intensity factor developed under plane-strain conditions, that is, in which plane sections remain plane, and stress buildup becomes three-dimensional in nature. This is appropriate not only because of the

complex geometry of most castings, but also because it represents the most severe and, therefore, conservative situation. The critical value of plane-strain stress-intensity factors is referred to as  $K_{Ic}$ , and the remainder of the fracture toughness discussion for casting focuses on that value for individual casting alloys.

The limited applicability of linear elastic fracture mechanics to most aluminum alloys, that is, other than very-high-strength heat treated alloys, must be emphasized. Since the analysis is based on the assumption that unstable crack growth develops in elastically stressed material, the fracture toughness approach is applicable primarily to relatively high-strength materials with relatively low ductility. The type of brittle fracture behavior assumed in the development of linear-elastic fracture-mechanics concepts is seldom experienced with the majority of aluminum alloys, cast or wrought. Nevertheless, it is useful to overview the approach, provide representative data for those alloys for which the analysis is useful, and illustrate ways of estimating the fracture toughness of the tougher alloys.

What can be noted in summary is that fracture toughness data such as those in Table 8.23 for several aluminum casting alloys is that they may be used for the following purposes:

|                                   |                                                                                                                                                                                                                                                                                                                                                                         |
|-----------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alloy selection                   | By merit rating based on values of $K_{Ic}$ and/or $K_{Ic}$<br>By determination of residual load-carrying capacity with due regard for initial size of the discontinuity, the rate of fatigue crack propagation, and the design life of the structure                                                                                                                   |
| Design of new structures          | Establish the design stress for a given component consistent with maximum expected crack length<br>Establish limiting crack length for a component on the basis of a given operating stress<br>Establish inspection criteria (including thoroughness and frequency) consistent with the potential initial crack size and the expected rate of fatigue crack propagation |
| Evaluation of existing structures | Estimate residual strength and tolerance for additional loading<br>Estimate residual life consistent with observed crack length, rate of fatigue crack propagation, and critical crack length                                                                                                                                                                           |

It is important to recognize that values of “flaw” or “crack” size, as referred to above, must take into account any design discontinuities to which the real flaw or crack are adjacent or from which they grow. For example, a  $\frac{3}{16}$  in. (4.8 mm) hole, with a  $\frac{1}{8}$  in. (3.2 mm) fatigue crack growing out of one side constitutes a flaw  $\frac{5}{16}$  in. (8 mm) in length. In addition, in the case of castings, it must include the size of any internal porosity that serves as a crack initiator.

Of the aluminum casting alloys for which plane-strain fracture toughness data are available (Table 8.23), premium engineered

castings of the 2xx.0 series consistently provided the highest values of  $K_{Ic}$ . For A201.0-T7, 224.0-T7, and 249.0-T7,  $K_{Ic}$  values were about or above  $30 \text{ ksi}\sqrt{\text{in.}}$  ( $33 \text{ MPa}\sqrt{\text{m}}$ ).

The fracture toughness values are plotted as a function of tensile yield strength in Fig. 8.23.

While there is insufficient data to establish any meaningful trends, the superiority of premium engineered A201.0-T7 is even clearer in this presentation; it clearly has the best combination of strength and fracture toughness of this group of alloys. In fact, it is also apparent that there is a general superiority of all of the premium engineered 2xx.0 alloy castings over those of premium engineered 3xx.0 alloy castings with respect to their combination of strength and toughness. Sand cast 356.0-T6 exhibited the poorest performance in this respect, consistent with indicators from notch tensile and tear tests.

### 8.5.4 Interrelation of Measures of Fracture Resistance

Based on analyses of thousands of data from tests of wrought alloys, there are fairly well defined and useful correlations between both NYR and UPE and the fracture toughness parameter  $K_{Ic}$  (Ref 24). For example, from data for wrought aluminum alloys, notch-yield ratio and unit propagation energy correlate well with  $K_{Ic}$  from the same lots of material as illustrated in Fig. 8.24 and 8.25, respectively.

These relationships are sufficiently well defined that in situations where  $K_{Ic}$  values have not been determined or where fully valid  $K_{Ic}$  values cannot be measured, the results of notch tensile and tear test results can be used to estimate plane-strain fracture toughness values.

Utilizing such correlations, it is possible to estimate the plane-strain fracture toughness of a few casting alloys for which sufficient NYR and UPE values are available, as illustrated in the far right columns of Table 8.24, where fracture parameters from the three tests are summarized. The estimated values are clearly identified, and that characterization should remain with them if/when they are taken out of this context for other use.

Caution must be exercised in the application of  $K_{Ic}$  values estimated in this manner; they are presented only to illustrate the range of  $K_{Ic}$  values that may be obtained from aluminum castings. This caution is particularly applicable for aluminum castings where individual cast components through their unique mold designs, metal flow characteristics, and chill procedures, may represent a wide range of fracture resistance. Ideally, once a fracture critical region is identified for a specific casting, a few fracture toughness tests would be made of specimens taken from those regions expected to experience the highest stresses.

## 8.6 Subcritical Crack Growth

As noted in Section 8.5.3, it is important when designing fracture critical structures to consider the case when a crack may initiate and grow as a result of service stresses, perhaps from an internal discontinuity of some type in the stress field. Discontinuities may be metallurgical in nature (e.g., forging defect or poros-

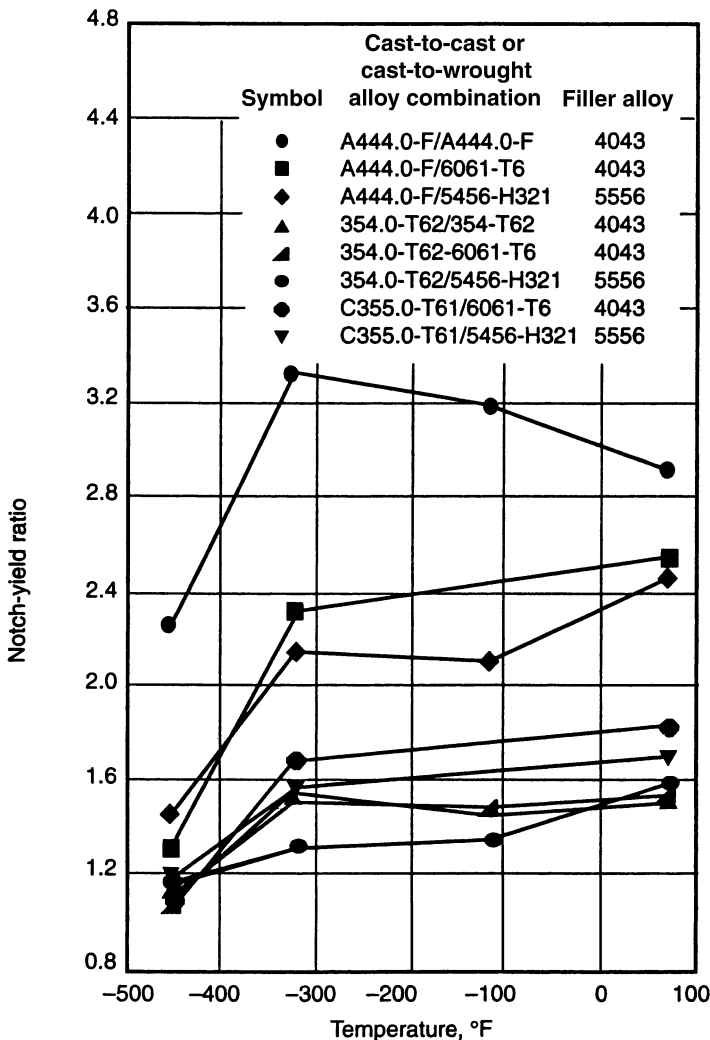


Fig. 8.16 Notch-yield ratio as a function of temperature for welds in aluminum alloy castings

ity) or design based (e.g., rivet hole or window). For the analyses of such situations, it is appropriate to consider that whatever flaw or discontinuity cannot be ruled out reliably by nondestructive testing may well be present somewhere in the structure and may serve as the initiation site of fatigue crack growth that must be tracked.

Subcritical crack growth may occur during service loading by three mechanisms, fatigue, creep, and stress corrosion. Tests have been devised to define the resistance of materials to each of these three types of crack growth (Ref 24). Regrettably, there are relatively few data published on the subcritical crack growth of aluminum castings, but it is useful to see what can be gleaned from the available information.

Each of the three types of subcritical crack growth are examined in the following sections.

### 8.6.1 Fatigue Crack Growth

Fatigue crack growth rate (FCGR) data are conventionally measured by recording the rate of growth of a crack at the root of the notch in compact tension specimens of the type in Appendix 3, Fig. A3.7, and presenting the data in terms of the rate of crack growth as a function of the stress-intensity factor,  $K$ . As the crack grows longer, the stress intensity increases, and at some point potentially approaches the limiting critical conditions established from the fracture toughness tests ( $K_{Ic}$  or  $K_{Ic}$ ) when complete fracture must be expected.

Fatigue crack growth tests may also be conducted in which the applied loads, and therefore stress intensities, are decreased gradually so that the limiting or “threshold” value of the applied  $K$  when growth no longer occurs may be measured.

The results of a programmed series of FCGR tests for A356.0-T6 castings produced by various methods, including conventional tilt (permanent) mold, squeeze cast, and vacuum high pressure (VRC/PRC) castings are presented in Fig. 8.26 and 8.27, for stress ratios of 0.1 and 0.5, respectively (Ref 18).

These figures illustrate that crack growth rates vary only slightly for the three casting processes, nor is there much difference in the threshold stress intensity levels for crack growth, as indicated by the data in Table 8.25.

Considering the scatter in the individual data from which the values in Table 8.25 are derived, it is difficult to conclude that the differences observed are significant. If there is any difference that may be worth investigating further, it is the advantage for the squeeze cast samples at 250 °F (120 °C).

Regrettably, such data are available for few casting alloys, and so once again it is useful to look at potentially useful correlations between more readily available test data and fatigue crack growth rates. Such a correlation has been noted between unit propagation energy from the tear test and fatigue crack growth rate for wrought aluminum alloys (Ref 24), as illustrated in Fig. 8.28; while no confirming test data are available for casting alloys, this relationship may be utilized to judge at least the relative ratings of cast alloys with respect to FCGR.

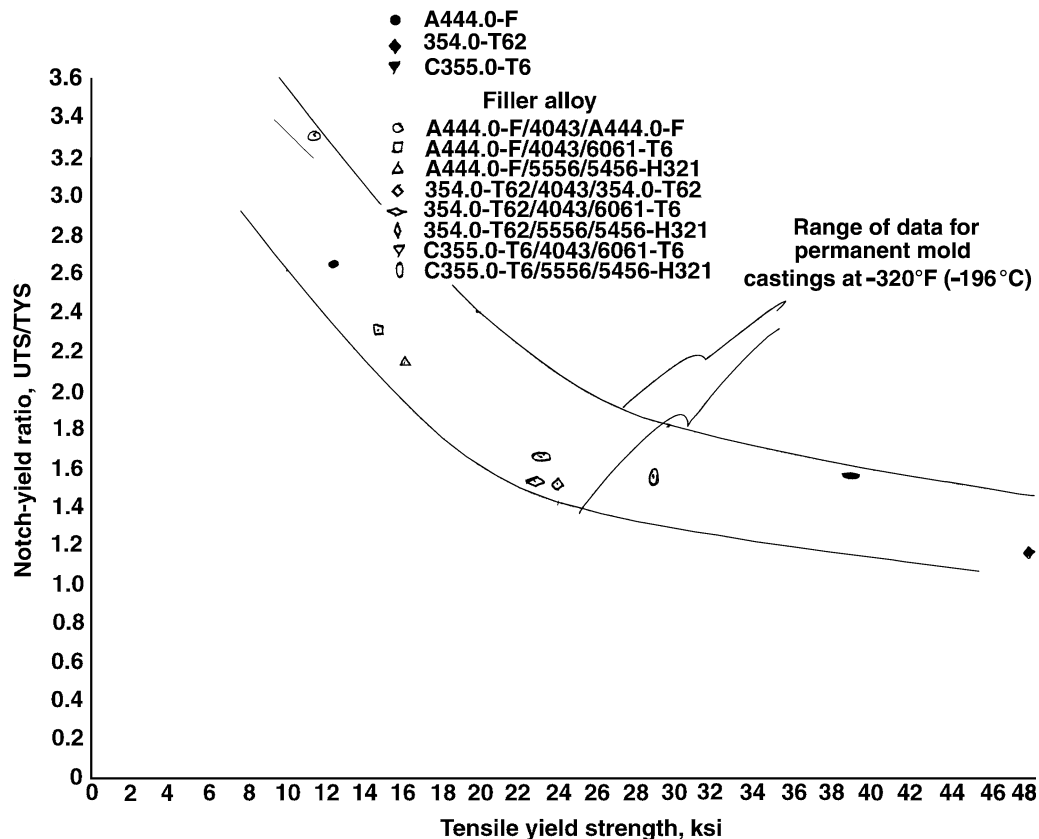


**Fig. 8.17** Notch-yield ratio versus tensile yield strength for welded aluminum alloy castings at -320 °F (-196 °C) for combinations of casting alloys and filler alloys (middle number)

### 8.6.2 Creep Crack Growth

Evaluations of notched tensile and compact tension specimens under sustained loads have shown that some wrought aluminum alloys widely used in high-temperature applications (e.g., 2219) may experience some time-dependent crack growth at certain temperatures, referred to as creep crack growth (Ref 24). Such data are typically presented as in Fig. 8.29, which presents creep crack growth rates,  $da/dt$ , as a function of the applied stress-intensity factor,  $K_I$ . As in the case of fatigue crack growth rates, presentation in this format permits tracking of the crack growth in fracture-mechanics terms, relatable to the critical fracture conditions defined by fracture toughness tests.

Such data have not been developed to the authors' knowledge for cast aluminum alloys. However, it would be good design practice to at least consider this possibility when designing aluminum castings for sustained loads at high temperatures in the presence of severe stress raisers, including internal discontinuities. Corroborating tests may be worthwhile, and in this case it is useful to note that sustained load tests of severely notched tensile specimens have been shown to be good indicators of potential problems of this type.

### 8.6.3 Stress-Corrosion Crack Growth

For certain wrought 2xxx and 7xxx aluminum alloys—especially when subjected to stresses in the short-transverse (through-the-thickness) direction of thick plate, forgings, and extrusions—the potential for intergranular stress-corrosion crack growth must be considered. While this phenomenon has long been studied with tensile loading of smooth specimen subjected to exposure in potentially troublesome environments, it too can be examined in

fracture mechanics terms of the rate of crack growth,  $da/dt$ , as a function of the applied stress-intensity factor,  $K_I$ .

Since most aluminum casting alloys, with notable exceptions, have not been found to be susceptible to stress-corrosion cracking (see Section 8.7), no such data have been developed for casting alloys and this phenomenon probably does not have to be addressed as a potential cause of subcritical crack propagation in most situations.

## 8.7 Corrosion Resistance

Rankings of the resistance of aluminum casting alloys to general corrosion and to stress-corrosion cracking are included in Table 8.26 (Ref 28). The solution potentials of a representative group of alloys are contained in Table 8.27.

A few specific comments about the corrosion resistance of specific alloy groups are also appropriate as presented below.

### 8.7.1 Aluminum-Copper Casting Alloys (2xx.x)

Alloys in which copper is the major alloying element are generally less resistant to corrosion than other alloy groups, and corrosion resistance tends to decrease with increasing copper content. This effect is attributed to the presence of minute galvanic cells created by the formation of copper-rich regions or films at the surface (28), which with increasing time, go into solution and replate onto the alloys to form metallic copper cathodes. Reduction of the copper ions and increased reaction of  $O^{2-}$  and  $H^+$  increase the corrosion rate.

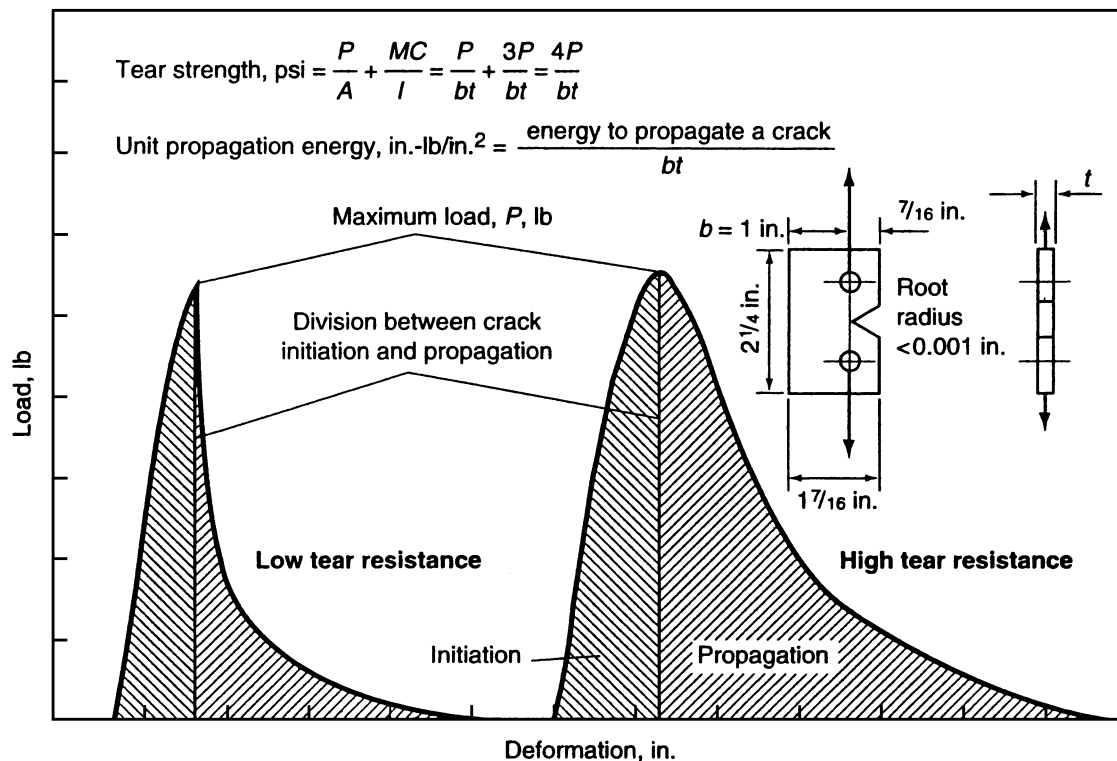


Fig. 8.18 Tear test specimen and representation of load-deformation curve from a tear test. A, area; M, moment; C, moment arm; I, moment of inertia

**Table 8.21 Results of tensile and tear tests of aluminum alloy castings at room temperature**

Specimens per Appendix 3, Fig. A3.6; each line represents average results of tests of duplicate specimens of one individual lot of material

| Alloy and temper            | Tensile tests             |                           |                     |     | Elongation in 2 in. % | Tear strength |     | TYR  | Tear tests                |                    | Total energy, in.-lb | Unit                     |                         |
|-----------------------------|---------------------------|---------------------------|---------------------|-----|-----------------------|---------------|-----|------|---------------------------|--------------------|----------------------|--------------------------|-------------------------|
|                             | Ultimate tensile strength | Tensile yield strength(a) | Energy required to: |     |                       |               |     |      | propagate a crack, in.-lb | propagation energy |                      |                          |                         |
|                             |                           |                           | ksi                 | MPa |                       | ksi           | MPa |      |                           |                    |                      | initiate a crack, in.-lb | in.-lb/in. <sup>2</sup> |
| Sand casting                |                           |                           |                     |     |                       |               |     |      |                           |                    |                      |                          |                         |
| X335.0-T6                   | 37.3                      | 257                       | 23.4                | 161 | 8.6                   | 38.4          | 265 | 1.64 | 8                         | 19                 | 27                   | 190                      | 33                      |
|                             | 35.3                      | 243                       | 22.6                | 156 | 6.8                   | 39.3          | 271 | 1.74 | 11                        | 19                 | 30                   | 195                      | 34                      |
| Average                     | 35.4                      | 244                       | 22.9                | 158 | 7.7                   | 38.8          | 268 | 1.69 | 10                        | 19                 | 29                   | 192                      | 34                      |
| 356.0-T4                    | 31.1                      | 214                       | 19.8                | 137 | 4.4                   | 32.8          | 226 | 1.66 | 7                         | 19(b)              | 26(b)                | 190(b)                   | 33(b)                   |
|                             | 29.4                      | 203                       | 17.6                | 121 | 2.3                   | 30.6          | 211 | 1.74 | 6                         | 19(b)              | 25(b)                | 190(b)                   | 33(b)                   |
| Average                     | 30.2                      | 208                       | 18.7                | 129 | 3.4                   | 31.7          | 219 | 1.70 | 6                         | 19(b)              | 26(b)                | 190(b)                   | 33(b)                   |
| 356.0-T6                    | 38.6                      | 266                       | 32.6                | 225 | 2.2                   | 32.7          | 226 | 1.00 | 4                         | 8                  | 12                   | 75                       | 13                      |
| 356.0-T7                    | 37.8                      | 261                       | 33.7                | 232 | 1.6                   | 39.2          | 270 | 0.87 | 3                         | 7                  | 10                   | 70                       | 12                      |
| 356.0-T71                   | 31.9                      | 220                       | 24.2                | 167 | 3.8                   | 34.8          | 240 | 1.44 | 7                         | 14                 | 21                   | 140                      | 25                      |
|                             | 29.4                      | 203                       | 20.7                | 143 | 4.1                   | 32.2          | 222 | 1.55 | 7                         | 11                 | 18                   | 110                      | 19                      |
|                             | 28.8                      | 199                       | 20.2                | 139 | 2.0                   | 30.6          | 211 | 1.51 | 6                         | 11                 | 17                   | 110                      | 19                      |
| Average                     | 30.0                      | 207                       | 21.7                | 150 | 3.3                   | 52.6          | 363 | 1.50 | 7                         | 12                 | 19                   | 120                      | 21                      |
| A356.0-T7                   | 37.1                      | 256                       | 30.5                | 210 | 4.4                   | 34.2          | 236 | 1.12 | 5                         | 8                  | 13                   | 75                       | 13                      |
|                             | 37.6                      | 259                       | 33.2                | 229 | 2.1                   | 33.6          | 232 | 1.01 | 4                         | 10                 | 14                   | 100                      | 18                      |
| Average                     | 37.4                      | 258                       | 31.8                | 219 | 3.2                   | 33.9          | 234 | 1.06 | 4                         | 9                  | 13                   | 88                       | 15                      |
| B535.0-F                    | 41.2                      | 284                       | 21.2                | 146 | 12.9                  | 47.2          | 326 | 2.23 | 35                        | 108                | 143                  | 1075                     | 188                     |
|                             | 42.6                      | 294                       | 21.0                | 145 | 12.6                  | 47.8          | 330 | 2.28 | 30                        | 74                 | 104                  | 740                      | 130                     |
| Average                     | 41.9                      | 289                       | 21.1                | 146 | 12.8                  | 47.5          | 328 | 2.26 | 32                        | 91                 | 124                  | 908                      | 159                     |
| Permanent mold casting      |                           |                           |                     |     |                       |               |     |      |                           |                    |                      |                          |                         |
| X335.0-T61                  | 40.8                      | 281                       | 28.4                | 196 | 8.5                   | 43.2          | 298 | 1.52 | 9                         | 22                 | 31                   | 220                      | 39                      |
|                             | 35.6                      | 246                       | 25.6                | 177 | 3.5                   | 43.0          | 297 | 1.68 | 9                         | 23                 | 32                   | 235                      | 41                      |
| Average                     | 38.2                      | 263                       | 23.8                | 164 | 6.0                   | 43.1          | 297 | 1.60 | 9                         | 22                 | 31                   | 228                      | 40                      |
| 354.0-T62                   | 50.1                      | 346                       | 45.5                | 314 | 1.1                   | 46.5          | 321 | 1.02 | 6                         | 13                 | 19                   | 130                      | 23                      |
|                             | 47.8                      | 330                       | 44.3                | 306 | 0.9                   | 45.9          | 317 | 1.04 | 6                         | 13                 | 19                   | 125                      | 22                      |
| Average                     | 49.0                      | 340                       | 44.9                | 310 | 1.0                   | 46.2          | 319 | 1.03 | 6                         | 13                 | 19                   | 128                      | 22                      |
| C355.0-T7                   | 37.0                      | 255                       | 31.0                | 214 | 2.1                   | 36.9          | 254 | 1.19 | 6                         | 8                  | 14                   | 85                       | 15                      |
|                             | 41.0                      | 283                       | 30.4                | 210 | 2.5                   | 33.2          | 229 | 1.04 | 4                         | 8                  | 12                   | 75                       | 13                      |
| Average                     | 39.0                      | 269                       | 30.7                | 212 | 2.3                   | 35.0          | 241 | 1.12 | 5                         | 8                  | 13                   | 80                       | 14                      |
| 356.0-T6                    | 35.8                      | 247                       | 31.1                | 214 | 1.4                   | 40.6          | 280 | 1.30 | 8                         | 10                 | 18                   | 105                      | 18                      |
|                             | 41.4                      | 286                       | 32.2                | 222 | 4.2                   | 34.2          | 236 | 1.06 | 4                         | 6                  | 10                   | 55                       | 10                      |
| Average                     | 38.6                      | 266                       | 31.6                | 218 | 2.8                   | 37.4          | 258 | 1.18 | 6                         | 8                  | 14                   | 80                       | 14                      |
| 356.0-T7                    | 28.4                      | 196                       | 21.4                | 148 | 4.3                   | 37.0          | 255 | 1.73 | 10                        | 16                 | 26                   | 165                      | 29                      |
|                             | 31.7                      | 219                       | 22.6                | 156 | 7.5                   | 38.3          | 264 | 1.70 | 10                        | 17                 | 27                   | 170                      | 30                      |
|                             | 29.6                      | 204                       | 22.0                | 152 | 3.2                   | 35.2          | 243 | 1.60 | 10                        | 17                 | 27                   | 170                      | 30                      |
| Average                     | 29.8                      | 206                       | 22.0                | 152 | 5.0                   | 36.8          | 254 | 1.68 | 10                        | 17                 | 27                   | 168                      | 29                      |
| A356.0-T61                  | 39.4                      | 272                       | 30.8                | 212 | 4.3                   | 43.2          | 298 | 1.40 | 9                         | 14                 | 23                   | 140                      | 25                      |
|                             | 41.7                      | 288                       | 30.4                | 210 | 7.5                   | 44.4          | 306 | 1.46 | 9                         | 12                 | 21                   | 120                      | 21                      |
| Average                     | 40.6                      | 280                       | 30.6                | 211 | 5.9                   | 43.8          | 302 | 1.43 | 9                         | 13                 | 22                   | 130                      | 23                      |
| A356.0-T62                  | 40.9                      | 282                       | 36.7                | 253 | 2.1                   | 46.2          | 319 | 1.26 | 9                         | 14                 | 23                   | 145                      | 25                      |
|                             | 43.6                      | 301                       | 36.3                | 250 | 3.9                   | 46.4          | 320 | 1.28 | 9                         | 13                 | 22                   | 130                      | 23                      |
| Average                     | 42.2                      | 291                       | 36.5                | 252 | 3.0                   | 46.3          | 319 | 1.27 | 9                         | 14                 | 23                   | 138                      | 24                      |
| A356.0-T7                   | 28.2                      | 194                       | 21.4                | 148 | 5.3                   | 29.8          | 206 | 1.86 | 14                        | 30                 | 44                   | 295                      | 52                      |
|                             | 30.7                      | 212                       | 22.2                | 153 | 8.5                   | 39.2          | 270 | 1.77 | 14                        | 25                 | 39                   | 250                      | 44                      |
| Average                     | 29.4                      | 203                       | 21.8                | 150 | 6.9                   | 34.5          | 238 | 1.82 | 14                        | 28                 | 42                   | 272                      | 48                      |
| 359.0-T62                   | 46.2                      | 319                       | 43.2                | 298 | 1.2                   | 44.7          | 308 | 1.04 | 7                         | 16                 | 23                   | 155                      | 27                      |
|                             | 47.4                      | 327                       | 43.1                | 297 | 1.6                   | 41.0          | 283 | 0.95 | 4                         | 12                 | 16                   | 115                      | 20                      |
| Average                     | 46.7                      | 322                       | 43.2                | 298 | 1.4                   | 42.8          | 295 | 1.00 | 6                         | 14                 | 20                   | 135                      | 24                      |
| A444.0-F                    | 23.2                      | 160                       | 9.7                 | 67  | 22.2                  | 27.6          | 190 | 2.85 | 19                        | 39                 | 58                   | 390                      | 68                      |
|                             | 22.5                      | 155                       | 9.6                 | 66  | 15.7                  | 28.2          | 194 | 2.94 | 28                        | 50                 | 78                   | 495                      | 87                      |
| Average                     | 22.8                      | 157                       | 9.6                 | 66  | 19.0                  | 27.9          | 192 | 2.90 | 24                        | 44                 | 68                   | 442                      | 77                      |
| A444.0-T4                   | 23.0                      | 159                       | 8.0                 | 55  | 24.4                  | 27.1          | 187 | 3.39 | 30                        | 57                 | 107                  | 580                      | 102                     |
| Premium engineered castings |                           |                           |                     |     |                       |               |     |      |                           |                    |                      |                          |                         |
| C355.0-T61                  | 43.6                      | 301                       | 30.3                | 209 | 6.4                   | 51.8          | 357 | 1.71 | 14                        | 28                 | 40                   | 275                      | 48                      |
| A356.0-T6                   | 41.6                      | 287                       | 30.2                | 208 | 8.8                   | 51.6          | 356 | 1.71 | 18                        | 34                 | 52                   | 345                      | 60                      |
| A357.0-T61                  | 51.2                      | 353                       | 40.0                | 276 | 11.4                  | 54.2          | 374 | 1.35 | 10                        | 19                 | 29                   | 190                      | 33                      |
| A357.0-T62                  | 53.9                      | 372                       | 46.4                | 320 | 5.3                   | 53.8          | 371 | 1.16 | 11                        | 12                 | 23                   | 125                      | 22                      |

TYR, tear strength to yield strength ratio. (a) For yield strength, offset = 0.2%. (b) Estimated; tear energy curve not well defined



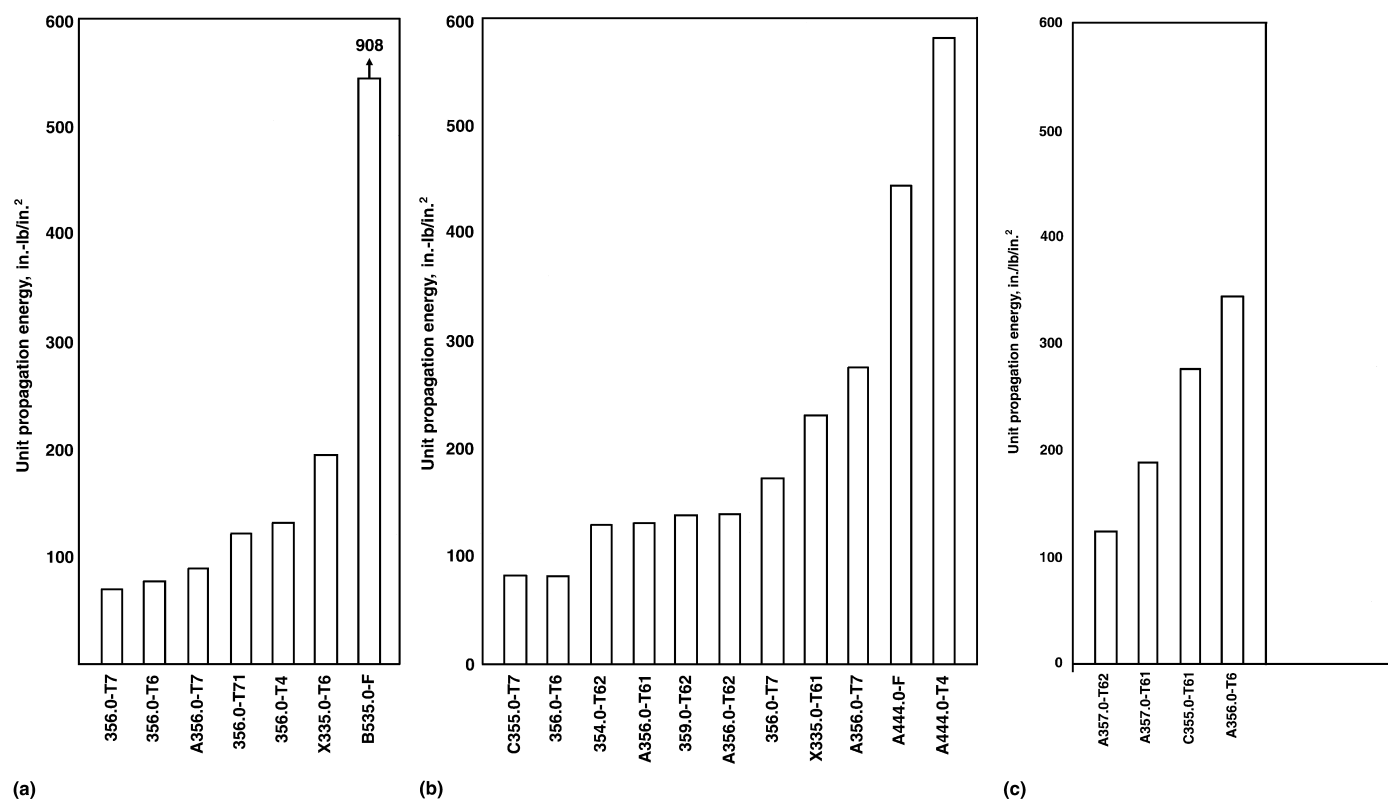


**Fig. 8.19** Ratings of aluminum alloy castings based on unit propagation energy from tear tests. (a) Sand castings. (b) Permanent mold castings. (c) Premium engineered castings

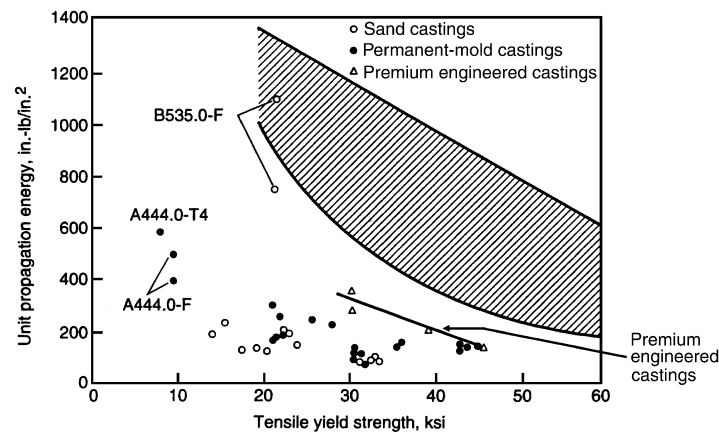


**Fig. 8.20** Unit propagation energy versus tensile yield strength for aluminum alloy castings

**Table 8.22 Representative tear and tensile tests results of groove welds in cast-to-cast and cast-to-wrought aluminum alloys at room temperature**

Specimens per Appendix 3, Fig. A3.6; each line represents average results of tests of duplicate specimens for one individual lot of material. Joint yield strength not determined; ratio of tear strength to yield strength not available. No postweld thermal treatment.

| Alloy and temper combination | Filler alloy | Tensile tests                    |     |                         |                                |               | Tear tests |                          |                           |                      |                         |                        |
|------------------------------|--------------|----------------------------------|-----|-------------------------|--------------------------------|---------------|------------|--------------------------|---------------------------|----------------------|-------------------------|------------------------|
|                              |              | Reduced section tensile strength |     | Free bend elongation, % | Tear specimen type (Fig. A3.6) | Tear strength |            | Energy required to:      |                           | Total energy, in.-lb | Unit propagation energy |                        |
|                              |              | ksi                              | MPa |                         |                                | ksi           | MPa        | initiate a crack, in.-lb | propagate a crack, in.-lb |                      | in.-lb/in. <sup>2</sup> | mN · m/mm <sup>2</sup> |
| Sand casting                 |              |                                  |     |                         |                                |               |            |                          |                           |                      |                         |                        |
| A444.0-F to A444.0-F         | 5556         | 37.8                             | 261 | 18.8                    | A                              | 51.0          | 352        | 60                       | 103                       | 163                  | 1030                    | 180                    |
|                              |              |                                  |     |                         | B                              | 46.9          | 323        | 38                       | 82                        | 120                  | 820                     | 144                    |
|                              |              |                                  |     |                         | C                              | 50.6          | 349        | 64                       | 94                        | 158                  | 935                     | 164                    |
| A444.0-F to 6061-T6          | 5556         | 32.5                             | 224 | 12.2                    | A                              | 49.5          | 341        | 56                       | 105                       | 161                  | 1050                    | 184                    |
|                              |              |                                  |     |                         | B                              | 45.0          | 310        | 32                       | 77                        | 109                  | 770                     | 135                    |
|                              |              |                                  |     |                         | C                              | 47.7          | 329        | 46                       | 92                        | 138                  | 920                     | 161                    |
| A444.0-F to 5456-H321        | 5556         | 42.6                             | 294 | 12.2                    | A                              | 53.0          | 366        | 66                       | 115                       | 181                  | 1185                    | 208                    |
|                              |              |                                  |     |                         | B                              | 49.6          | 342        | 38                       | 91                        | 129                  | 910                     | 159                    |
|                              |              |                                  |     |                         | C                              | 50.1          | 346        | 61                       | 99                        | 160                  | 990                     | 173                    |
| 356.0 to 6063-T4             | 4043         | 28.5                             | 197 | 4.1                     | A                              | 26.9          | 186        | 3                        | 16                        | 19                   | 160                     | 28                     |
|                              |              |                                  |     |                         | B                              | 37.4          | 258        | 11                       | 24                        | 34                   | 240                     | 42                     |
|                              |              |                                  |     |                         | C                              | 34.2          | 236        | 6                        | 32                        | 38                   | 325                     | 57                     |
| 356.0-T6 to 6061-T6          | 5556         | 28.4                             | 196 | 2.0                     | A                              | 29.6          | 204        | 6                        | 15                        | 21                   | 150                     | 26                     |
|                              |              |                                  |     |                         | B                              | 34.4          | 237        | 9                        | 21                        | 30                   | 210                     | 37                     |
|                              |              |                                  |     |                         | C                              | 31.8          | 219        | 9                        | 18                        | 27                   | 185                     | 32                     |
|                              | 4043         | 27.0                             | 186 | 6.9                     | A                              | 30.3          | 209        | 7                        | 16                        | 23                   | 175                     | 31                     |
|                              |              |                                  |     |                         | B                              | 34.4          | 237        | 10                       | 31                        | 41                   | 310                     | 54                     |
|                              |              |                                  |     |                         | C                              | 25.7          | 177        | 6                        | 33                        | 39                   | 330                     | 58                     |
| 356.0-T7 to 6061-T6          | 5556         | 26.8                             | 185 | 4.6                     | A                              | 30.0          | 207        | 7                        | 14                        | 21                   | 145                     | 25                     |
|                              |              |                                  |     |                         | B                              | 34.2          | 236        | 12                       | 20                        | 32                   | 205                     | 36                     |
|                              |              |                                  |     |                         | C                              | 30.0          | 207        | 8                        | 32                        | 40                   | 320                     | 56                     |
|                              | 4043         | 25.8                             | 178 | 7.2                     | A                              | 29.7          | 205        | 6                        | 22                        | 28                   | 220                     | 39                     |
|                              |              |                                  |     |                         | B                              | 32.8          | 226        | 11                       | 30                        | 41                   | 295                     | 52                     |
|                              |              |                                  |     |                         | C                              | 26.6          | 183        | 8                        | 38                        | 46                   | 380                     | 67                     |
| 356.0-T71 to 356.0-T71       | 4043         | 26.5                             | 183 | 6.1                     | A                              | 28.8          | 199        | 8                        | 18                        | 26                   | 175                     | 31                     |
|                              |              |                                  |     |                         | B                              | 32.4          | 223        | 14                       | 32                        | 46                   | 320                     | 56                     |
|                              |              |                                  |     |                         | C                              | 27.8          | 192        | 8                        | 24                        | 32                   | 245                     | 43                     |
| 356.0-T71 to 6061-T6         | 4043         | 26.7                             | 184 | 9.4                     | A                              | 29.4          | 203        | 8                        | 20                        | 28                   | 205                     | 36                     |
|                              |              |                                  |     |                         | B                              | 33.4          | 230        | 15                       | 30                        | 45                   | 305                     | 53                     |
|                              |              |                                  |     |                         | C                              | 27.6          | 190        | 9                        | 44                        | 53                   | 435                     | 76                     |
| 356.0-T71 to 5456-H321       | 4043         | 25.7                             | 177 | 5.7                     | A                              | 30.8          | 212        | 8                        | 14                        | 22                   | 140                     | 25                     |
|                              |              |                                  |     |                         | B                              | 32.8          | 226        | 8                        | 18                        | 26                   | 185                     | 32                     |
|                              |              |                                  |     |                         | C                              | 29.6          | 204        | 11                       | 16                        | 27                   | 165                     | 29                     |
| A357.0-T7 to 6061-T6         | 5556         | 25.9                             | 179 | 8.2                     | A                              | 51.2          | 353        | 61                       | 112                       | 173                  | 1120                    | 196                    |
|                              |              |                                  |     |                         | B                              | 50.3          | 347        | 42                       | 100                       | 142                  | 995                     | 174                    |
|                              |              |                                  |     |                         | C                              | 50.2          | 346        | 60                       | 101                       | 161                  | 1010                    | 177                    |
| Permanent mold casting       |              |                                  |     |                         |                                |               |            |                          |                           |                      |                         |                        |
| C355.0-T7 to 6061-T6         | 4043         | 32.0                             | 221 | 16.6                    | A                              | 36.4          | 251        | 12                       | 45                        | 57                   | 445                     | 78                     |
|                              |              |                                  |     |                         | B                              | 35.1          | 242        | 10                       | 28                        | 38                   | 275                     | 48                     |
|                              |              |                                  |     |                         | C                              | 40.0          | 276        | 14                       | 30                        | 44                   | 305                     | 53                     |
| 356.0-T6 to 356.0-T6         | 4043         | 28.1                             | 194 | 11.4                    | A                              | 34.0          | 234        | 14                       | 34                        | 48                   | 340                     | 60                     |
|                              |              |                                  |     |                         | B                              | 32.8          | 226        | 13                       | 34                        | 47                   | 340                     | 60                     |
|                              |              |                                  |     |                         | C                              | 32.7          | 226        | 11                       | 26                        | 37                   | 265                     | 46                     |
| 356.0-T6 to 6061-T6          | 4043         | 28.8                             | 199 | 12.5                    | A                              | 35.2          | 243        | 13                       | 46                        | 59                   | 455                     | 80                     |
|                              |              |                                  |     |                         | B                              | 34.2          | 236        | 11                       | 29                        | 40                   | 290                     | 51                     |
|                              |              |                                  |     |                         | C                              | 33.6          | 232        | 10                       | 28                        | 38                   | 275                     | 48                     |
| 356.0-T6 to 5456-H321        | 4043         | 29.5                             | 203 | 14.3                    | A                              | 39.4          | 272        | 28                       | 41                        | 71                   | 410                     | 72                     |
|                              |              |                                  |     |                         | B                              | 32.7          | 226        | 6                        | 18                        | 24                   | 175                     | 31                     |
|                              |              |                                  |     |                         | C                              | 39.4          | 272        | 17                       | 42                        | 59                   | 420                     | 74                     |
| 356.0-T7 to 356.0-T7         | 4043         | 25.6                             | 177 | 8.2                     | A                              | 34.2          | 236        | 22                       | 31                        | 53                   | 310                     | 54                     |
|                              |              |                                  |     |                         | B                              | 31.8          | 219        | 14                       | 33                        | 47                   | 330                     | 58                     |
|                              |              |                                  |     |                         | C                              | 31.0          | 214        | 13                       | 36                        | 49                   | 365                     | 64                     |
| 356.0-T7 to 6061-T6          | 4043         | 27.6                             | 190 | 9.8                     | A                              | 38.2          | 263        | 27                       | 38                        | 65                   | 375                     | 66                     |
|                              |              |                                  |     |                         | B                              | 34.3          | 237        | 15                       | 36                        | 51                   | 355                     | 62                     |
|                              |              |                                  |     |                         | C                              | 43.6          | 301        | 34                       | 70                        | 104                  | 700                     | 123                    |

(continued)

Table 8.22 (continued)

| Alloy and temper combination       | Filler alloy | Tensile tests                    |                        |                         |                                | Tear tests    |     |                          |                           | Unit<br>propagation energy |     |                      |  |
|------------------------------------|--------------|----------------------------------|------------------------|-------------------------|--------------------------------|---------------|-----|--------------------------|---------------------------|----------------------------|-----|----------------------|--|
|                                    |              | Reduced section tensile strength |                        | Free bend elongation, % | Tear specimen type (Fig. A3.6) | Tear strength |     | Energy required to:      |                           |                            |     | Total energy, in.-lb |  |
|                                    |              | ksi                              | MPa                    |                         |                                | ksi           | MPa | initiate a crack, in.-lb | propagate a crack, in.-lb |                            |     |                      |  |
|                                    |              | in.-lb/in. <sup>2</sup>          | mN · m/mm <sup>2</sup> |                         |                                |               |     |                          |                           |                            |     |                      |  |
| Permanent mold casting (continued) |              |                                  |                        |                         |                                |               |     |                          |                           |                            |     |                      |  |
| 356.0-T7 to 5456-H321              | 4043         | 26.6                             | 183                    | 4.0                     | A                              | 37.4          | 258 | 38                       | 30                        | 68                         | 295 | 52                   |  |
|                                    |              |                                  |                        |                         | B                              | 24.3          | 168 | 2                        | 10                        | 12                         | 105 | 18                   |  |
|                                    |              |                                  |                        |                         | C                              | 33.0          | 228 | 13                       | 31                        | 44                         | 310 | 54                   |  |
| A356.0-T61 to 6061-T6              | 4043         | 28.6                             | 197                    | 9.8                     | A                              | 36.8          | 254 | 25                       | 50                        | 75                         | 495 | 87                   |  |
|                                    |              |                                  |                        |                         | B                              | 33.4          | 230 | 10                       | 35                        | 45                         | 350 | 61                   |  |
|                                    |              |                                  |                        |                         | C                              | 35.2          | 243 | 14                       | 42                        | 56                         | 415 | 73                   |  |
| A356.0-T62 to 6061-T6              | 4043         | 26.7                             | 184                    | 10.5                    | A                              | 37.6          | 259 | 32                       | 48                        | 70                         | 475 | 83                   |  |
|                                    |              |                                  |                        |                         | B                              | 34.2          | 236 | 15                       | 36                        | 51                         | 365 | 64                   |  |
|                                    |              |                                  |                        |                         | C                              | 37.8          | 261 | 20                       | 52                        | 72                         | 520 | 91                   |  |
| A356.0-T7 to 6061-T6               | 4043         | 25.2                             | 174                    | 11.8                    | A                              | 39.0          | 269 | 37                       | 41                        | 78                         | 410 | 72                   |  |
|                                    |              |                                  |                        |                         | B                              | 34.0          | 234 | 16                       | 40                        | 56                         | 395 | 69                   |  |
|                                    |              |                                  |                        |                         | C                              | 33.6          | 232 | 11                       | 27                        | 38                         | 270 | 47                   |  |

The undesirable corrosion effects of copper in aluminum can be minimized with good heat treating and quenching practices. A high rate of quench and sufficient artificial aging will be beneficial (Ref 28).

Some aluminum-copper alloys in the T4 and underaged conditions are among the most susceptible known to stress-corrosion failure.

### 8.7.2 Al-Si-Cu and/or Mg Casting Alloys (3xx.x)

While elemental silicon is present in the 3xx.x series alloys, and silicon is cathodic to the aluminum matrix, the effects of silicon on corrosion resistance are minimal because the silicon particles are highly polarized and the resultant current density is low.

The corrosion resistance of the 3xx.x series, as of the 2xx.x series, is closely related to the copper content and also to impurity levels. Modifications of several of the basic alloy compositions to restrict impurity levels have benefited corrosion resistance as well as certain mechanical properties including toughness.

### 8.7.3 Aluminum-Silicon Casting Alloys (4xx.x)

As noted for the 3xx.x alloys, the effects of silicon on the corrosion resistance of aluminum casting alloys are minimal, and this group as a whole has relatively good corrosion resistance.

### 8.7.4 Aluminum-Magnesium Casting Alloys (5xx.x)

Aluminum-magnesium casting alloys have excellent resistance to corrosion and are resistant to a wide range of chemical and food products, making them especially useful in these industries and in marine applications.

### 8.7.5 Aluminum-Zinc Casting Alloys (7xx.x)

Aluminum-zinc alloys, because of their zinc contents, are anodic to most other aluminum casting alloys and have generally good corrosion resistance. They are better than the 2xx.x series for general corrosion resistance, but inferior to the 5xx.x series.

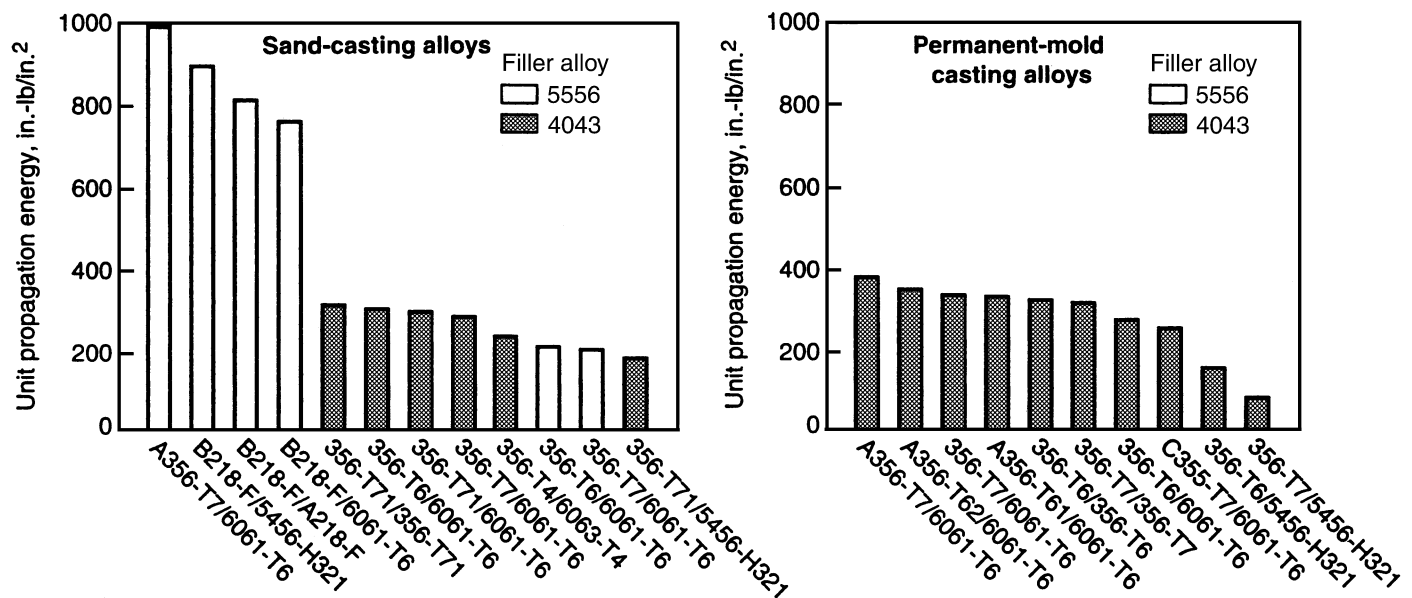


Fig. 8.21 Ratings of welds in aluminum castings based on unit propagation energy from tear tests

**Table 8.23 Results of plane strain fracture toughness tests of representative aluminum alloy premium engineered castings**

Individual results of single cast slabs from which specimens were machined; tests in accordance with ASTM Method E 399 at time tests were made to. Specimens generally machined from two different directions in casting; fracture results were averaged independent of direction.

| Alloy and temper           | Testing direction(a) | Tensile tests             |                        |                        | Plane-strain fracture toughness tests |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        |      |                                      |                              |                        |      |
|----------------------------|----------------------|---------------------------|------------------------|------------------------|---------------------------------------|----------------------------------|-----|------------------------------|------------------------------------------|-------------------------|-----------------------------------------|-------------------------------|----------------------------------------|----------------------------------------|------|--------------------------------------|------------------------------|------------------------|------|
|                            |                      | Ultimate tensile strength | Tensile yield strength | Elongation in 2 in., % | Type of specimen(b)                   | Specimen thickness (B), in. (mm) |     | Specimen width (W), in. (mm) | Crack length (a <sub>0</sub> ), in. (mm) | Ratio a <sub>0</sub> /W | Critical load P <sub>c</sub> , kips (N) | Maximum load P <sub>max</sub> | Ratio P <sub>max</sub> /P <sub>0</sub> | fracture toughness, (K <sub>Ic</sub> ) |      | Valid measure of K <sub>Ic</sub> (c) | Critical crack-size index(d) |                        |      |
|                            |                      |                           |                        |                        |                                       | ksi                              | MPa |                              |                                          |                         |                                         |                               |                                        | ksi                                    | MPa  |                                      | ksi · in. <sup>1/2</sup>     | MPa · m <sup>1/2</sup> | in.  |
| Sand casting               |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        |      |                                      |                              |                        |      |
| 356.0-T7                   | L                    | 37.8                      | 261                    | 33.7                   | 232                                   | 1.6                              | CC  | 0.375                        | 1.500                                    | 0.500                   | 0.33                                    | 13.00                         | 13.80                                  | 1.06                                   | 15.4 | 16.9                                 | Yes                          | 0.21                   | 5.3  |
| Premium engineered casting |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        |      |                                      |                              |                        |      |
| A201.0-T7                  | L                    | 63.3                      | 437                    | 57.4                   | 396                                   | 7.0                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.38 (35.1)             | 0.55                                    | 5.85                          | 6.49                                   | 1.11                                   | 33.8 | 37.2                                 | Yes                          | 0.35                   | 8.8  |
|                            | T                    | 64.2                      | 443                    | 58.8                   | 406                                   | 7.0                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.37 (34.8)             | 0.55                                    | 6.12                          | 6.60                                   | 1.08                                   | 34.5 | 38.0                                 | Yes                          | 0.33                   | 8.3  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.35 (34.3)             | 0.54                                    | 6.00                          | 6.46                                   | 1.08                                   | 33.1 | 36.4                                 | Yes                          | 0.34                   | 8.7  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         | 6.00                          |                                        |                                        | 33.6 | 37.0                                 | Yes                          | 0.32                   | 8.0  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        |      |                                      | Yes                          | 0.34                   | 8.6  |
| 224.0-T7                   | L                    | 53.3                      | 368                    | 39.6                   | 273                                   | 6.8                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.40 (35.6)             | 0.56                                    | 4.60                          | 7.44                                   | 1.62                                   | 27.2 | 29.9                                 | No(e)                        | 0.47                   | 12.0 |
|                            | T                    | 54.9                      | 379                    | 42.5                   | 293                                   | 6.5                              | CT  | 1.25 (31.8)                  | 2.50 (63.6)                              | 1.40 (35.6)             | 0.56                                    | 5.44                          | 7.40                                   | 1.36                                   | 31.8 | 35.0                                 | No                           | 0.64                   | 16.4 |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.38 (35.1)             | 0.55                                    | 5.00                          | 7.02                                   | 1.40                                   | 28.6 | 31.5                                 | No                           | 0.45                   | 11.5 |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         | 5.81                          | 7.58                                   | 1.30                                   | 33.1 | 36.4                                 | No                           | 0.61                   | 15.4 |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        | 30.2 | 33.2                                 | No                           | 0.54                   | 13.7 |
| 249.0-T7                   | L                    | 56.8                      | 392                    | 47.6                   | 328                                   | 7.2                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.37 (34.8)             | 0.55                                    | 5.38                          | 5.82                                   | 1.08                                   | 30.2 | 33.2                                 | Yes                          | 0.40                   | 10.2 |
|                            | T                    | 58.3                      | 402                    | 50.9                   | 351                                   | 7.5                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.39 (35.3)             | 0.55                                    | 5.02                          | 5.35                                   | 1.06                                   | 29.1 | 32.0                                 | Yes                          | 0.37                   | 9.5  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.37 (34.8)             | 0.55                                    | 5.40                          | 6.10                                   | 1.13                                   | 30.4 | 33.4                                 | Yes                          | 0.36                   | 9.1  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.34 (34.0)             | 0.53                                    | 5.38                          | 5.80                                   | 1.08                                   | 29.1 | 32.0                                 | Yes                          | 0.33                   | 8.3  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        | 32.7 | 32.7                                 | Yes                          | 0.36                   | 9.1  |
| 354.0-T6                   | L                    | 48.4                      | 334                    | 43.0                   | 297                                   | 1.5                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.34 (34.0)             | 0.54                                    | 3.40                          | 3.50                                   | 1.03                                   | 18.5 | 20.4                                 | Yes                          | 0.19                   | 4.7  |
|                            | T                    | 47.6                      | 328                    | 42.9                   | 296                                   | 1.0                              | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.31 (33.3)             | 0.52                                    | 3.44                          | 3.50                                   | 1.02                                   | 18.0 | 19.8                                 | Yes                          | 0.18                   | 4.5  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.24 (31.5)             | 0.50                                    | 3.65                          | 3.72                                   | 1.02                                   | 17.5 | 19.3                                 | Yes                          | 0.17                   | 4.2  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.27 (32.3)             | 0.51                                    | 3.68                          | 3.88                                   | 1.05                                   | 18.2 | 20.0                                 | Yes                          | 0.18                   | 4.6  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        | 18.0 | 19.8                                 | Yes                          | 0.18                   | 4.6  |
| C355.0-T6                  | L                    | 44.2                      | 305                    | 40.7                   | 281                                   | 1.5                              | CT  | 1.25 (31.6)                  | 2.50 (63.5)                              | 1.27 (32.3)             | 0.51                                    | 3.68                          | 4.08                                   | 1.11                                   | 18.3 | 20.1                                 | Yes                          | 0.20                   | 5.1  |
|                            | T                    | 43.0                      | 297                    | 41.0                   | 283                                   | <0.5                             | CT  | 1.25 (31.8)                  | 2.50 (63.5)                              | 1.32 (33.5)             | 0.53                                    | 3.46                          | 3.80                                   | 1.10                                   | 18.3 | 20.1                                 | Yes                          | 0.20                   | 5.1  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.25 (31.8)             | 0.50                                    | 3.81                          | 4.12                                   | 1.08                                   | 18.6 | 20.5                                 | Yes                          | 0.21                   | 5.2  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 1.31 (33.3)             | 0.52                                    | 3.70                          | 3.98                                   | 1.07                                   | 19.3 | 21.2                                 | Yes                          | 0.22                   | 5.6  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        | 18.7 | 20.6                                 | Yes                          | 0.21                   | 5.3  |
| A357.0-T62                 | L                    | 50.2                      | 346                    | 43.2                   | 298                                   | 2.5                              | CT  | 0.75 (19.0)                  | 1.50 (38.1)                              | 0.73 (18.5)             | 0.48                                    | 1.83                          | 2.00                                   | 1.04                                   | 19.3 | 21.2                                 | Yes                          | 0.20                   | 5.1  |
|                            | T                    | 53.7                      | 370                    | 43.3                   | 299                                   | 6.5                              | CT  | 0.75 (19.0)                  | 1.50 (38.1)                              | 0.78 (19.8)             | 0.52                                    | 1.88                          | 1.92                                   | 1.02                                   | 21.0 | 23.1                                 | Yes                          | 0.24                   | 6.0  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 0.74 (18.8)             | 0.50                                    | 1.90                          | 1.98                                   | 1.04                                   | 19.6 | 23.6                                 | Yes                          | 0.20                   | 5.2  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          | 0.68 (17.3)             | 0.45                                    | 1.82                          | 1.93                                   | 1.06                                   | 19.2 | 21.1                                 | No                           | ...                    | ...  |
|                            |                      |                           |                        |                        |                                       |                                  |     |                              |                                          |                         |                                         |                               |                                        |                                        | 20.5 | 22.6                                 | Yes                          | 0.21                   | 5.3  |

(a) L, longitudinal; T, transverse. (b) CC, center-cracked specimens; CT, compact tension specimens (Appendix 3, Fig. A3.7); all specimens were precracked by fatigue. (c) Based on criteria in ASTM E 399 at time tests were made. (d) A relative measure of crack tolerance of material, defined as  $(K_{IC}/\sqrt{YS})^2$ . (e)  $P_{max}/PQ$  ratio too high

Many wrought aluminum-zinc alloys of the comparable 7xxx series are susceptible to stress-corrosion cracking (SCC) under short-transverse stressing and require special aging treatments for added protection; this is less of a concern in castings where grain deformation is not present. Nevertheless, some in-service failures have been observed in certain alloys such as 707.0-T5 and 771.0-T5, and some caution is advised to avoid conditions that may lead to intergranular attack.

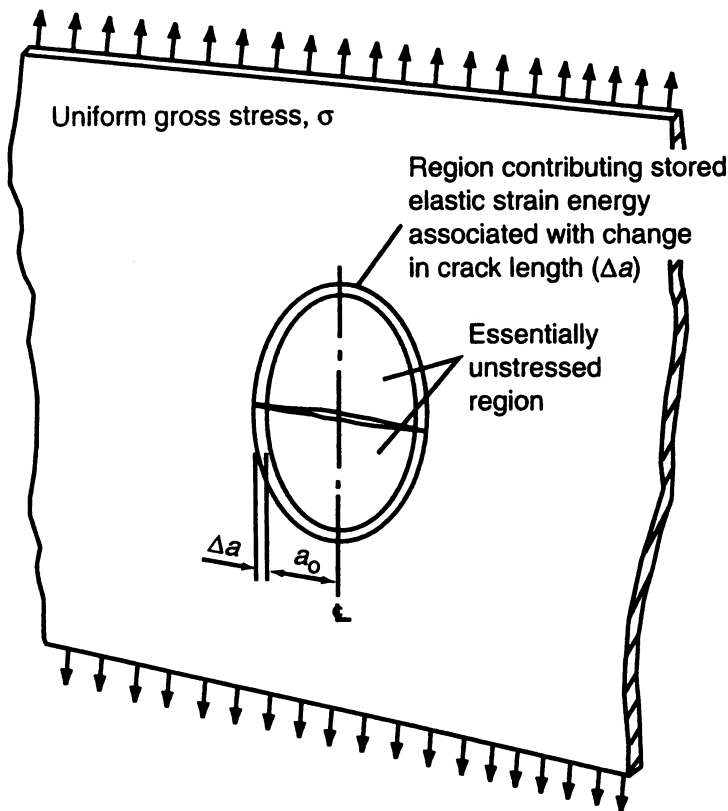


Fig. 8.22 Large elastically stressed panel containing a crack

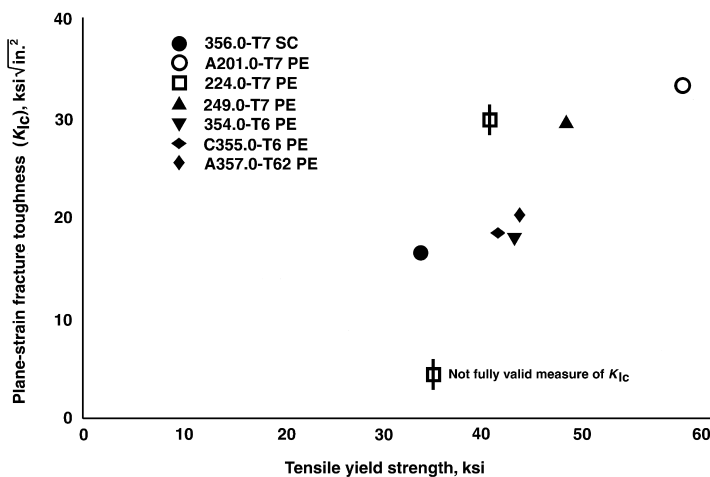


Fig. 8.23 Plane-strain fracture toughness,  $K_{IC}$ , versus tensile yield strength for selected aluminum alloy castings. SC, sand cast alloy; PE, premium engineered alloy

### 8.7.6 Aluminum-Tin Casting Alloys (8xx.x)

Tin in aluminum castings is cathodic to the aluminum matrix and results in some decrease in general corrosion resistance in aqueous saline solutions. These alloys are quite successfully used in other environments.

## 8.8 Properties of Cast Aluminum Matrix Composites

Cast aluminum matrix composites (AIMMCs) are discussed separately because less information is available in the way of typical and statistical minimum mechanical and physical properties for these products. For this reason, the authors recommend that these products be used cautiously and with the understanding that the appropriate design mechanical properties for specific products may

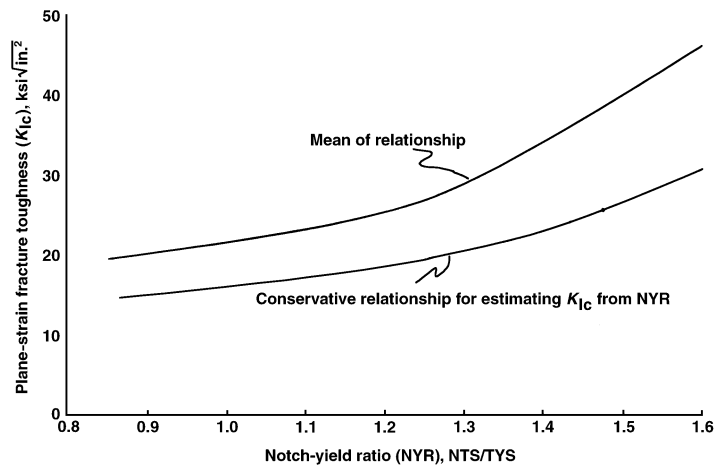


Fig. 8.24 Plane-strain fracture toughness,  $K_{IC}$ , versus notch-yield ratio for some cast aluminum alloys compared to the mean values of the relationship for wrought aluminum alloys

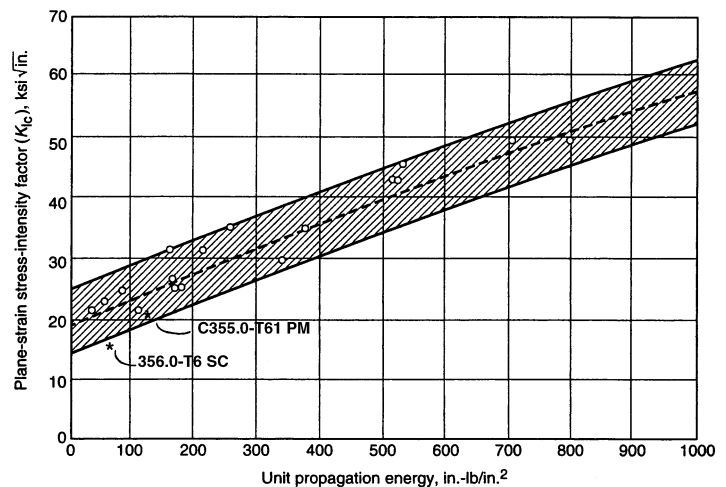


Fig. 8.25 Plane-strain fracture toughness,  $K_{IC}$ , versus notch-yield ratio for selected cast aluminum alloys compared to the range of such values for wrought aluminum alloys. SC, sand cast; PM, permanent mold



**Table 8.24 Summary of rounded average fracture parameters for representative aluminum casting alloys**

Average values taken from previous tables as footnoted. Values averaged when data for multiple lots are available.

| Alloy and temper           | Tensile yield strength |     | Elongation in 2 in., % | Notch-yield ratio(a) | Unit propagation energy(b) |            | Measured plane-strain fracture toughness ( $K_{Ic}$ )(c) |                        | Conservative estimated plane-strain fracture toughness ( $K_{Ic}$ )(d) |                          | Estimated relative critical crack-size index(c) |        |
|----------------------------|------------------------|-----|------------------------|----------------------|----------------------------|------------|----------------------------------------------------------|------------------------|------------------------------------------------------------------------|--------------------------|-------------------------------------------------|--------|
|                            | ksi                    | MPa |                        |                      | in. · lb/in. <sup>2</sup>  | mN · m/mm2 | ksi · in. <sup>1/2</sup>                                 | MPa · m <sup>1/2</sup> | ksi · in. <sup>1/2</sup>                                               | MPa · in. <sup>1/2</sup> | in.                                             | mm     |
| Sand casting               |                        |     |                        |                      |                            |            |                                                          |                        |                                                                        |                          |                                                 |        |
| 240.0-F                    | 26.0                   | 179 | 1.4                    | 0.87                 | ...                        | ...        | ...                                                      | ...                    | 16                                                                     | 18                       | 0.62                                            | 16     |
| 242.0-F                    | 20.4                   | 141 | 2.1                    | 1.34                 | ...                        | ...        | ...                                                      | ...                    | 21                                                                     | 23                       | 1.03                                            | 26     |
| 295.0-T6                   | 27.1                   | 187 | 6.4                    | 1.75                 | ...                        | ...        | ...                                                      | ...                    | >35                                                                    | >38                      | >1.67                                           | >42    |
| 308.0-F                    | 18.5                   | 128 | 1.8                    | 1.19                 | ...                        | ...        | ...                                                      | ...                    | 19                                                                     | 21                       | 1.03                                            | 26     |
| X335.0-T6                  | 22.9                   | 158 | 7.7                    | 1.64                 | 192                        | 34         | ...                                                      | ...                    | 26                                                                     | 29                       | 1.14                                            | 29     |
| 356.0-T4                   | 18.7                   | 129 | 3.4                    | 1.69                 | 128                        | 22         | ...                                                      | ...                    | 19                                                                     | 21                       | 1.02                                            | 26     |
| 356.0-T6                   | 32.6                   | 225 | 2.2                    | 1.15                 | 75                         | 13         | ...                                                      | ...                    | 18                                                                     | 20                       | 0.55                                            | 14     |
| 356.0-T7                   | 33.7                   | 232 | 1.6                    | 1.02                 | 70                         | 12         | 15.4(f)                                                  | 16.9(f)                | ...                                                                    | ...                      | 0.21(f)                                         | 5.3(f) |
| 356.0-T71                  | 21.7                   | 150 | 3.3                    | 1.54                 | 120                        | 21         | ...                                                      | ...                    | 23                                                                     | 25                       | 1.06                                            | 27     |
| A356.0-T6                  | 30.2                   | 208 | 8.8                    | 1.70                 | ...                        | ...        | ...                                                      | ...                    | >35                                                                    | >38                      | >1.34                                           | >34    |
| A356.0-T7                  | 31.8                   | 219 | 3.2                    | 1.31                 | 88                         | 15         | ...                                                      | ...                    | 21                                                                     | 23                       | 0.66                                            | 17     |
| 520.0-T4                   | 31.6                   | 218 | 2.1                    | 1.22                 | ...                        | ...        | ...                                                      | ...                    | 20                                                                     | 22                       | 0.63                                            | 16     |
| B535.0-F                   | 21.1                   | 146 | 12.8                   | 2.10                 | 908                        | 159        | ...                                                      | ...                    | >50                                                                    | >55                      | >5.6                                            | >142   |
| A612.0-F                   | 34.8                   | 240 | 3.2                    | 1.31                 | ...                        | ...        | ...                                                      | ...                    | 21                                                                     | 23                       | 0.60                                            | 15     |
| Permanent mold casting     |                        |     |                        |                      |                            |            |                                                          |                        |                                                                        |                          |                                                 |        |
| X335.0-T61                 | 23.8                   | 164 | 6.0                    | 1.60                 | 228                        | 40         | ...                                                      | ...                    | 28                                                                     | 31                       | 1.18                                            | 30     |
| 354.0-T62                  | 44.9                   | 310 | 1.0                    | 1.18                 | 128                        | 22         | ...                                                      | ...                    | 22                                                                     | 24                       | 0.49                                            | 12     |
| C335.0-T7                  | 30.7                   | 212 | 2.3                    | 1.39                 | 80                         | 14         | ...                                                      | ...                    | 20                                                                     | 22                       | 0.65                                            | 17     |
| 356.0-T6                   | 31.6                   | 218 | 2.8                    | 1.36                 | 80                         | 14         | ...                                                      | ...                    | 23                                                                     | 25                       | 0.73                                            | 18     |
| 356.0-T7                   | 22.0                   | 152 | 5.0                    | 1.60                 | 168                        | 29         | ...                                                      | ...                    | 30                                                                     | 33                       | 1.36                                            | 35     |
| A356.0-T61                 | 30.6                   | 211 | 5.9                    | 1.65                 | 130                        | 23         | ...                                                      | ...                    | 25                                                                     | 28                       | 0.82                                            | 21     |
| A356.0-T62                 | 35.5                   | 245 | 3.0                    | 1.24                 | 138                        | 24         | ...                                                      | ...                    | 22                                                                     | 24                       | 0.62                                            | 16     |
| A356.0-T7                  | 21.8                   | 150 | 6.9                    | 1.72                 | 272                        | 48         | ...                                                      | ...                    | 30                                                                     | 33                       | 1.38                                            | 35     |
| 359.0-T62                  | 43.2                   | 298 | 1.4                    | 1.08                 | 135                        | 24         | ...                                                      | ...                    | 19                                                                     | 21                       | 0.44                                            | 11     |
| A444.0-F                   | 9.6                    | 66  | 19.0                   | 2.96                 | 442                        | 77         | ...                                                      | ...                    | >50                                                                    | >55                      | >27                                             | >690   |
| A444.0-T4                  | 8.0                    | 55  | 24.4                   | 3.72                 | 580                        | 102        | ...                                                      | ...                    | >50                                                                    | >55                      | >39                                             | >1000  |
| Premium engineered casting |                        |     |                        |                      |                            |            |                                                          |                        |                                                                        |                          |                                                 |        |
| A201.0-T7                  | 58.1                   | 401 | 7.0                    | 1.38                 | ...                        | ...        | 33.6                                                     | 37.0                   | ...                                                                    | ...                      | 0.34                                            | 8.6    |
| 224.0-T7                   | 41.4                   | 286 | 6.6                    | 1.60                 | ...                        | ...        | 30.2                                                     | 33.2                   | ...                                                                    | ...                      | 0.54                                            | 13.7   |
| 249.0-T7                   | 49.2                   | 339 | 7.4                    | 1.40                 | ...                        | ...        | 29.7                                                     | 32.7                   | ...                                                                    | ...                      | 0.36                                            | 9.1    |
| 354.0-T6                   | 43.0                   | 297 | 1.2                    | 1.01                 | ...                        | ...        | 18.0                                                     | 19.8                   | ...                                                                    | ...                      | 0.18                                            | 4.6    |
| C355.0-T6                  | 40.8                   | 281 | 1.0                    | 1.07                 | ...                        | ...        | 18.6                                                     | 20.6                   | ...                                                                    | ...                      | 0.21                                            | 5.31   |
| C355.0-T61                 | 30.3                   | 209 | 6.4                    | 1.74                 | 275                        | 48         | ...                                                      | ...                    | 30                                                                     | 33                       | 0.99                                            | 25     |
| A356.0-T6                  | 30.2                   | 208 | 8.8                    | 1.70                 | 345                        | 60         | ...                                                      | ...                    | >35                                                                    | >38                      | >1.67                                           | >42    |
| A357.0-T6                  | 43.2                   | 298 | 4.5                    | 1.12                 | ...                        | ...        | ...                                                      | ...                    | 18                                                                     | 20                       | 0.42                                            | 11     |
| A357.0-T61                 | 40.0                   | 276 | 11.4                   | 1.44                 | 190                        | 33         | ...                                                      | ...                    | 25                                                                     | 28                       | 0.63                                            | 16     |
| A357.0-T62                 | 44.7                   | 308 | 5.8                    | 1.28                 | 125                        | 22         | 19.8                                                     | 20.8                   | ...                                                                    | ...                      | 0.2                                             | 5.0    |

(a) Values from Table 8.17. (b) Values from Table 8.21. (c) Values from Table 8.23, fully valid except as noted in (f). (d) Square of ratio  $K_{Ic}/TYS$ , a relative measure of critical crack size tolerance. (e) For those alloys and tempers for which fracture toughness tests were not made; estimated conservatively from notch-tensile and tear test results based on correlations. (f) Invalid test because of high  $P_{max}/PQ$  value; must be considered an estimate

have to be developed with additional testing at the time of their proposed application.

Typical values of several AIMMCs published by NADCA and several producers are presented in Table 8.28, their typical physical properties in Table 8.29, and their performance characteristics in Table 8.30 (Ref 28–30).

As noted in these tables, among the information provided are data for two cast aluminum matrix alloys, 301.0 and 303.0, each containing two different percentages of silicon carbide (SiC) particulate, 10% and 20%. Attention is called to the fact that these composites are referred to by some sources in the literature with designations consistent neither with the Aluminum Association registration records nor with the ANSI Standard for MMC nomenclature. The correct designations based on the compositions given in Ref 6, 301.0 and 303.0, are presented in Tables 8.28 through 8.30, with footnotes to the published designations. Similarly, data for matrix alloy 361.0 are presented with the appropriate Aluminum Association designation, not the designation under which the products were produced, also as footnoted in the tables.

The most significant differences between the properties of the composites and those of the matrix alloys are the elastic moduli: for the composites, the moduli are 50 to 100% higher than those of the matrix alloys, depending on the percentage of SiC particulate included. The SiC particulate, with its own modulus near  $100 \times 10^6$  psi (700 GPa), contributes materially to the stiffness of the finished product. The higher moduli are the principal reason for the production and application of aluminum metal matrix composites.

Among the other advantages of the composites that have proven important in commercial applications are the lower coefficients of thermal expansion (CTE) and the higher thermal conductivity. In particular, the lower CTEs better match those of some of the materials with which they are used (in applications such as sinks in satellite electronics), resulting in lower local stresses and minimizing the risk of thermal fatigue failure.

Aluminum MMCs also have superior fatigue properties in comparison to unreinforced aluminum alloys, as illustrated by Fig. 8.30. With reinforcement, the fatigue strengths at specific lives are

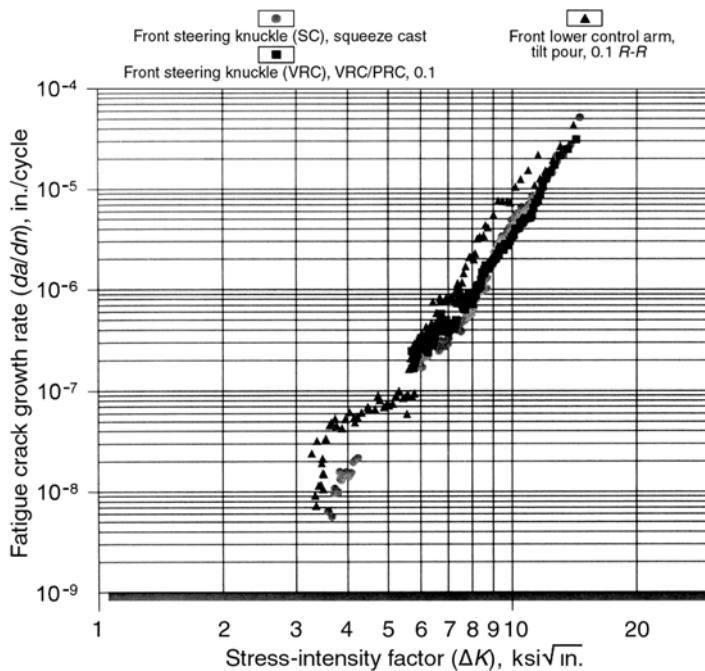


**Fig. 8.26** Fatigue crack growth rate ( $R = 0.1$ ) versus stress-intensity factor at room temperature for A356.0-T6 aluminum alloy castings produced by various processes

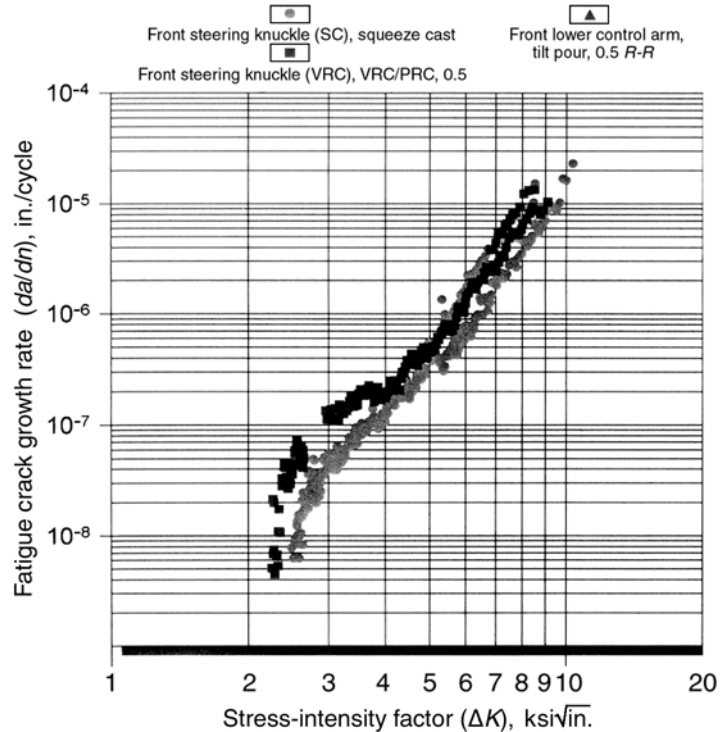


**Fig. 8.27** Fatigue crack growth rate ( $R = 0.5$ ) versus stress-intensity factor at room temperature for A356.0-T6 aluminum alloy castings produced by various processes

**Table 8.25** Threshold stress intensities for fatigue crack propagation for alloy A356.0-T6

| Casting process | Threshold stress intensity at room temperature |                         |                           |                         | Threshold stress intensity at 250 °F (120 °C) |                         |                           |                         |
|-----------------|------------------------------------------------|-------------------------|---------------------------|-------------------------|-----------------------------------------------|-------------------------|---------------------------|-------------------------|
|                 | $R = 0.1$                                      |                         | $R = 0.5$                 |                         | $R = 0.1$                                     |                         | $R = 0.5$                 |                         |
|                 | ksi $\sqrt{\text{in.}^2}$                      | MPa $\sqrt{\text{m}^2}$ | ksi $\sqrt{\text{in.}^2}$ | MPa $\sqrt{\text{m}^2}$ | ksi $\sqrt{\text{in.}^2}$                     | MPa $\sqrt{\text{m}^2}$ | ksi $\sqrt{\text{in.}^2}$ | MPa $\sqrt{\text{m}^2}$ |
| Tilt mold (PM)  | 3.41                                           | 3.75                    | 2.35                      | 2.58                    | 3.92                                          | 4.31                    | 2.4                       | 2.64                    |
| Squeeze         | 3.32                                           | 3.65                    | 2.78                      | 3.05                    | 4.17                                          | 4.58                    | 3.14                      | 3.45                    |
| Vacuum          | 3.84                                           | 4.22                    | 2.37                      | 2.60                    | 3.18                                          | 3.49                    | 2.37                      | 2.60                    |

PM, permanent mold.  $R$ , fatigue stress ratio, the ratio of the minimum stress to the maximum stress in each cycle of loading. Source: Ref 18

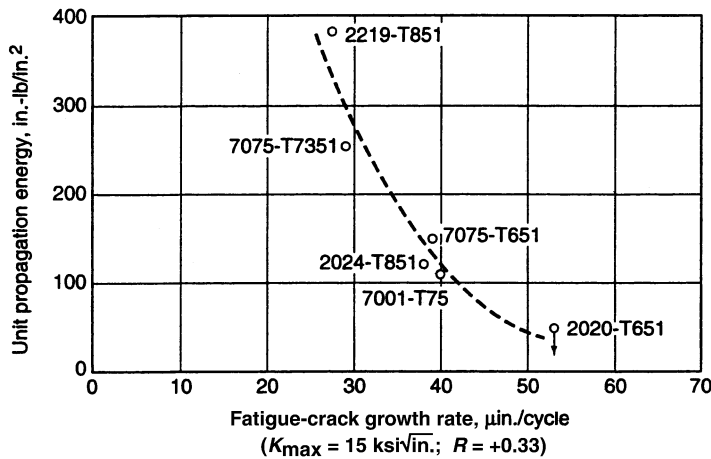


**Fig. 8.28** Relationship between unit propagation energy from the tear test and fatigue crack growth rate for wrought aluminum alloys.  $K_{\max} = 15 \text{ ksi}\sqrt{\text{in.}}$ ;  $R = 0.33$ .

20 to 50% higher, with the endurance limit ( $10^7$  cycles) indicated as nearly twice the value as for unreinforced material.

Finally, there appears to be an added advantage in higher damping capacity for aluminum MMCs versus unreinforced alloys, although this is difficult to demonstrate quantitatively. As illustrated in the decay curves in Fig. 8.31, externally induced vibrations decay relatively quickly in the aluminum MMC as compared with those in conventional aluminum alloy 5052 and other structural alloys.

It is important to note (from Table 8.28) that the benefits of higher moduli and fatigue strength, plus lower CTE, bring some trade-off in substantially lower elongation and fracture toughness than those of the matrix alloys. This is supported by the fact that in the cases where such data are presented, the plane strain fracture toughness of the aluminum MMCs was in the range of 11 to 17 ksi $\sqrt{\text{in}}$  (12 to 19 MPa $\sqrt{\text{m}}$ ), well below the level that would be expected of Al-Si-Mg alloys; however, the very high silicon content of 361.0 may also contribute to the lower toughness.

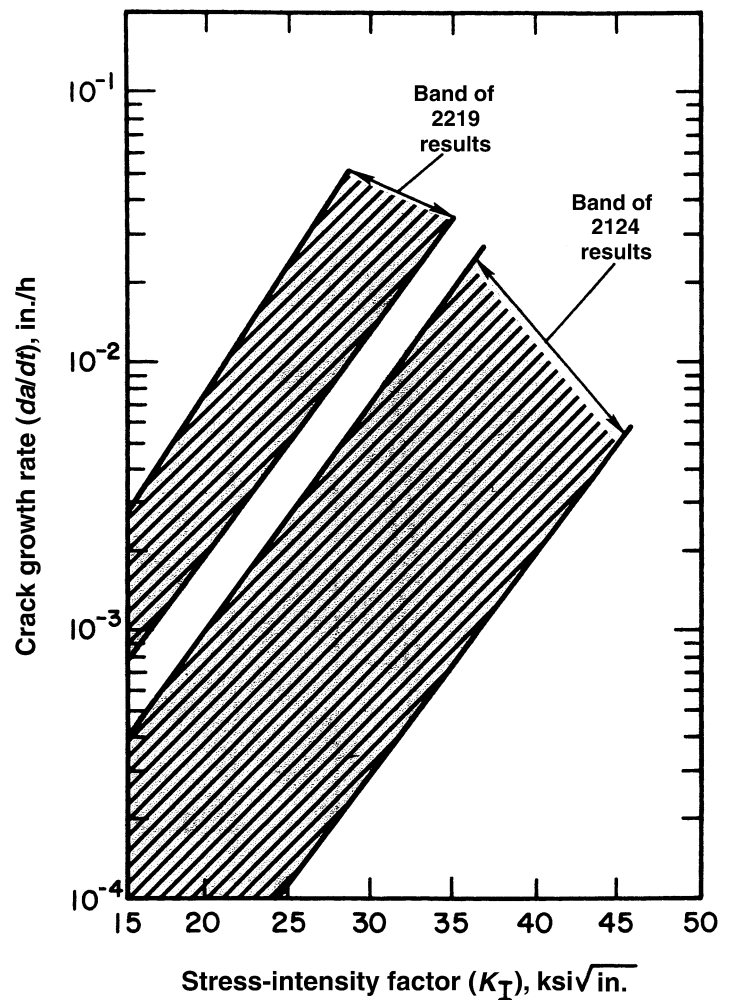


**Fig. 8.29** Creep crack growth as a function of applied stress-intensity factor for selected wrought aluminum alloys

**Table 8.26** Relative ratings of resistance to general corrosion and to stress-corrosion cracking of aluminum casting alloys

| Resistance to corrosion |                  |            |        | Resistance to corrosion |        |            |        |
|-------------------------|------------------|------------|--------|-------------------------|--------|------------|--------|
| Alloy                   | Temper           | General(a) | SCC(b) | Alloy                   | Temper | General(a) | SCC(b) |
| Sand castings           |                  |            |        | 355.0                   | All    | C          | A      |
| 208.0                   | F                | B          | B      | C355.0                  | T61    | C          | A      |
| 224.0                   | T7               | C          | B      | 356.0                   | All    | B          | A      |
| 240.0                   | F                | D          | C      | A356.0                  | T61    | B          | A      |
| 242.0                   | All              | D          | C      | F356.0                  | All    | B          | A      |
| A242.0                  | T75              | D          | C      | A357.0                  | T61    | B          | A      |
| 249.0                   | T7               | C          | B      | 358.0                   | T6     | B          | A      |
| 295.0                   | All              | C          | C      | 359.0                   | All    | B          | A      |
| 319.0                   | F, T5            | C          | B      | B443.0                  | F      | B          | A      |
|                         | T6               | C          | C      | A444.0                  | T4     | B          | A      |
| 355.0                   | All              | C          | A      | 513.0                   | F      | A          | A      |
| C355.0                  | T6               | C          | A      | 705.0                   | T5     | B          | B      |
| 356.0                   | T6, T7, T71, T51 | B          | A      | 707.0                   | T5     | B          | C      |
| A356.0                  | T6               | B          | A      | 711.0                   | T5     | B          | A      |
| 443.0                   | F                | B          | A      | 713.0                   | T5     | B          | B      |
| 512.0                   | F                | A          | A      | 850.0                   | T5     | C          | B      |
| 513.0                   | F                | A          | A      | 851.0                   | T5     | C          | B      |
| 514.0                   | F                | A          | A      | 852.0                   | T5     | C          | B      |
| 520.0                   | T4               | A          | C      | Die castings            |        |            |        |
| 535.0                   | F                | A          | A      |                         |        |            |        |
| B535.0                  | F                | A          | A      | 360.0                   | F      | C          | A      |
| 705.0                   | T5               | B          | B      | A360.0                  | F      | C          | A      |
| 707.0                   | T5               | B          | C      | 364.0                   | F      | C          | A      |
| 710.0                   | T5               | B          | B      | 380.0                   | F      | E          | A      |
| 712.0                   | T5               | B          | C      | A380.0                  | F      | E          | A      |
| 713.0                   | T5               | B          | B      | 383.0                   | F      | E          | A      |
| 771.0                   | T6               | C          | C      | 384.0                   | F      | E          | A      |
| 850.0                   | T5               | C          | B      | 390.0                   | F      | E          | A      |
| 851.0                   | T5               | C          | B      | 392.0                   | F      | E          | A      |
| 852.0                   | T5               | C          | B      | 413.0                   | F      | C          | A      |
| Permanent mold castings |                  |            |        | A413.0                  | F      | C          | A      |
|                         |                  |            |        | C443.0                  | F      | B          | A      |
| 242.0                   | T571, T61        | D          | C      | 518.0                   | F      | A          | A      |
| 308.0                   | F                | C          | B      | Rotor metal(c)          |        |            |        |
| 319.0                   | F                | C          | B      |                         |        |            |        |
|                         | T6               | C          | C      | 100.1                   | ...    | A          | A      |
| 332.0                   | T5               | C          | B      | 150.1                   | ...    | A          | A      |
| 336.0                   | T551, T65        | C          | B      | 170.1                   | ...    | A          | A      |
| 354.0                   | T61, T62         | C          | A      |                         |        |            |        |

(a) Relative ratings of general corrosion resistance are in decreasing order of merit, based on exposures to NaCl solution by intermittent spray or immersion. (b) Relative ratings of resistance to SCC are based on service experience and on laboratory tests of specimens exposed to alternate immersion in 3.5% NaCl solution. A, no known instance of failure in service when properly manufactured; B, failure not anticipated in service from residual stresses or from design and assembly stresses below about 45% of the minimum guaranteed yield strength given in applicable specifications; C, failures have occurred in service with either this specific alloy/temper combination or with alloy/temper combinations of this type; designers should be aware of the potential SCC problem that exists when these alloys and tempers are used under adverse conditions. (c) For electric motor rotors. Source: Ref 28

**Table 8.27** Solution potentials of cast aluminum alloys

| Alloy | Temper | Type of mold(a) | Potential(b), V |
|-------|--------|-----------------|-----------------|
| 208.0 | F      | S               | -0.77           |
| 238.0 | F      | P               | -0.74           |
| 295.0 | T4     | S or P          | -0.70           |
|       | T6     | S or P          | -0.71           |
|       | T62    | S or P          | -0.73           |
| 296.0 | T4     | S or P          | -0.71           |
| 308.0 | F      | P               | -0.75           |
| 319.0 | F      | S               | -0.81           |
|       | F      | P               | -0.76           |
| 355.0 | T4     | S or P          | -0.78           |
|       | T6     | S or P          | -0.79           |
| 356.0 | T6     | S or P          | -0.82           |
| 443.0 | F      | S               | -0.83           |
|       | F      | P               | -0.82           |
| 514.0 | F      | S               | -0.87           |
| 520.0 | T4     | S or P          | -0.89           |
| 710.0 | F      | S               | -0.99           |

(a) S, sand; P, permanent. (b) Potential versus standard calomel electrode measured in an aqueous solution of 53 g/L NaCl plus 3 g/L H<sub>2</sub>O<sub>2</sub> at 25 °C (77 °F). Source: Ref 28

**Table 8.28 Typical physical properties of cast aluminum metal matrix composites (MMCs)**

Metric values calculated from engineering values

| Alloy                           | MMC designation                | Temper | Density             |                   | Specific gravity | Average coefficient of thermal expansion |           | Approx melting range |         | Thermal conductivity |         |              | Electrical conductivity(c) |          |             |          | Specific heat |              |          |
|---------------------------------|--------------------------------|--------|---------------------|-------------------|------------------|------------------------------------------|-----------|----------------------|---------|----------------------|---------|--------------|----------------------------|----------|-------------|----------|---------------|--------------|----------|
|                                 |                                |        | lb/in. <sup>3</sup> | g/cm <sup>3</sup> |                  | 68-212 °F                                | 20-100 °C | °F                   |         | °C                   |         | At 72 °F     |                            | At 66 °F |             | At 25 °C |               | At 66 °Fmb;0 | At 20 °C |
|                                 |                                |        |                     |                   |                  |                                          |           | per °F               | per °C  | Eng. units           | W/m · K | Volume %IACS | Weight %IACS               | MS/m     | Volume MS/m |          |               |              |          |
|                                 |                                |        |                     |                   |                  |                                          |           |                      |         |                      |         |              |                            |          |             |          |               |              |          |
| Sand and permanent mold casting |                                |        |                     |                   |                  |                                          |           |                      |         |                      |         |              |                            |          |             |          |               |              |          |
| 339.0                           | 339.0/SiC/10p                  | F      | 0.099               | 2.75              | 2.75             | 11.2                                     | 20.2      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | O      | 0.099               | 2.75              | 2.75             | 11.2                                     | 20.2      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | T5     | 0.099               | 2.75              | 2.75             | 11.2                                     | 20.2      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 | 339.0/SiC/20p                  | T6     | 0.999               | 2.75              | 2.75             | 11.2                                     | 20.2      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | F      | 0.102               | 2.81              | 2.81             | 9.9                                      | 17.8      | ...                  | ...     | ...                  | 83.8    | 145          | ...                        | ...      | ...         | 0.197    | 824           | ...          |          |
|                                 |                                | O      | 0.102               | 2.81              | 2.81             | 9.9                                      | 17.8      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
| 359.0                           | 359.0/SiC/10p                  | T5     | 0.102               | 2.81              | 2.81             | 9.9                                      | 17.8      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | T6     | 0.102               | 2.81              | 2.81             | 9.9                                      | 17.8      | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | T6     | 0.098               | 2.71              | 2.71             | 11.5                                     | 20.7      | 1045-1115            | 565-605 | ...                  | ...     | ...          | ...                        | ...      | ...         | 0.210    | 879           | ...          |          |
|                                 | 359.0/SiC/20p                  | O      | 0.100               | 2.77              | 2.77             | 9.7                                      | 17.5      | 1045-1115            | 565-605 | ...                  | ...     | ...          | ...                        | ...      | ...         | 0.200    | 837           | ...          |          |
|                                 |                                | T6     | 0.100               | 2.77              | 2.77             | 9.7                                      | 17.5      | 1045-1115            | 565-605 | 106.9                | 185     | ...          | ...                        | ...      | 0.200       | 837      | ...           |              |          |
|                                 |                                | T71    | 0.100               | 2.77              | 2.77             | 9.7                                      | 17.5      | 1045-1115            | 565-605 | 116.1                | 201     | ...          | ...                        | ...      | 0.200       | 837      | ...           |              |          |
| Sand casting                    |                                |        |                     |                   |                  |                                          |           |                      |         |                      |         |              |                            |          |             |          |               |              |          |
| 361.0(a)                        | 361.0/SiC/30p                  | T6     | 0.100               | 2.78              | 2.78             | 8.0                                      | 14.5      | ...                  | ...     | ...                  | 92.5    | 160          | ...                        | ...      | ...         | 0.190    | 820           |              |          |
| Investment casting              |                                |        |                     |                   |                  |                                          |           |                      |         |                      |         |              |                            |          |             |          |               |              |          |
| 361.0(a)                        | 361.0/SiC/30p<br>361.0/SiC/40p | T6P    | 0.101               | 2.80              | 2.80             | 7.8                                      | 14.1      | ...                  | ...     | ...                  | 92.5    | 160          | ...                        | ...      | ...         | 0.190    | 820           | 0.29         |          |
|                                 |                                | F      | 0.104               | 2.87              | 2.87             | 6.6                                      | 11.9      | ...                  | ...     | ...                  | 106.4   | 183          | ...                        | ...      | ...         | 0.170    | 763           | ...          |          |
|                                 |                                | T6     | 0.104               | 2.87              | 2.87             | 6.6                                      | 11.9      | ...                  | ...     | ...                  | 106.4   | 183          | ...                        | ...      | ...         | 0.170    | 763           | 0.28         |          |
| Die casting                     |                                |        |                     |                   |                  |                                          |           |                      |         |                      |         |              |                            |          |             |          |               |              |          |
| 301.0(b)                        | 301.0/SiC/10p                  | F      | 0.100               | 2.76              | 2.76             | 10.7                                     | 19.3      | 1000-1100            | 540-595 | 71.6                 | 124     | 22.0         | 71                         | 13       | 41          | 0.201    | 842           | 0.3          |          |
|                                 |                                | O      | 0.100               | 2.76              | 2.76             | 10.7                                     | 19.3      | 1000-1100            | 540-595 | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | T5     | 0.100               | 2.76              | 2.76             | 10.7                                     | 19.3      | 1000-1100            | 540-595 | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
| 301.0(b)                        | 301.0/SiC/20p                  | F      | 0.102               | 2.82              | 2.82             | 9.4                                      | 16.9      | 1000-1100            | 540-595 | 83.2                 | 144     | 20.5         | 78                         | 12       | 45          | 0.198    | 829           | 0.29         |          |
|                                 |                                | O      | 0.102               | 2.82              | 2.82             | 9.4                                      | 16.9      | 1000-1100            | 540-595 | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
|                                 |                                | T5     | 0.102               | 2.82              | 2.82             | 9.4                                      | 16.9      | 1000-1100            | 540-595 | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          |          |
| 303.0(b)                        | 303.0/SiC/10p                  | F      | 0.097               | 2.65              | 2.65             | ...                                      | ...       | ...                  | ...     | ...                  | ...     | 161          | 32.7                       | 125      | 19          | 72       | 0.208         | 871          | ...      |
|                                 |                                | O      | 0.097               | 2.65              | 2.65             | ...                                      | ...       | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          | ...      |
|                                 |                                | T5     | 0.097               | 2.65              | 2.65             | ...                                      | ...       | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          | ...      |
| 303.0(b)                        | 303.0/SiC/20p                  | F      | 0.098               | 2.71              | 2.71             | ...                                      | ...       | ...                  | ...     | ...                  | ...     | 168          | 24.7                       | 94       | 14          | 55       | 0.193         | 808          | 0.29     |
|                                 |                                | O      | 0.098               | 2.71              | 2.71             | ...                                      | ...       | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          | ...      |
|                                 |                                | T5     | 0.098               | 2.71              | 2.71             | ...                                      | ...       | ...                  | ...     | ...                  | ...     | ...          | ...                        | ...      | ...         | ...      | ...           | ...          | ...      |
| 361.0(a)                        | 361.0/SiC/18p<br>361.0/SiC/30p | F      | 0.100               | 2.77              | 2.77             | 9.0                                      | 16.2      | ...                  | ...     | ...                  | 76.3    | 132          | ...                        | ...      | ...         | 0.180    | 802           | 0.31         |          |
|                                 |                                | F      | 0.101               | 2.80              | 2.80             | 7.8                                      | 14.1      | ...                  | ...     | ...                  | 92.3    | 158          | ...                        | ...      | ...         | ...      | ...           | 0.29         |          |
|                                 |                                | T5P    | 0.101               | 2.80              | 2.80             | 7.8                                      | 14.1      | ...                  | ...     | ...                  | 92.3    | 158          | ...                        | ...      | ...         | ...      | ...           | 0.29         |          |

(a) In referenced publications, aluminum casting alloy 361.0 is referred to as Al-10Si-1Mg or Al-10Si-1Mg-1Fe. (b) In referenced NADCA specifications, aluminum casting alloys 301.0 and 303.0 are referred to as 360 and 380, respectively. Source: Ref 7, 29, 30

(a) In referenced publications, aluminum casting alloy 361.0 is referred to as Al-10Si-1Mg or Al-10Si-1Mg-1Fe. (b) In referenced NADCA specifications, aluminum casting alloys 301.0 and 303.0 are referred to as 360 and 380, respectively. Source: Ref 7, 29, 30



Table 8.29 Typical mechanical properties of cast aluminum metal matrix composites (MMCs) at room temperature

Metric values calculated from engineering values. Values are representative of separately cast test bars, not of specimens taken from commercial castings.

| Matrix alloy                    | MMC designation                | Temper | Tension           |     |                   |     |                              |          |                            |                        |                                       |      | Modulus of elasticity(c) |                        |                     |
|---------------------------------|--------------------------------|--------|-------------------|-----|-------------------|-----|------------------------------|----------|----------------------------|------------------------|---------------------------------------|------|--------------------------|------------------------|---------------------|
|                                 |                                |        | Ultimate strength |     | Yield strength(a) |     | Elongation in 2 in. or 4D, % | Hardness | Fatigue endurance limit(b) |                        | Fracture toughness (K <sub>IC</sub> ) |      |                          |                        |                     |
|                                 |                                |        | ksi               | MPa | ksi               | MPa |                              |          | ksi · in. <sup>1/2</sup>   | MPa · m <sup>1/2</sup> | ksi                                   | MPa  | ksi · in. <sup>1/2</sup> | MPa · m <sup>1/2</sup> | 10 <sup>6</sup> psi |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| Sand and permanent mold casting |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| 339.0                           | 339.0/SiC/10p                  | F      | 37                | 255 | 26                | 179 | 0.7                          | 57       | ...                        | ...                    | ...                                   | ...  | ...                      | 12.8                   | 88                  |
|                                 |                                | O      | 33                | 228 | 20                | 138 | 1.0                          | 43       | ...                        | ...                    | ...                                   | ...  | ...                      | 12.8                   | 88                  |
|                                 |                                | T5     | 39                | 269 | 36                | 248 | 0.3                          | 63       | ...                        | ...                    | ...                                   | ...  | ...                      | 12.8                   | 88                  |
|                                 |                                | T6     | 54                | 372 | 52                | 359 | 0.3                          | 79       | ...                        | ...                    | ...                                   | ...  | ...                      | 12.8                   | 88                  |
|                                 | 339.0/SiC/20p                  | F      | 38                | 262 | 31                | 214 | 0.4                          | 70       | ...                        | ...                    | ...                                   | ...  | ...                      | 14.6                   | 101                 |
|                                 |                                | O      | 33                | 228 | 27                | 186 | 0.4                          | 53       | ...                        | ...                    | ...                                   | ...  | ...                      | 14.6                   | 101                 |
|                                 |                                | T5     | 41                | 283 | 39                | 269 | 0.2                          | 75       | ...                        | ...                    | ...                                   | ...  | ...                      | 14.6                   | 101                 |
|                                 |                                | T6     | 54                | 372 | ...               | ... | ...                          | 86       | ...                        | ...                    | ...                                   | ...  | ...                      | 14.6                   | 101                 |
| 359.0                           | 359.0/SiC/10p                  | T6     | 49                | 338 | 44                | 303 | 1.2                          | 55       | ...                        | ...                    | 15.8                                  | 17.4 | ...                      | 12.5                   | 86                  |
|                                 |                                | O      | 32                | 221 | 24                | 165 | 2.8                          | 73       | ...                        | ...                    | ...                                   | ...  | ...                      | 14.4                   | 99                  |
|                                 |                                | T6     | 52                | 359 | 49                | 338 | 0.4                          | 77       | ...                        | 50                     | 14.4                                  | 15.9 | ...                      | 14.4                   | 99                  |
|                                 |                                | T71    | 38                | 262 | 31                | 214 | 1.9                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 14.4                   | 99                  |
| Sand casting                    |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| 361.0(e)                        | 361.0/SiC/30p                  | T6     | 54                | 371 | ...               | ... | 0.4                          | ...      | ...                        | 19                     | 132                                   | 13.4 | 14.7                     | 18.1                   | 125                 |
| Investment casting              |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| 361.0(e)                        | 361.0/SiC/30p<br>361.0/SiC/40p | T6     | 51                | 350 | 38                | 260 | 0.5                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 18.1                   | 125                 |
|                                 |                                | F      | 33                | 226 | 29                | 199 | 0.5                          | ...      | ...                        | 17                     | 115                                   | 11.0 | 12.1                     | 21.9                   | 151                 |
|                                 |                                | T6     | 54                | 370 | 39                | 270 | 0.4                          | ...      | ...                        | 22                     | 150                                   | ...  | ...                      | 21.3                   | 147                 |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| Die casting                     |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| 301(d)                          | 301.0/SiC/10p                  | F      | 50                | 345 | 35                | 241 | 1.2                          | 77       | ...                        | ...                    | ...                                   | ...  | ...                      | 13.6                   | 94                  |
|                                 |                                | O      | 40                | 276 | 22                | 152 | 1.7                          | 55       | ...                        | ...                    | ...                                   | ...  | ...                      | 13.6                   | 94                  |
|                                 |                                | T5     | 54                | 372 | 48                | 331 | 0.7                          | 84       | ...                        | ...                    | ...                                   | ...  | ...                      | 13.6                   | 94                  |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
|                                 | 301.0/SiC/20p                  | F      | 51                | 352 | 44                | 303 | 0.4                          | 82       | ...                        | 22                     | 130                                   | ...  | ...                      | 16.5                   | 114                 |
|                                 |                                | O      | 44                | 303 | 27                | 186 | 0.8                          | 62       | ...                        | ...                    | ...                                   | ...  | ...                      | 16.5                   | 114                 |
|                                 |                                | T5     | 58                | 400 | ...               | ... | ...                          | 87       | ...                        | ...                    | ...                                   | ...  | ...                      | 16.5                   | 114                 |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| 303(d)                          | 303.0/SiC/10p                  | F      | 45                | 310 | 32                | 221 | 0.9                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 13.2                   | 91                  |
|                                 |                                | O      | 36                | 248 | 21                | 145 | 2.0                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 13.2                   | 91                  |
|                                 |                                | T5     | 51                | 352 | 46                | 317 | 0.5                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 13.2                   | 91                  |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
|                                 | 303.0/SiC/20p                  | F      | 44                | 303 | 36                | 248 | 0.5                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 15.7                   | 108                 |
|                                 |                                | O      | 38                | 262 | 23                | 159 | 1.5                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 15.7                   | 108                 |
|                                 |                                | T5     | 53                | 365 | 49                | 338 | 0.3                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 15.7                   | 108                 |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |
| 361.0(e)                        | 361.0/SiC/18p<br>361.0/SiC/30p | F      | 43                | 295 | 32                | 220 | 1.0                          | ...      | ...                        | ...                    | ...                                   | 11.7 | 12.8                     | 15.4                   | 106                 |
|                                 |                                | F      | 45                | 309 | 22                | 155 | 0.4                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 18.1                   | 125                 |
|                                 |                                | T5P    | 44                | 307 | 34                | 235 | 0.3                          | ...      | ...                        | ...                    | ...                                   | ...  | ...                      | 18.1                   | 125                 |
|                                 |                                |        |                   |     |                   |     |                              |          |                            |                        |                                       |      |                          |                        |                     |

(a) For tensile yield strengths, offset = 0.2%. (b) Based on 10,000,000 cycles of axial stress stress ( $R = 0.1$ ) fatigue loading (Source: Duralcan, USA). (c) Average of tension and compression moduli; compressive modulus is nominally about 2% greater than the tension modulus. (d) In referenced publications, aluminum casting alloys 301.0 and 303.0 are referred to as 380 and 360, respectively, obsolete designations. (e) In referenced publications, aluminum casting alloy 361.0 is referred to as Al-10Si-1Mg or Al-10Si-1Mg-1Fe. Source: Ref 7, 29, 30

**Table 8.30** Relative casting and finishing characteristics of die cast aluminum metal matrix composites (MMCs)

Ratings are from 1 (most desirable) to 5 (least desirable). In referenced NADCA specifications, aluminum casting alloys are referred to as 360 and 380, respectively.

| Alloy | MMC designation | Casting characteristics    |                               |                    |                       | Finishing characteristics |               |                    |            |            | Performance characteristics |                               |                    |
|-------|-----------------|----------------------------|-------------------------------|--------------------|-----------------------|---------------------------|---------------|--------------------|------------|------------|-----------------------------|-------------------------------|--------------------|
|       |                 | Resistance to hot cracking | Fluidity/die filling capacity | Pressure tightness | Anti-soldering to die | Machinability             | Polishability | Electroplatability | Anodizing  |            | Corrosion resistance        | Elevated temperature strength | Resistance to wear |
|       |                 |                            |                               |                    |                       |                           |               |                    | Appearance | Protection |                             |                               |                    |
| 301.0 | 301.0/SiC/10P   | 1                          | 1                             | 2                  | 3                     | 4                         | 5             | 2                  | 4          | 5          | 5                           | 1                             | 1                  |
|       | 301.0/SiC/20P   | 1                          | 1                             | 2                  | 3                     | 4                         | 5             | 2                  | 4          | 5          | 5                           | 1                             | 1                  |
| 303.0 | 303.0/SiC/10P   | 1                          | 1                             | 2                  | 2                     | 4                         | 5             | 2                  | 4          | 4          | 3                           | 1                             | 1                  |
|       | 303.0/SiC/20P   | 1                          | 1                             | 2                  | 2                     | 4                         | 5             | 2                  | 4          | 4          | 3                           | 1                             | 1                  |

Source: Ref 7; Duralcan cited as original reference

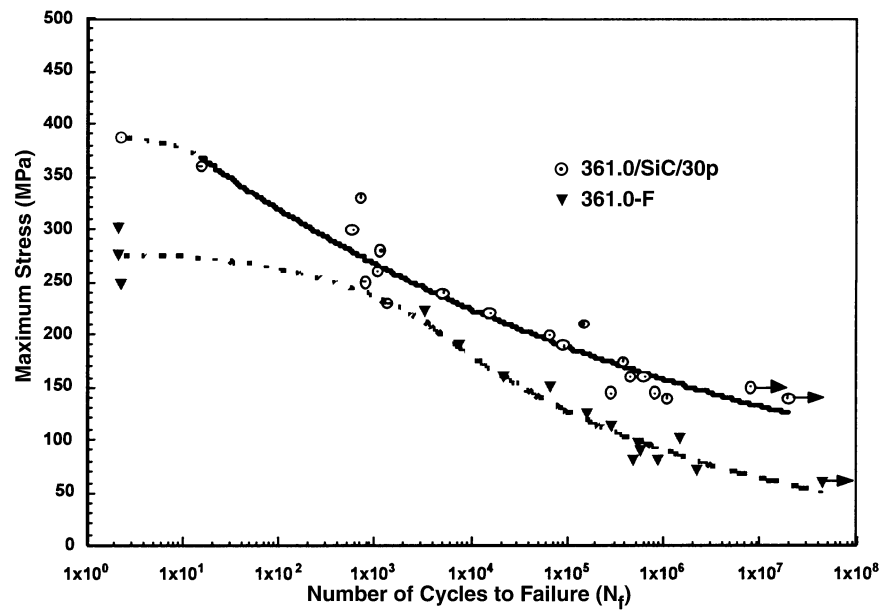


**Fig. 8.30** Fatigue curves ( $R = -1.0$ ) for cast reinforced and unreinforced alloy 361.0 at room temperature. The reinforced composite is 361.0/SiC/30p. Source: Ref 30

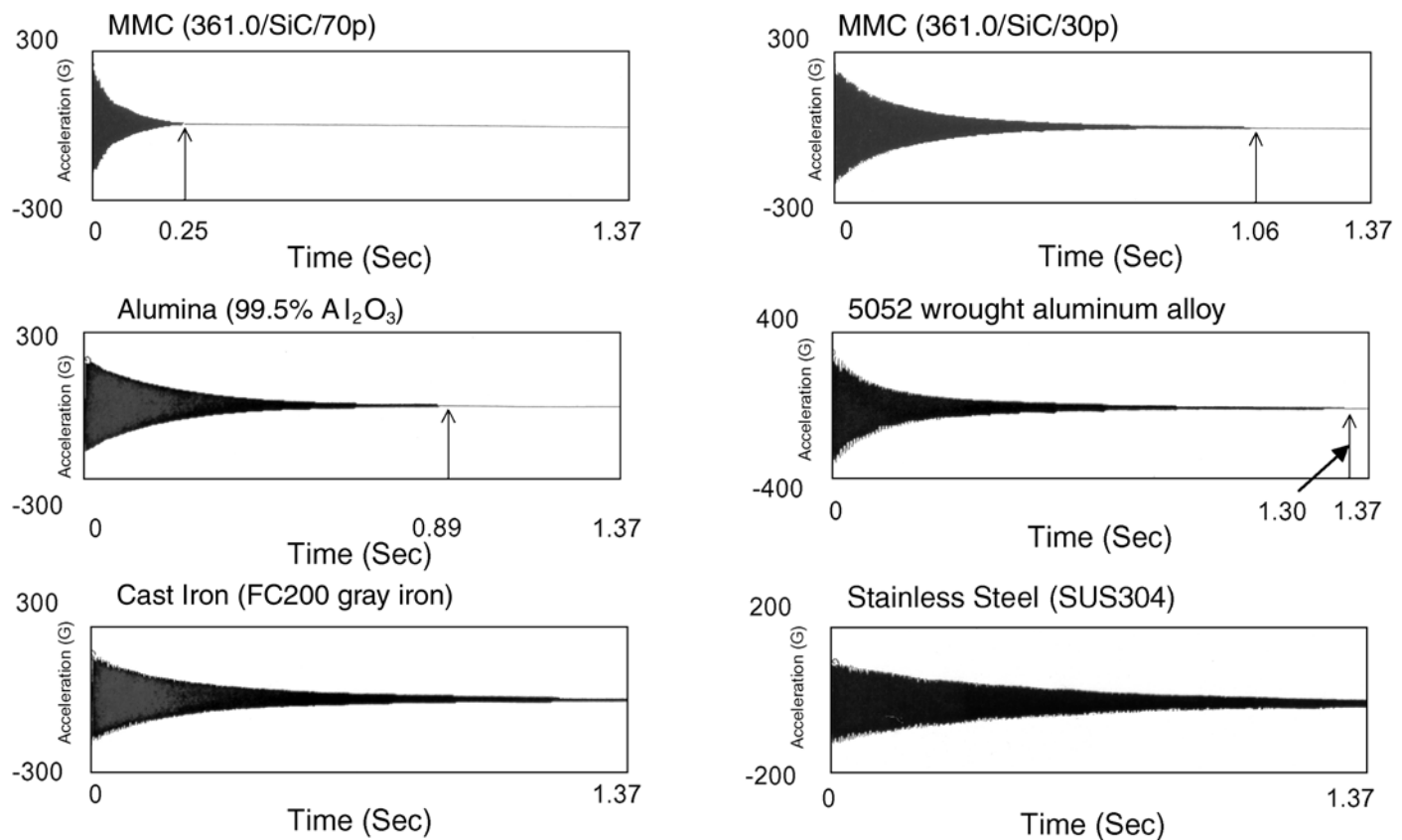


**Fig. 8.31** Comparison of vibration damping performance for selected aluminum MMCs and other structural alloys. Frequency range, 0.01 Hz to 5 kHz; impacting force, approximately 49 lbf (220 N); specimen size,  $9.4 \times 1.2 \times 0.4$  in. ( $240 \times 30 \times 10$  mm). The specimen is suspended in air and impacted in the center, then the acceleration at an edge is measured. Source: Ref 30

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## DATA SET 1

# Aging Response Curves

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This data set contains aging response curves for a wide range of aluminum casting alloys. Included where available are both:

- *Room-temperature, or “natural,” aging response curves* (Fig. D1.1 to D1.49). Properties were measured after holding specimens at room temperature for various times after casting (F temper) or after solution heat treatment (T4 temper).
- *Artificial or “high-temperature” aging response curves* (Fig. D1.50 to D1.111). Properties were measured after holding specimens at various elevated temperatures for various times from the as-cast condition or after solution heat treatment. These are captioned “high temperature,” but the implication is that any artificial aging above room temperature is included.

The curves in each group are presented in the numeric sequence of the casting alloy designation.

The intent in making such measurements is to determine the extent of the effects of time and temperature on precipitation hardening or softening. All of the aging response curves presented were developed at the Alcoa Laboratories Cleveland Casting Research Division. The curves are printed with customary static mechanical property units obtained through uniaxial tensile testing. To convert strengths in ksi to SI units (MPa) multiply by 6.895.

The tensile tests were conducted in accordance with the iteration of ASTM E 8, “Standard Test Methods for Tension Testing of Metallic Materials,” that was current at the time of the testing.

The aging response curves included herein are the results of measurements on individual lots considered representative of the respective alloys and tempers. They have not been normalized to any typical or average properties for the individual alloys and tempers. The testing may have predated the registry of the current alloy designation, but the composition of the tested material is within the limits of the designation. In a number of cases, the results of measurements made on several lots of the same alloy and temper are included.

The properties considered are as follows:

- *Yield strength* is determined by the 0.2% offset method.
- *Ultimate strength (tensile strength)* is the load at fracture divided by the original cross section of the specimen.
- *Elongation* is determined from a 2 in. (50 mm) gage length specimen.
- *Brinell hardness (HB)* testing employed a 4.9 kN (500 kgf) load with a 10 mm ball, in accordance with ASTM E 10.

Test specimens were separately cast, in conformance with Appendix 3, Fig. A3.1. The casting method is given in the caption if it was given in the original test document. If the process is not stated, it was not stipulated in the original record.

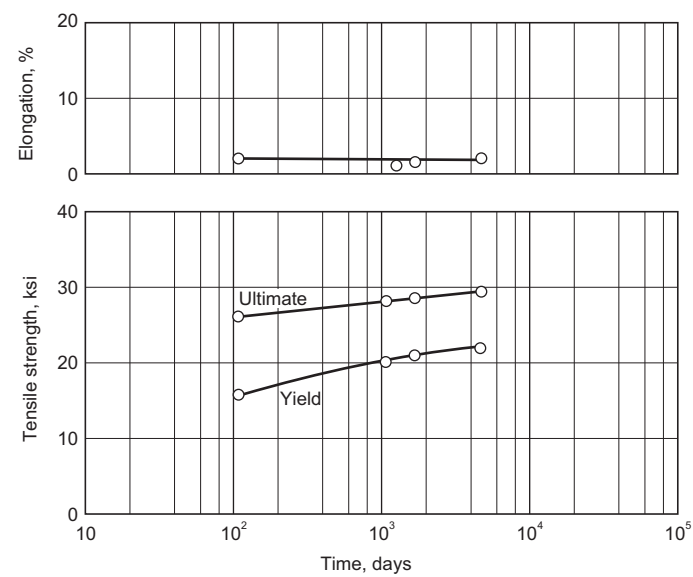


**Fig. D1.1** Room-temperature aging characteristics for aluminum alloy 208.0-F, sand cast

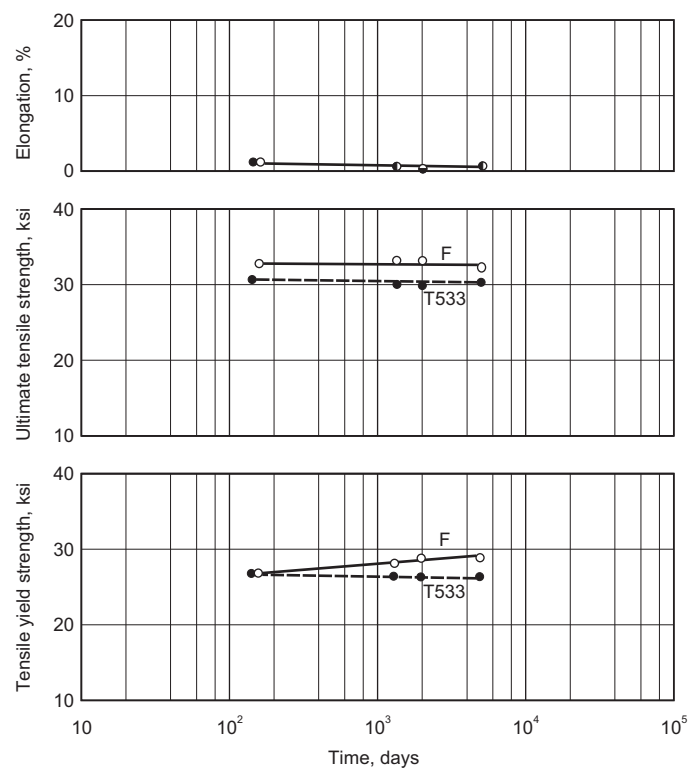


**Fig. D1.2** Room-temperature aging characteristics for aluminum alloy 213.0-F and -T533, permanent mold

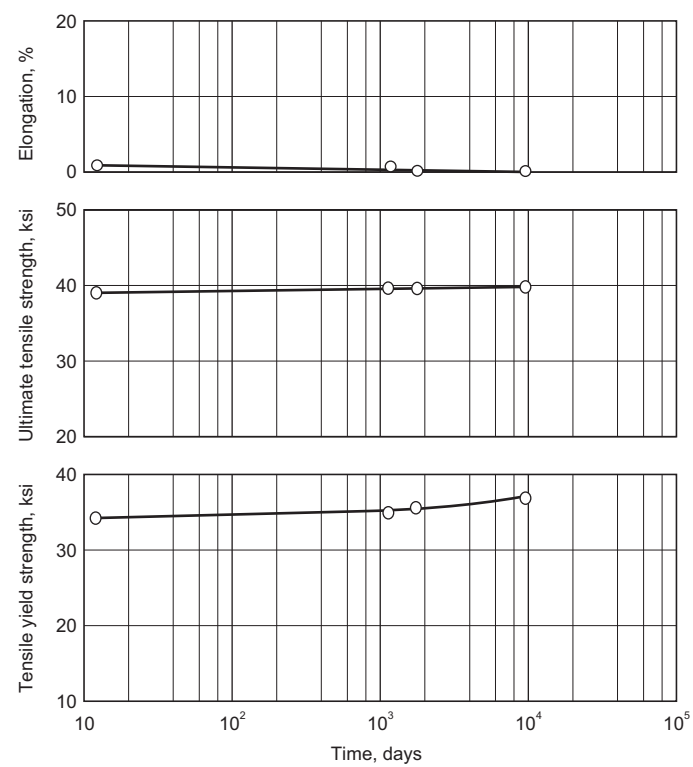


**Fig. D1.3** Room-temperature aging characteristics for aluminum alloy 242.0-T571, permanent mold

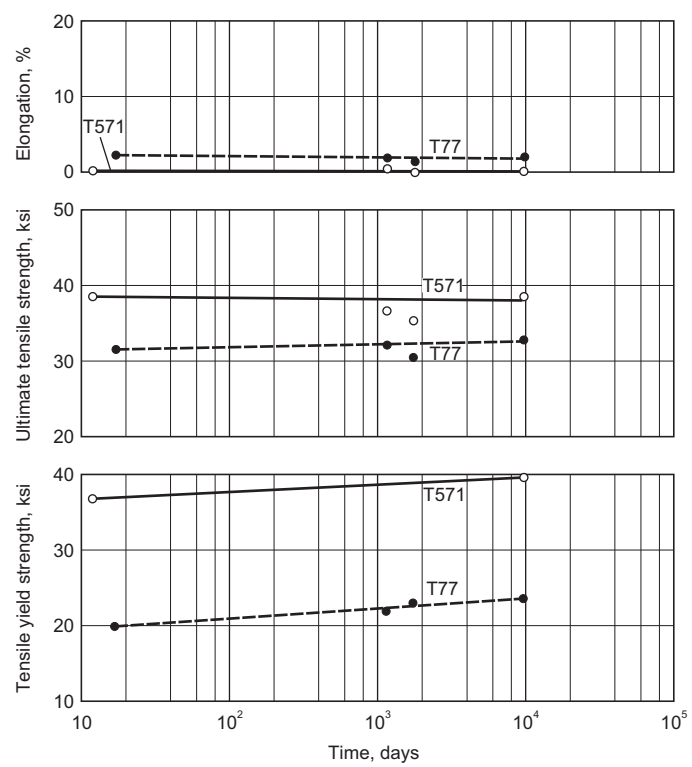


**Fig. D1.4** Room-temperature aging characteristics for aluminum alloy 242.0-T571 and -T77, sand cast

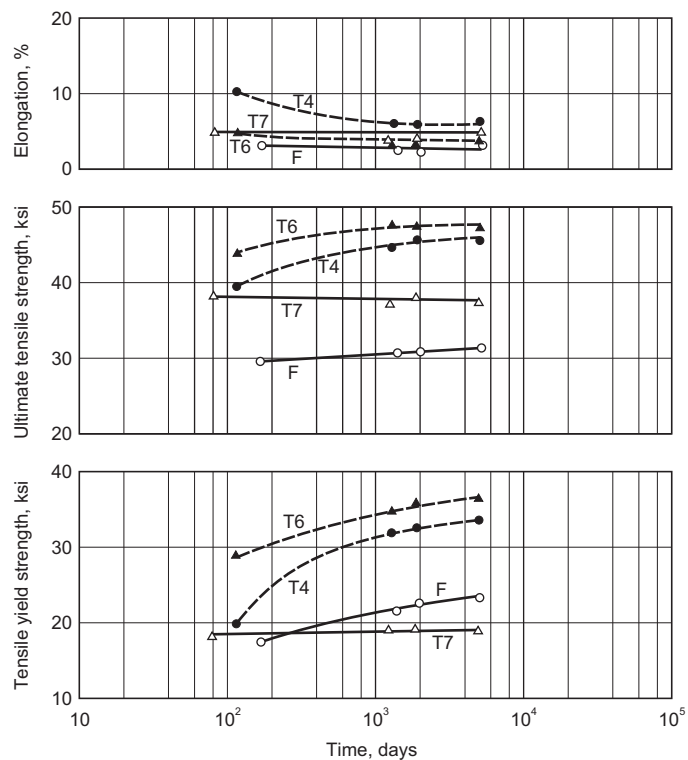


Fig. D1.5 Room-temperature aging characteristics for aluminum alloy 295.0-F, -T4, -T6, and -T7, sand cast

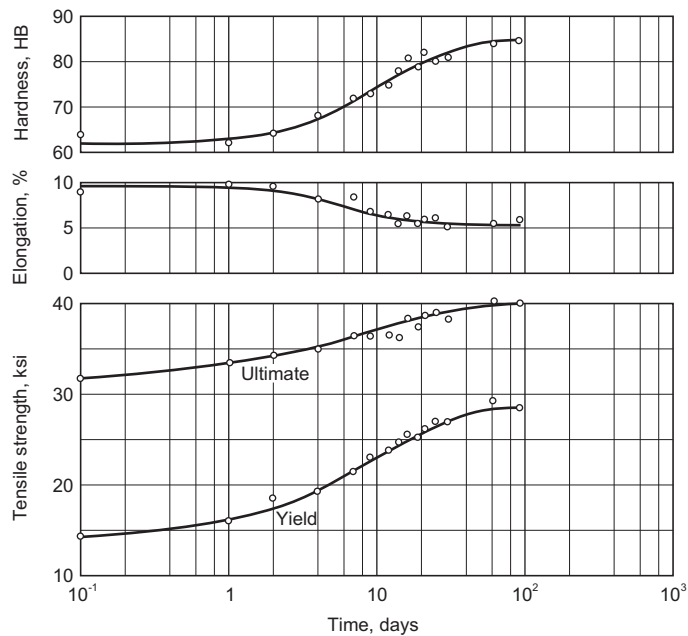


Fig. D1.7 Room-temperature aging characteristics for aluminum alloy 295.0-T4, sand cast

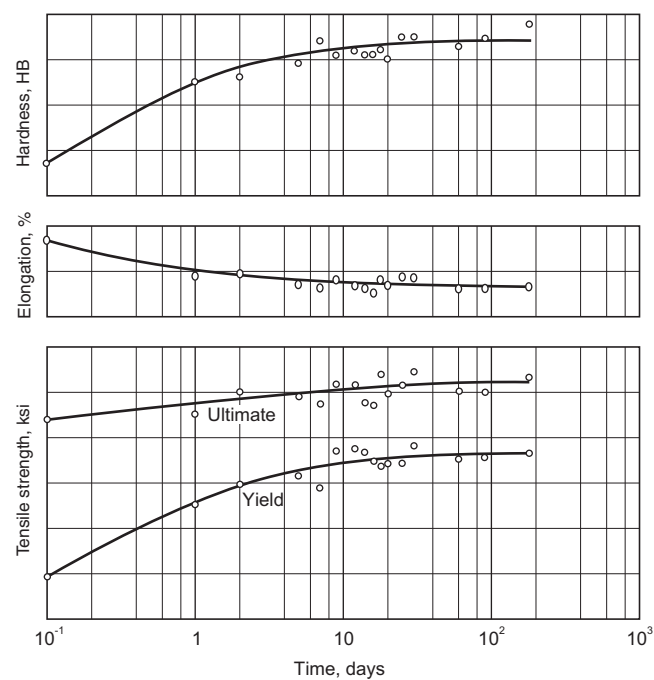


Fig. D1.6 Room-temperature aging characteristics for aluminum alloy 295.0-T4, permanent mold

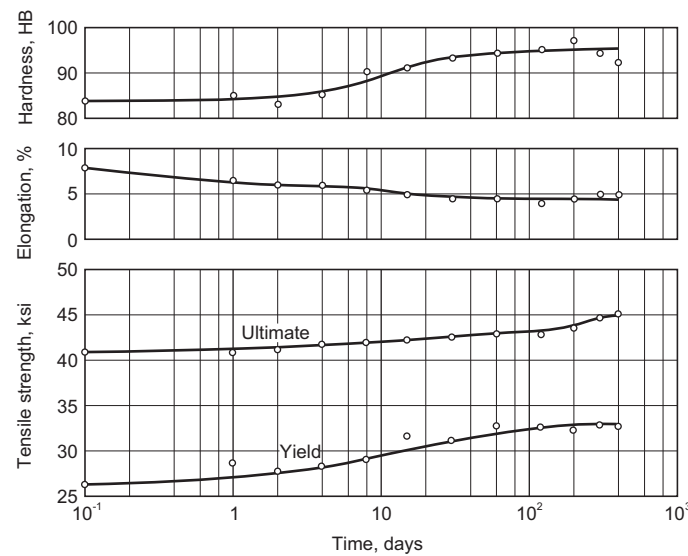


Fig. D1.8 Room-temperature aging characteristics for aluminum alloy 295.0-T6, permanent mold

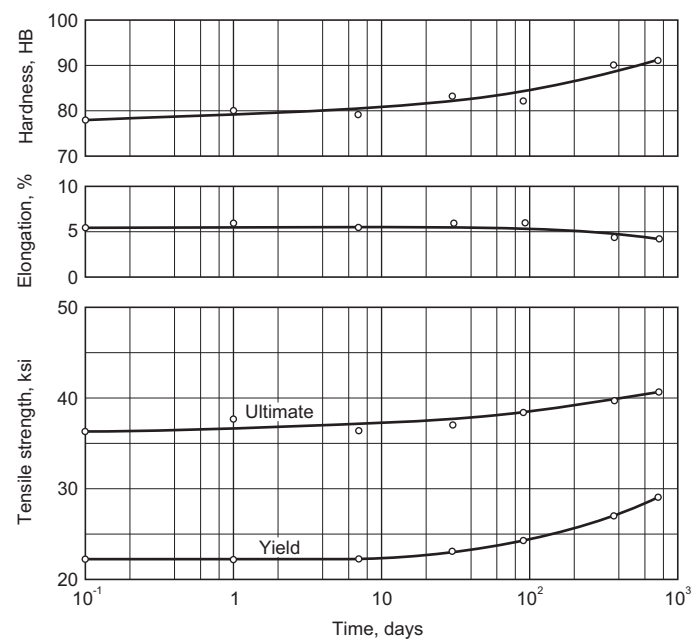


Fig. D1.9 Room-temperature aging characteristics for aluminum alloy 295.0-T6, sand cast

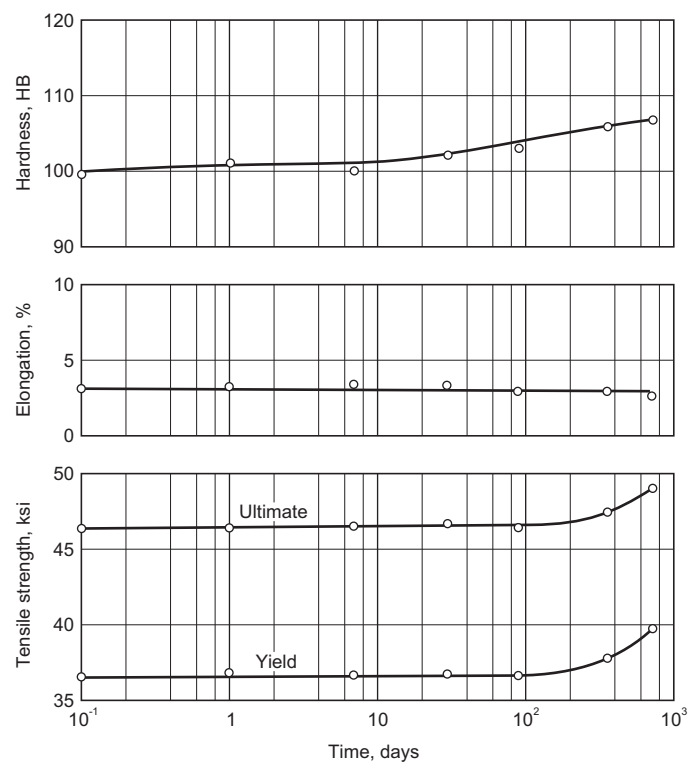


Fig. D1.10 Room-temperature aging characteristics for aluminum alloy 295.0-T62, permanent mold

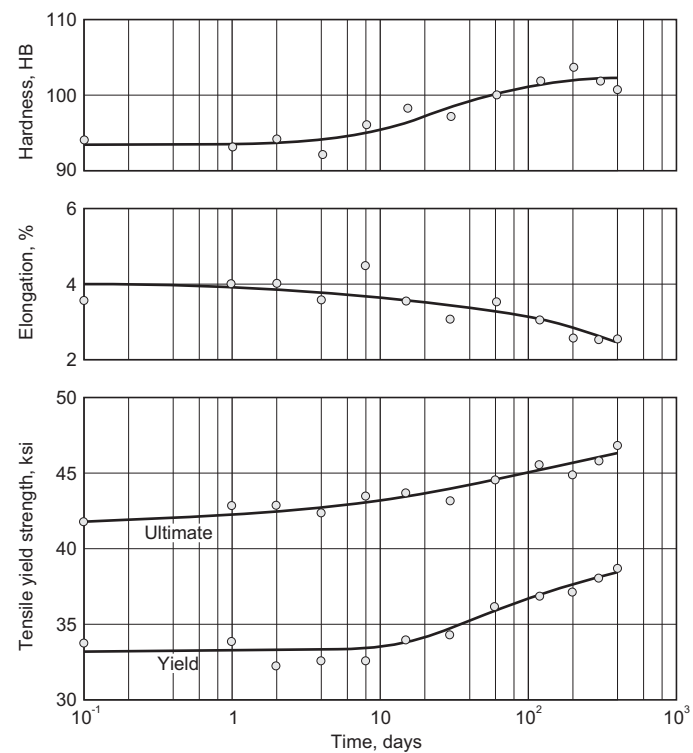


Fig. D1.11 Room-temperature aging characteristics for aluminum alloy 295.0-T62, sand cast

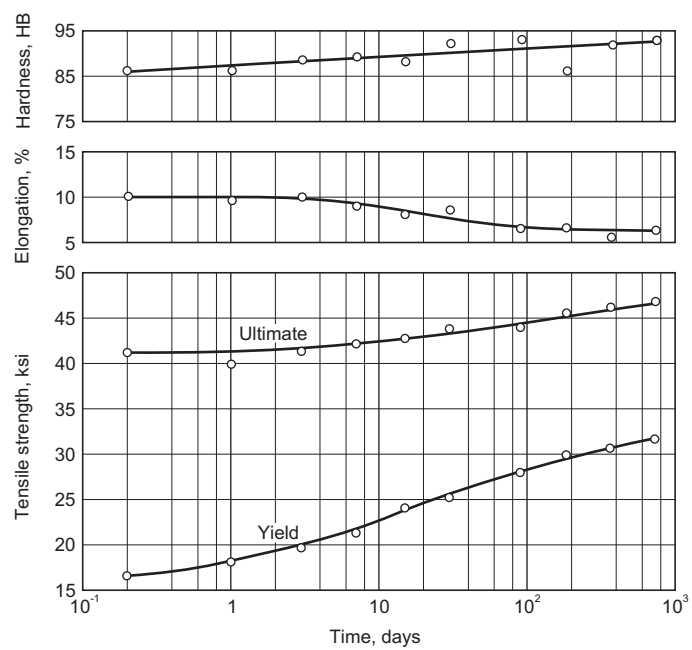


Fig. D1.12 Room-temperature aging characteristics for aluminum alloy 296.0-T4, permanent mold

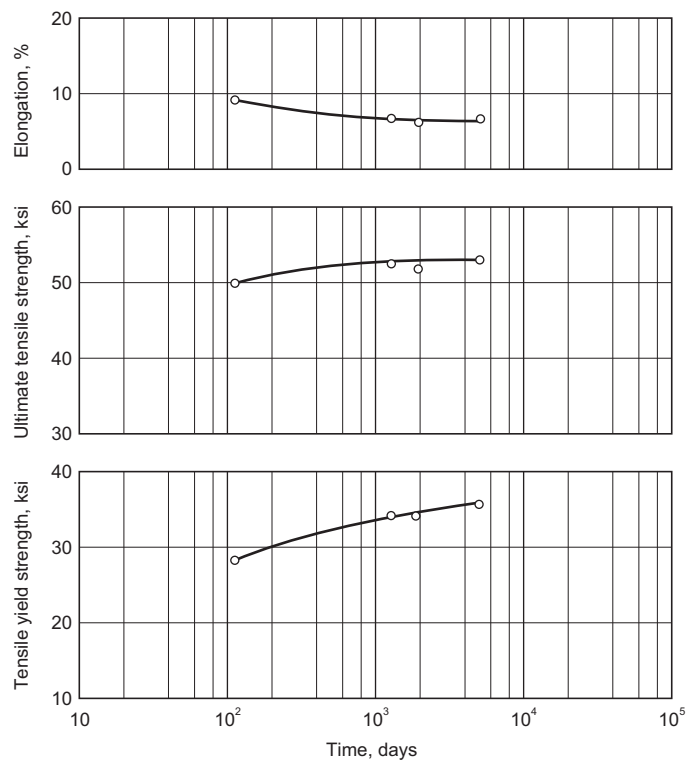


Fig. D1.13 Room-temperature aging characteristics for aluminum alloy 296.0-T6, permanent mold

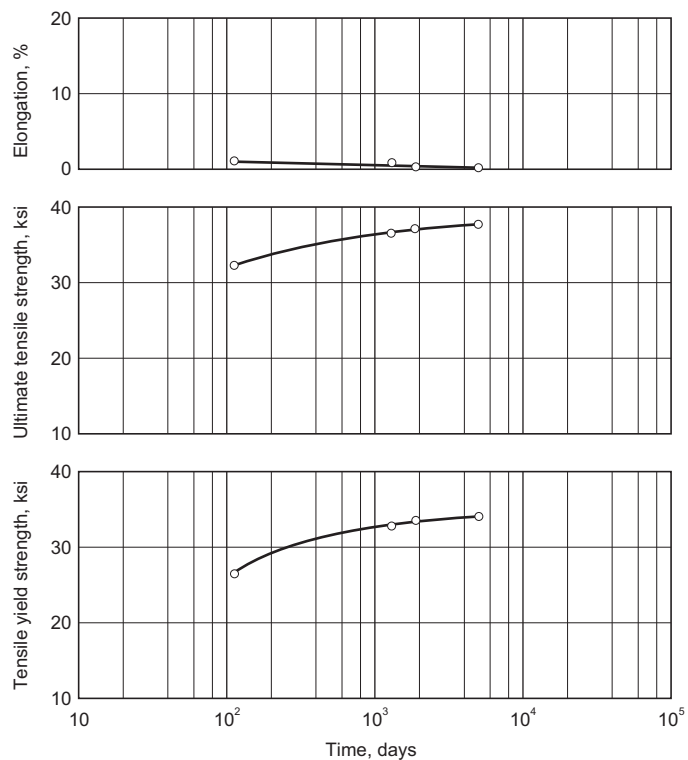


Fig. D1.14 Room-temperature aging characteristics for aluminum alloy 296.0-T6, sand cast

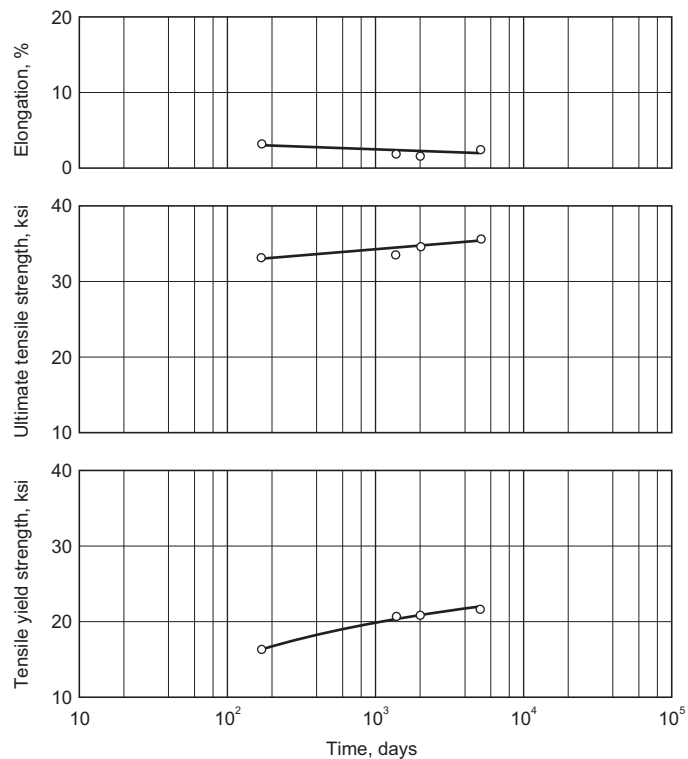


Fig. D1.15 Room-temperature aging characteristics for aluminum alloy 308.0-F, permanent mold

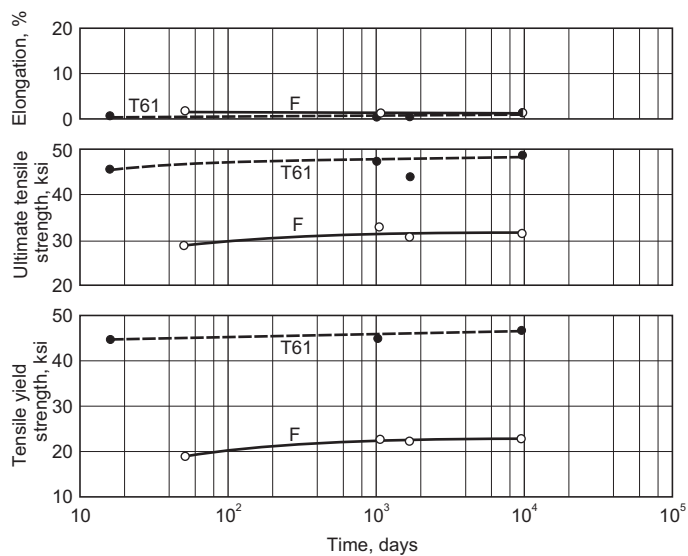


Fig. D1.16 Room-temperature aging characteristics for aluminum alloy 319.0-F and -T61, permanent mold



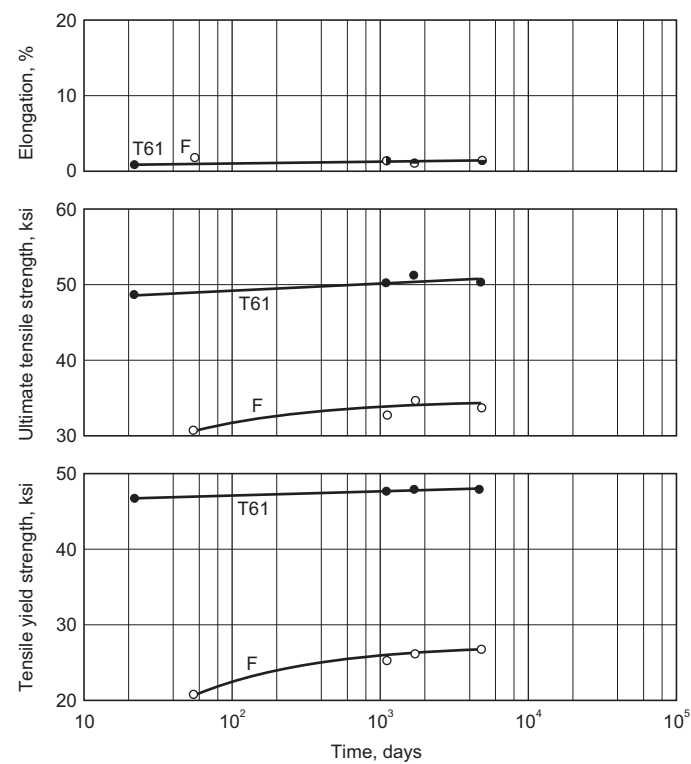


Fig. D1.17 Room-temperature aging characteristics for aluminum alloy 319.0-F, and -T61, sand cast

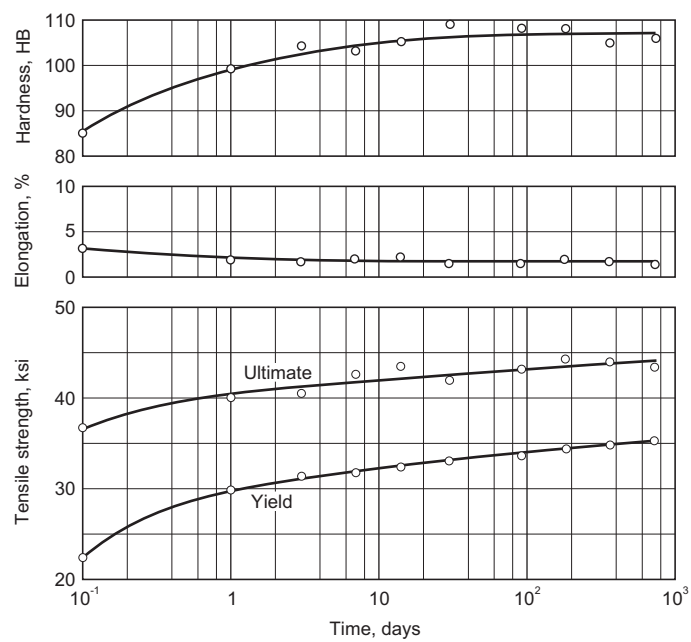


Fig. D1.18 Room-temperature aging characteristics for aluminum alloy 319.0-T4

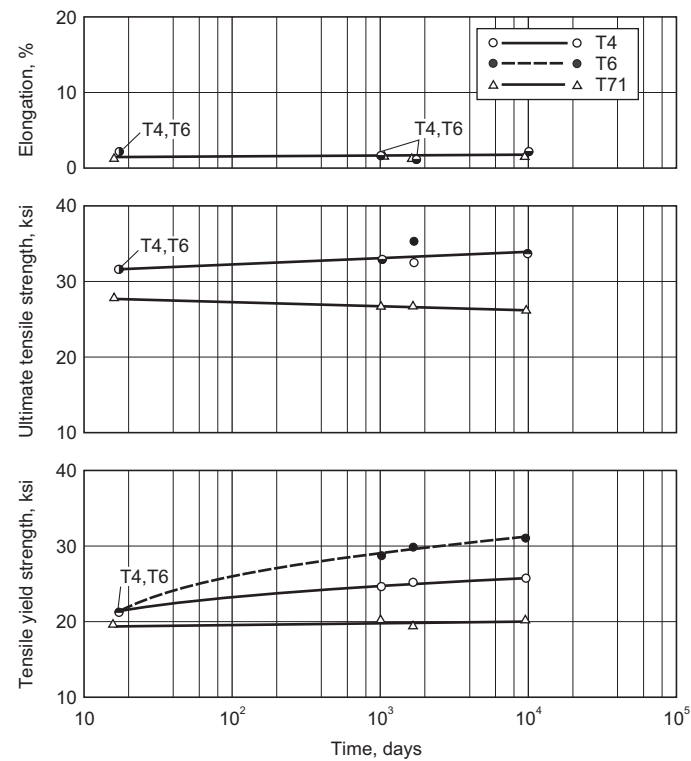


Fig. D1.19 Room-temperature aging characteristics for aluminum alloy 319.0-T4, -T6, and -T71, permanent mold

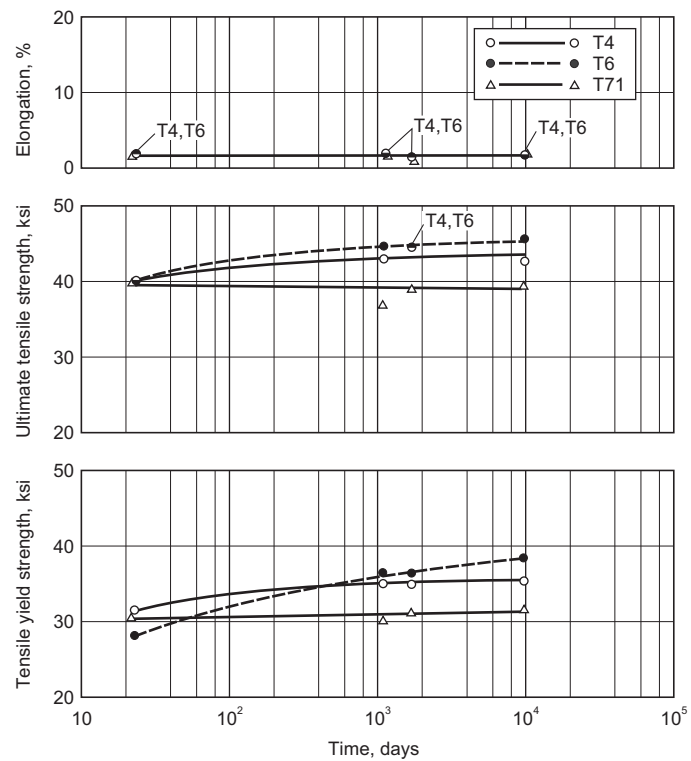


Fig. D1.20 Room-temperature aging characteristics for aluminum alloy 319.0-T4, -T6, and -T71, sand cast

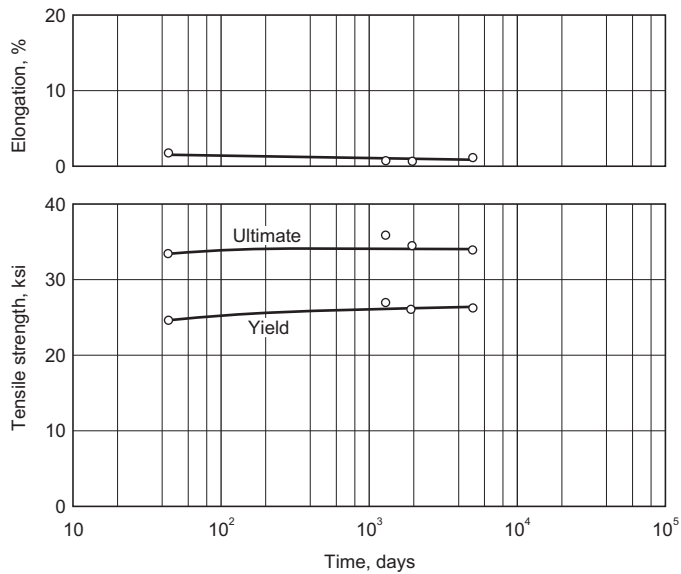


Fig. D1.21 Room-temperature aging characteristics for aluminum alloy 333.0-T5, permanent mold

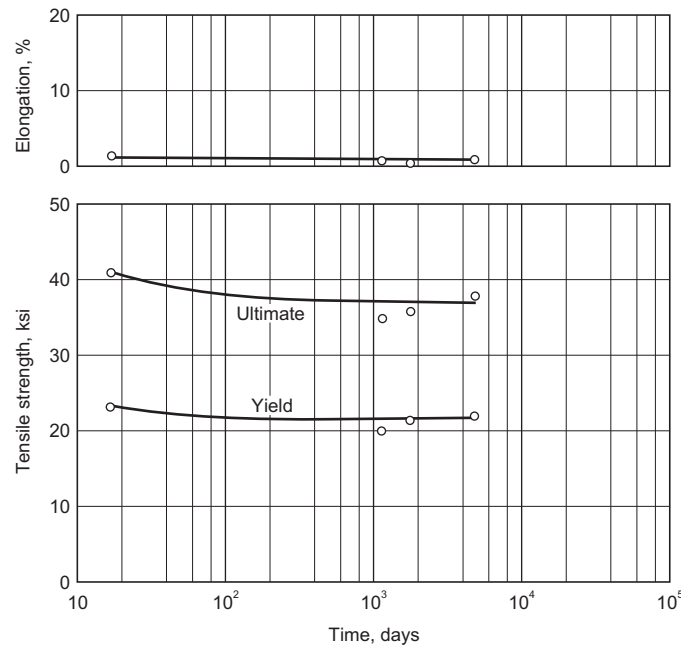


Fig. D1.22 Room-temperature aging characteristics for aluminum alloy 336.0-T551, permanent mold

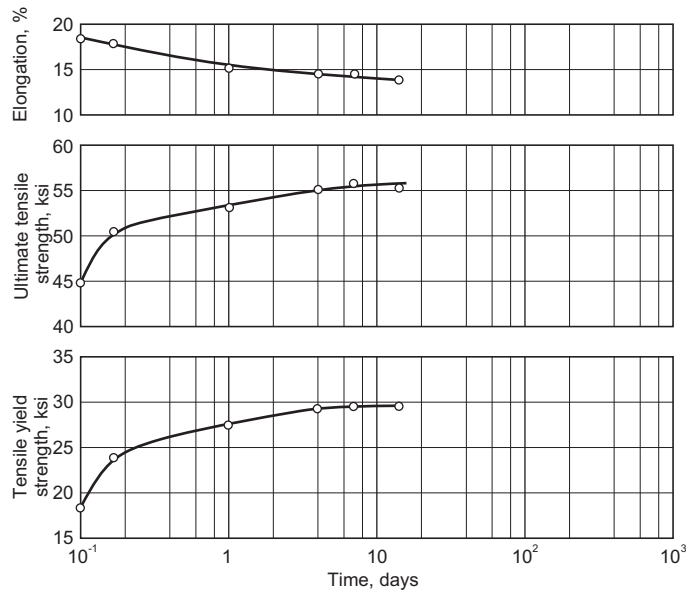


Fig. D1.23 Room-temperature aging characteristics for aluminum alloy 354.0-T4, permanent mold

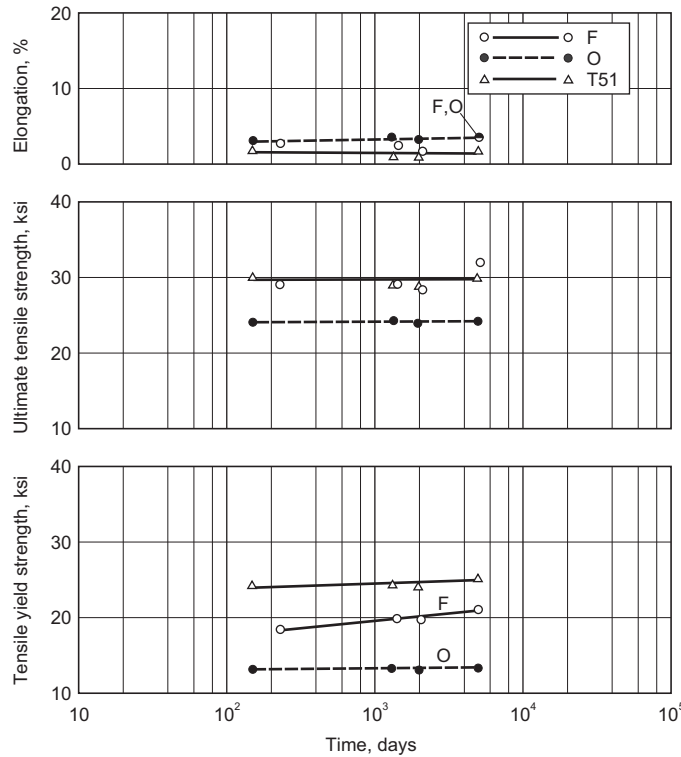


Fig. D1.24 Room-temperature aging characteristics for aluminum alloy 355.0-F, -O, and -T51, permanent mold

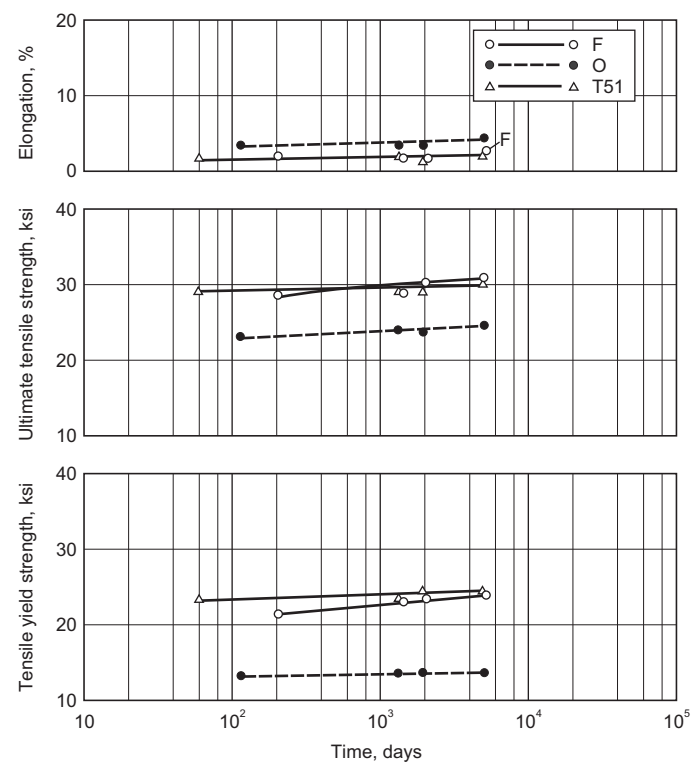


Fig. D1.25 Room-temperature aging characteristics for aluminum alloy 355.0-F, -O, and -T51, sand cast

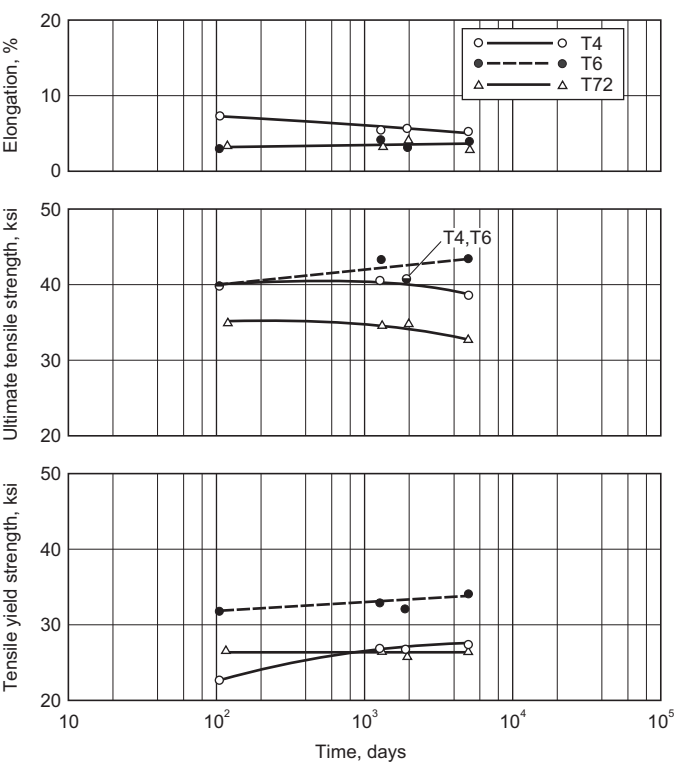


Fig. D1.26 Room-temperature aging characteristics for aluminum alloy 355.0-T4, -T6, and -T72, permanent mold

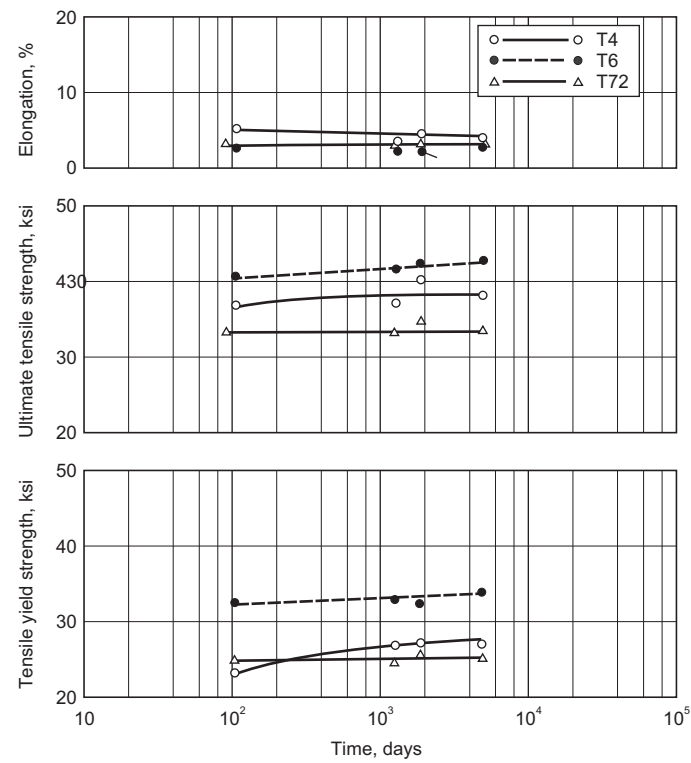


Fig. D1.27 Room-temperature aging characteristics for aluminum alloy 355.0-T4, -T6, and -T72, sand cast.

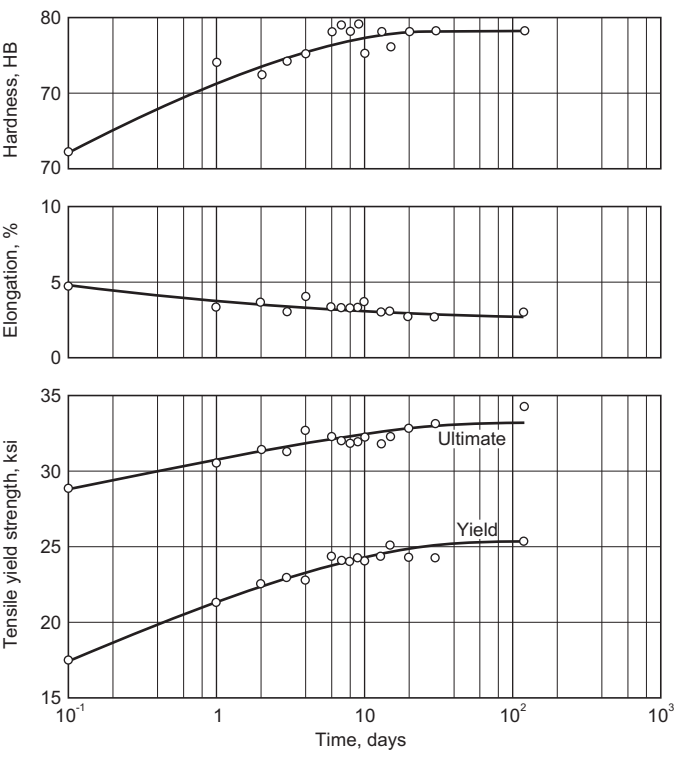


Fig. D1.28 Room-temperature aging characteristics for aluminum alloy 355.0-T4, aging time 120 days and less

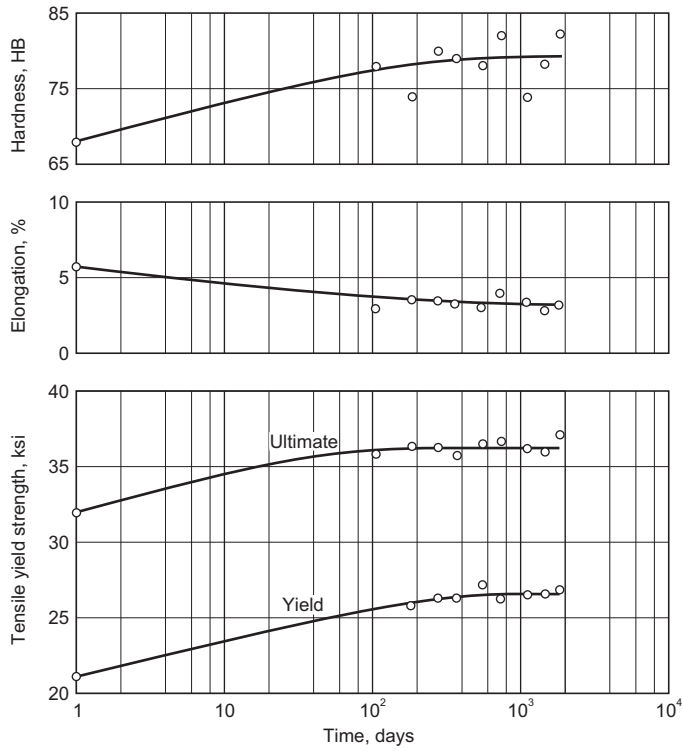


**Fig. D1.29** Room-temperature aging characteristics for aluminum alloy 355.0-T4, long-term data approaching 2000 days

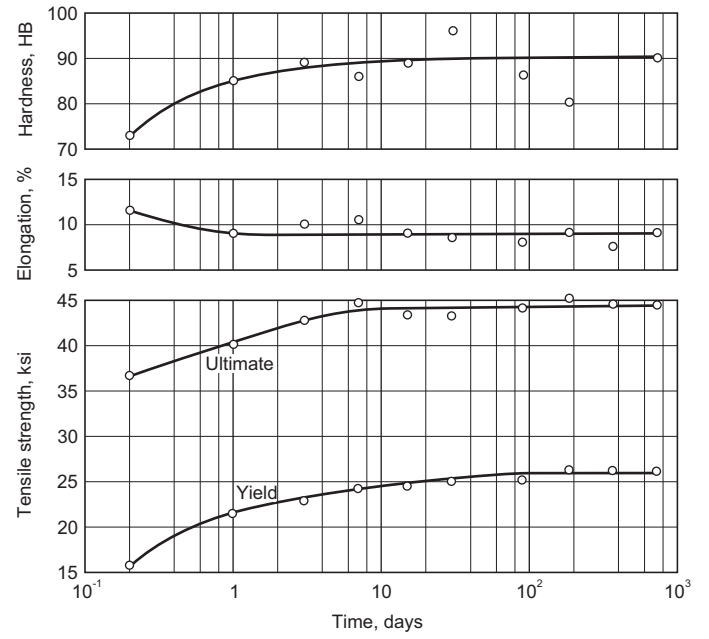


**Fig. D1.30** Room-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

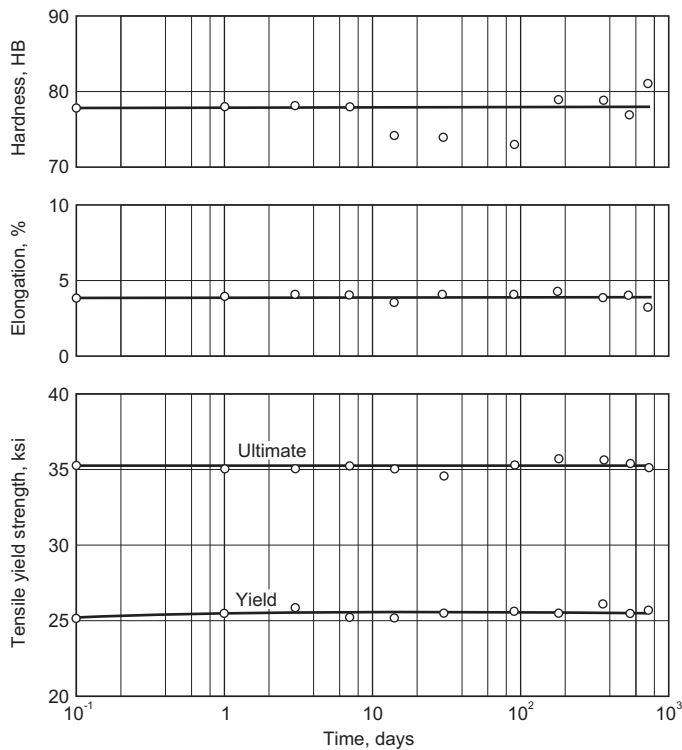


**Fig. D1.31** Room-temperature aging characteristics for aluminum alloy 355.0-T6

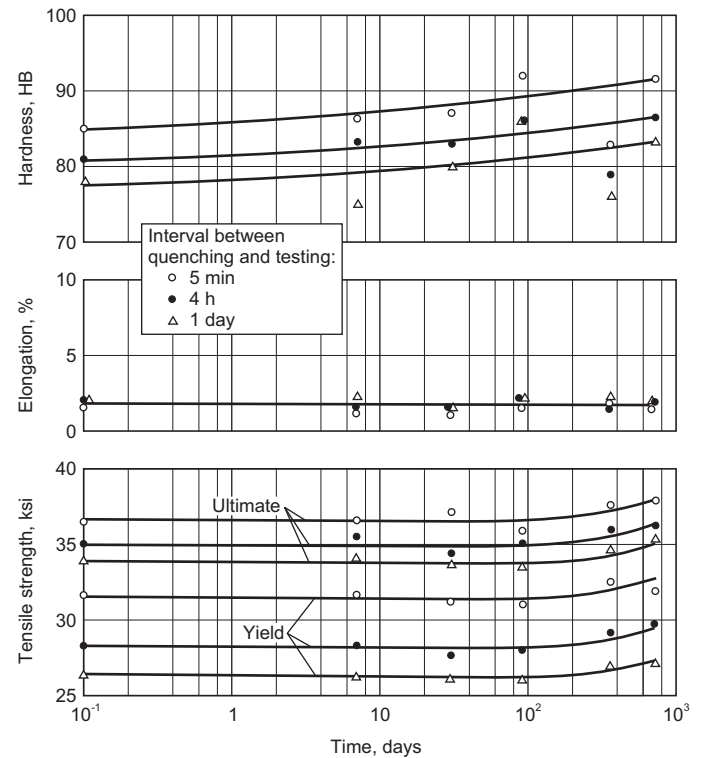


**Fig. D1.32** Room-temperature aging characteristics for aluminum alloy 355.0-T6. Effect of time interval between quenching and aging on properties

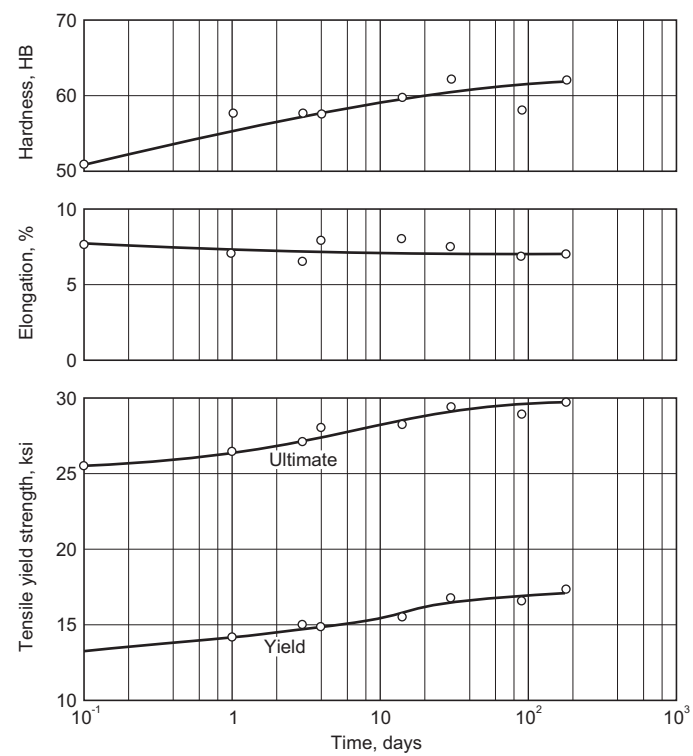


**Fig. D1.33** Room-temperature aging characteristics for aluminum alloy 356.0-T4. Shorter-term data, less than 200 days

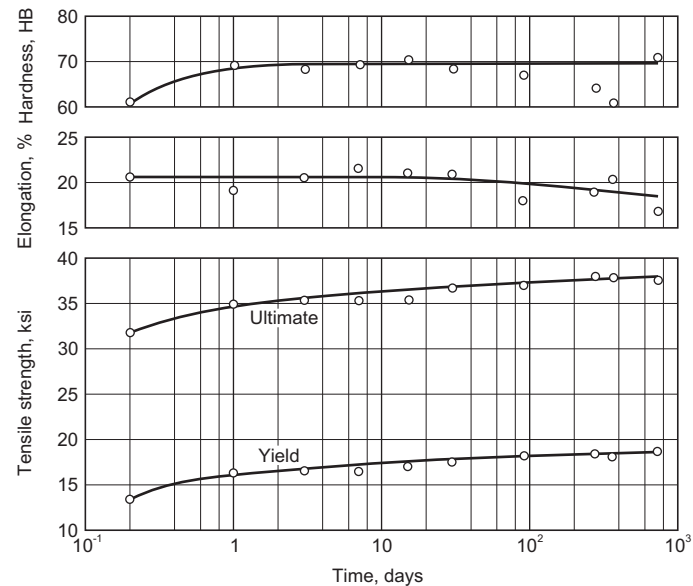


**Fig. D1.35** Room-temperature aging characteristics for aluminum alloy 356.0-T4

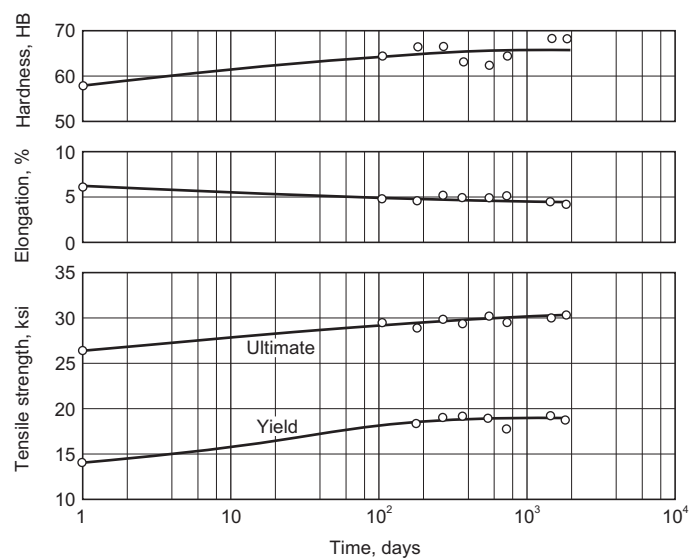


**Fig. D1.34** Room-temperature aging characteristics for aluminum alloy 356.0-T4. Longer-term data, approaching 2000 days

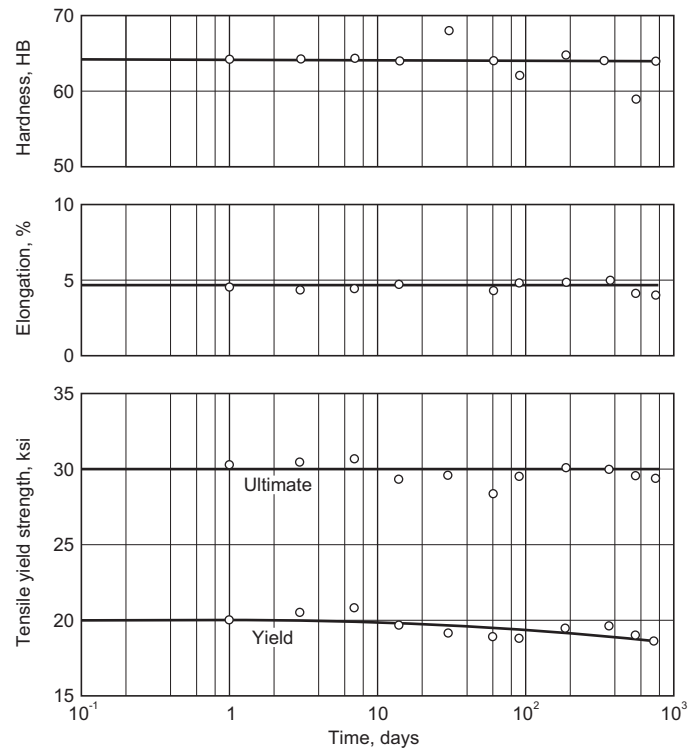


**Fig. D1.36** Room-temperature aging characteristics for aluminum alloy 356.0-T6



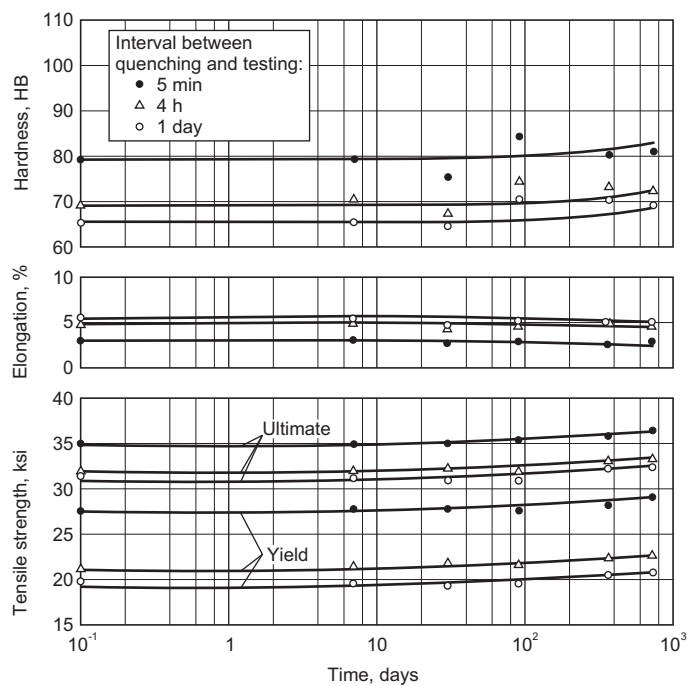


Fig. D1.37 Room-temperature aging characteristics for aluminum alloy 356.0-T6. Effect of time interval between quenching and aging

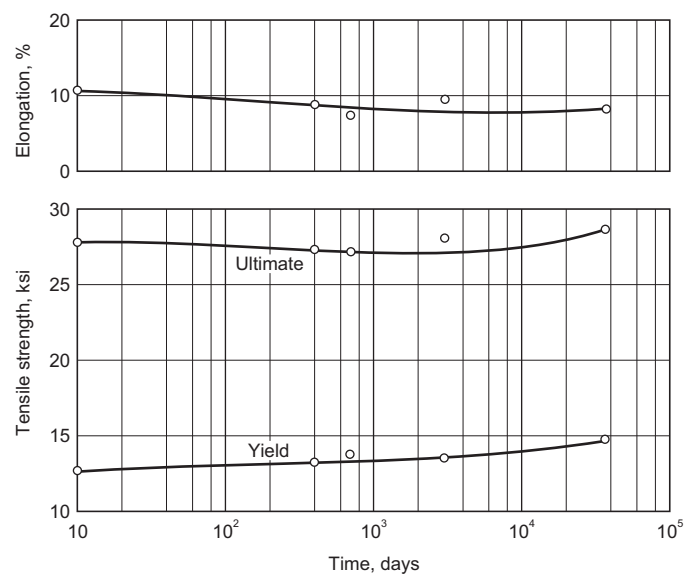


Fig. D1.38 Room-temperature aging characteristics for aluminum alloy 364.0-T4, die cast

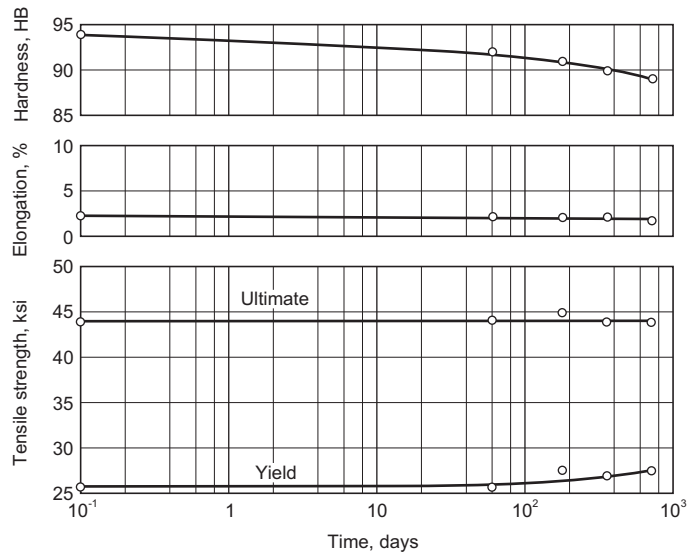


Fig. D1.39 Room-temperature aging characteristics for aluminum alloy 380.0-T5, die cast

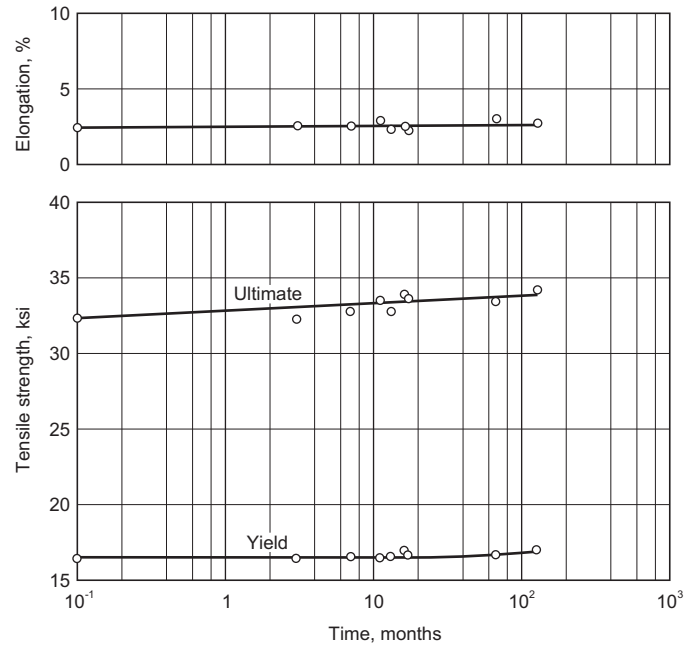


Fig. D1.40 Room-temperature aging characteristics for aluminum alloy 413.0-F, die cast

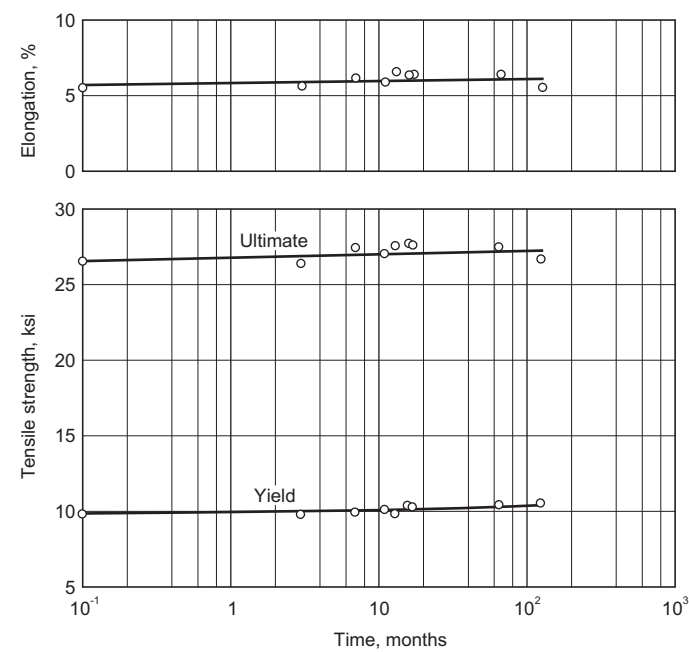


**Fig. D1.41** Room-temperature aging characteristics for aluminum alloy 443.0-F, die cast

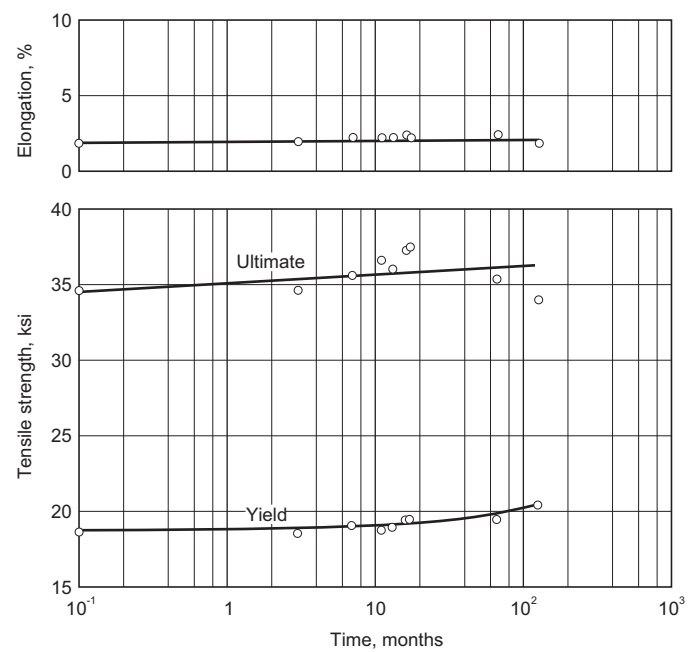


**Fig. D1.42** Room-temperature aging characteristics for aluminum alloy C433.0-F, die cast. Long-term data, up to 125 months

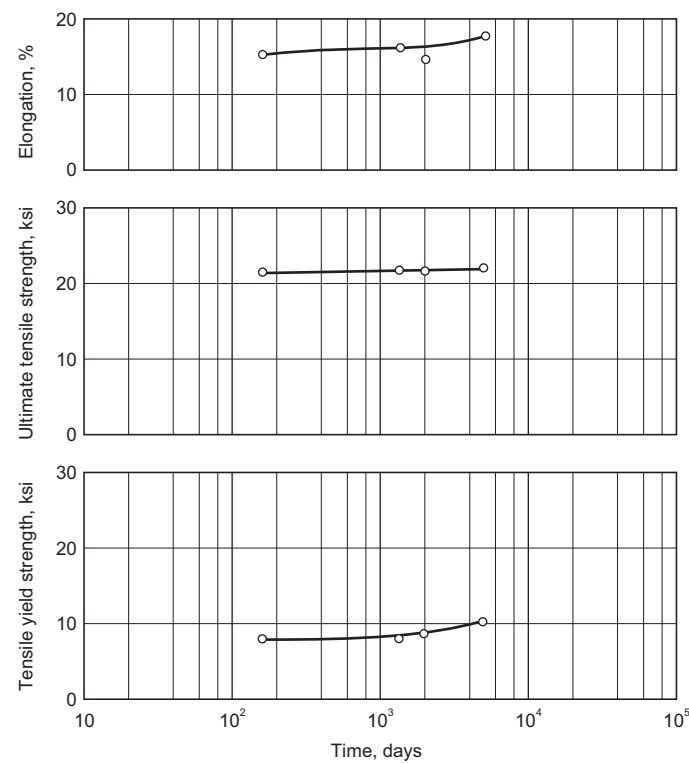


**Fig. D1.43** Room-temperature aging characteristics for aluminum alloy C433.0-F, sand cast. Long-term data, up to 5000 days

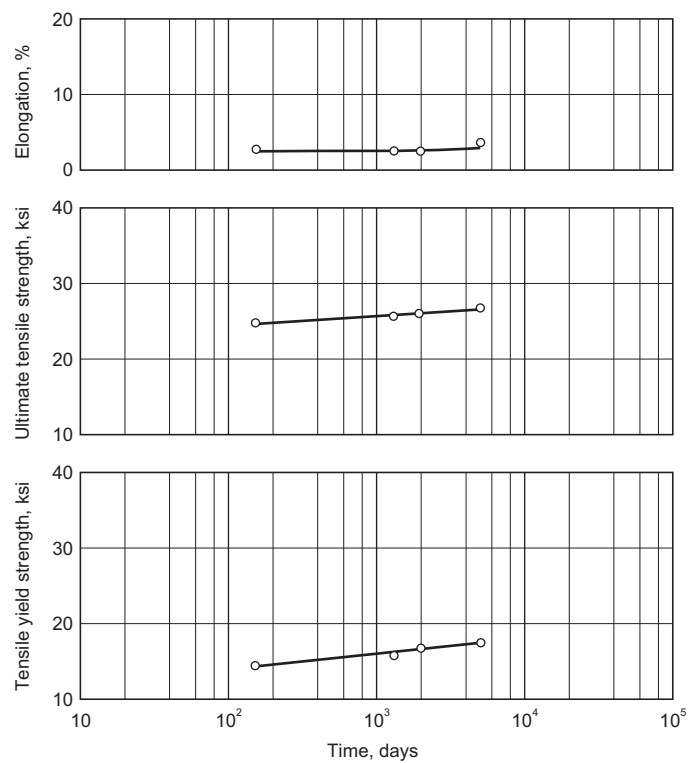


**Fig. D1.44** Room-temperature aging characteristics for aluminum alloy 512.0-F, sand cast

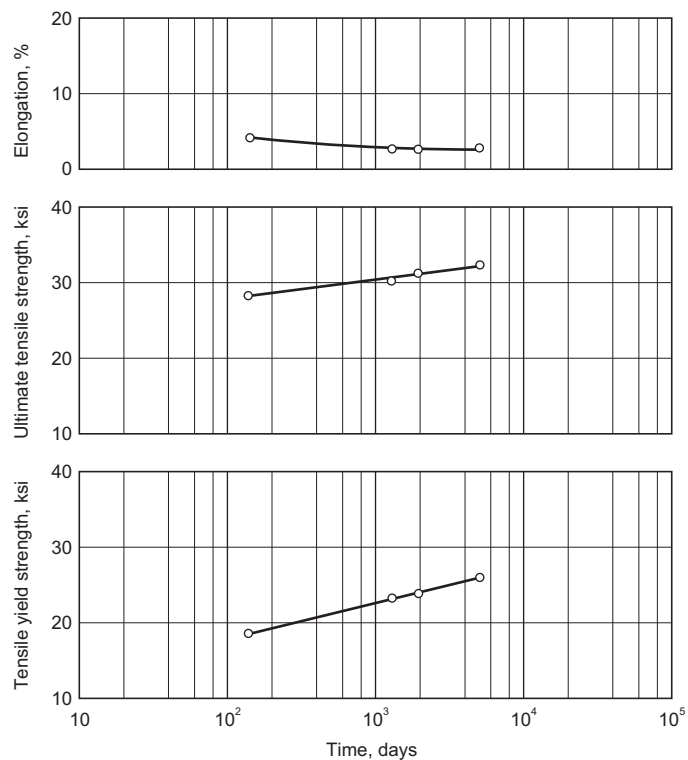


**Fig. D1.45** Room-temperature aging characteristics for aluminum alloy 513.0-F, sand cast

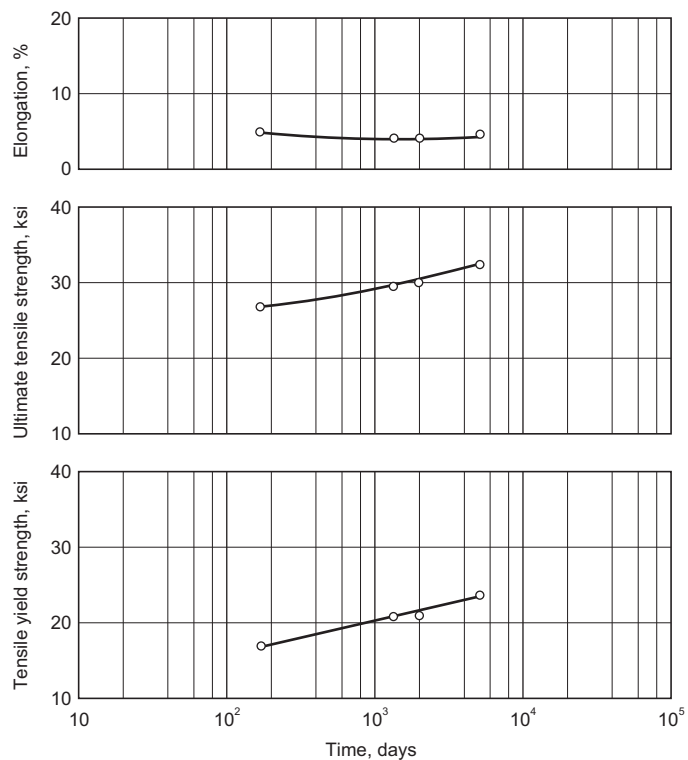


**Fig. D1.46** Room-temperature aging characteristics for aluminum alloy 513.0-F, permanent mold

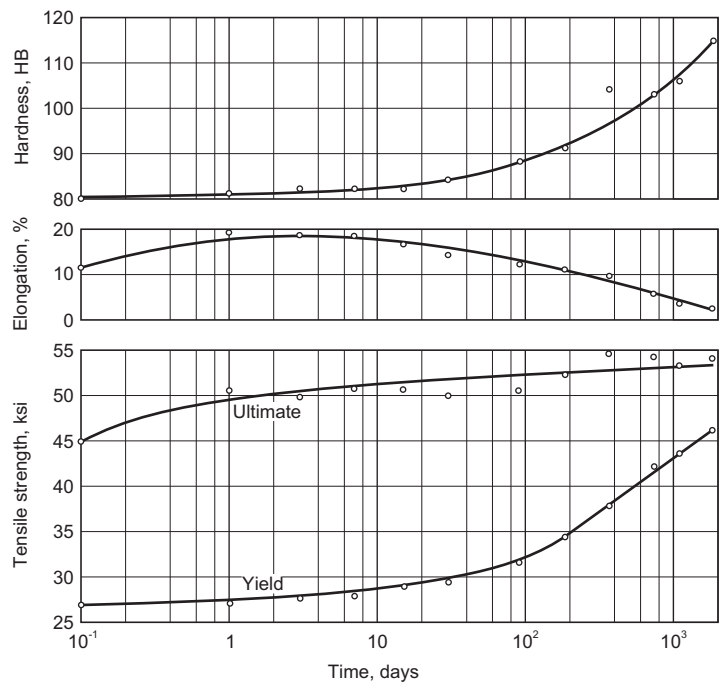


**Fig. D1.47** Room-temperature aging characteristics for aluminum alloy 520.0-T4

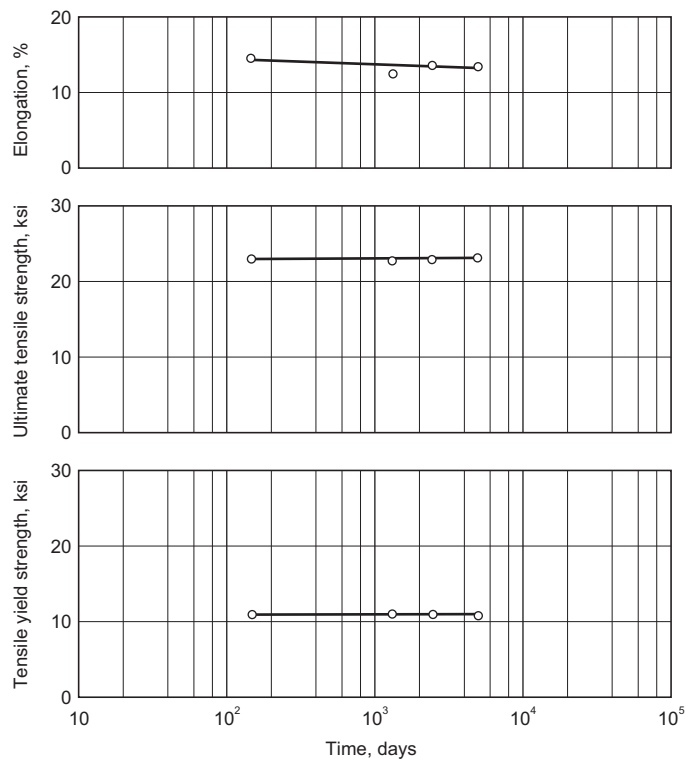


**Fig. D1.48** Room-temperature aging characteristics for aluminum alloy 850.0-T5, permanent mold

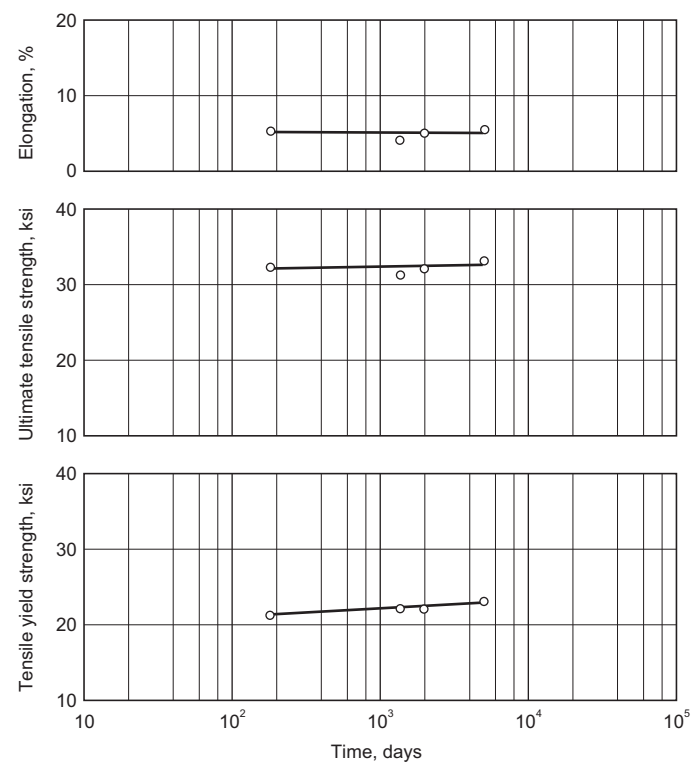


Fig. D1.49 Room-temperature aging characteristics for aluminum alloy 852.0-T5, permanent mold

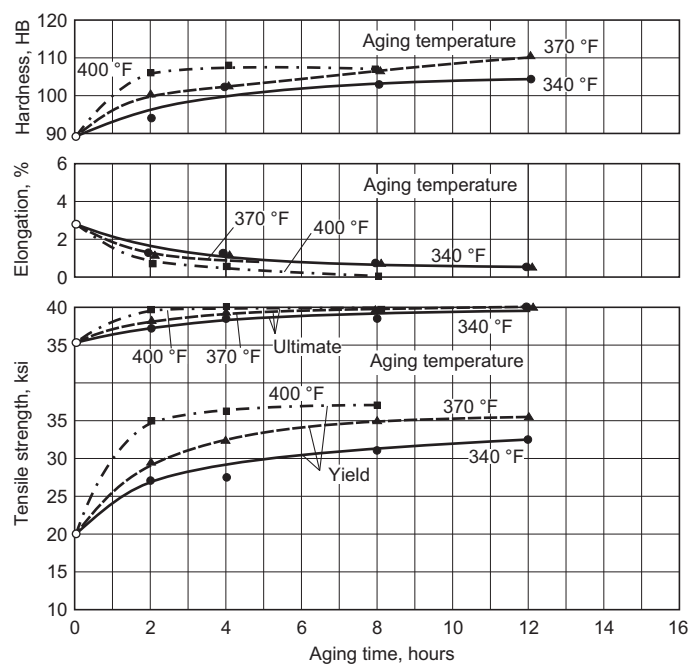


Fig. D1.50 High-temperature aging characteristics for aluminum alloy 242.0-F, permanent mold

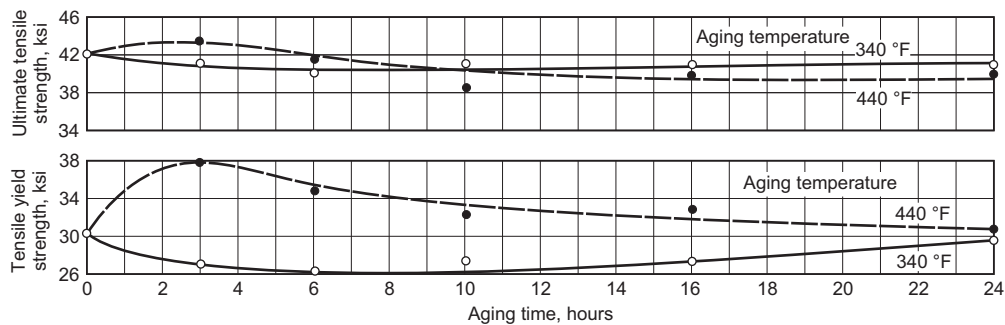


Fig. D1.51 High-temperature aging characteristics for aluminum alloy 242.0-F, permanent mold. Specimens were aged for 2 years at room temperature prior to aging at these temperatures.

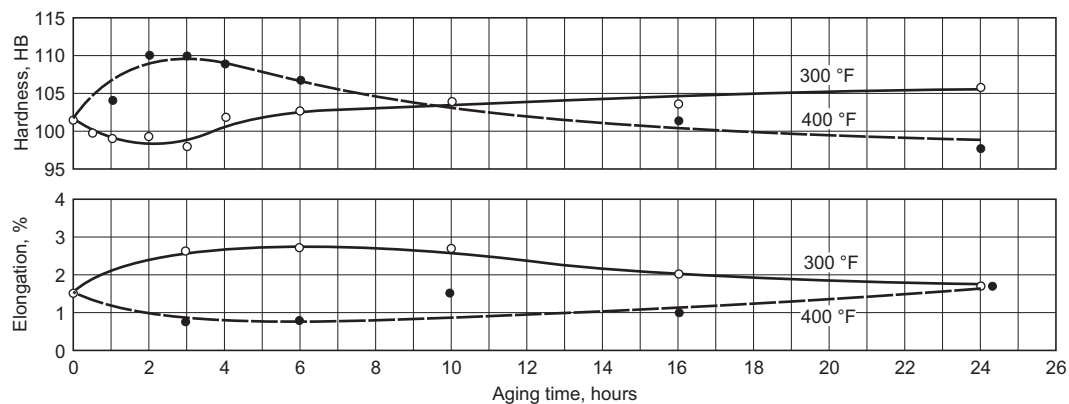


Fig. D1.52 High-temperature aging characteristics for aluminum alloy 242.0-F, permanent mold

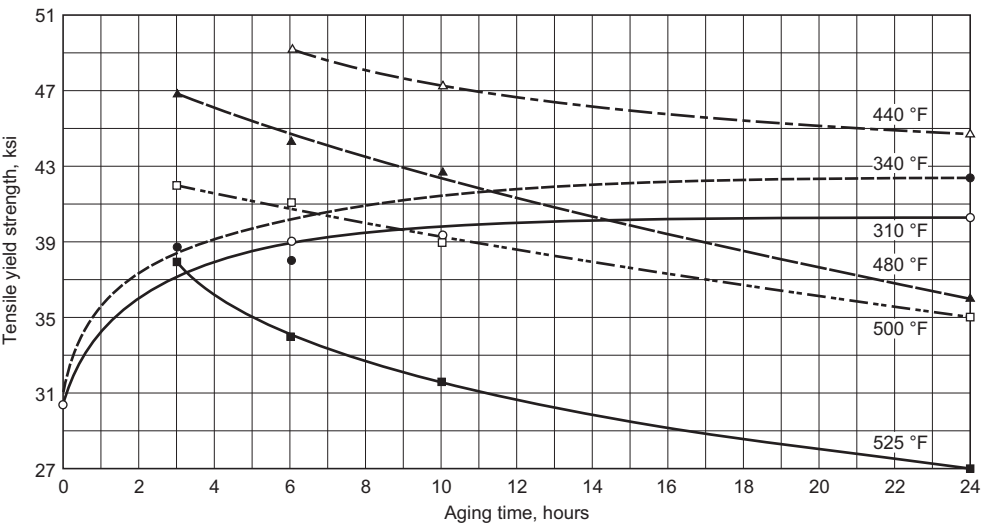


**Fig. D1.53** High-temperature aging characteristics for aluminum alloy 242.0-T4, permanent mold. Solution heat treatment: 6 h at 960 °F, quenched in 110 °F water

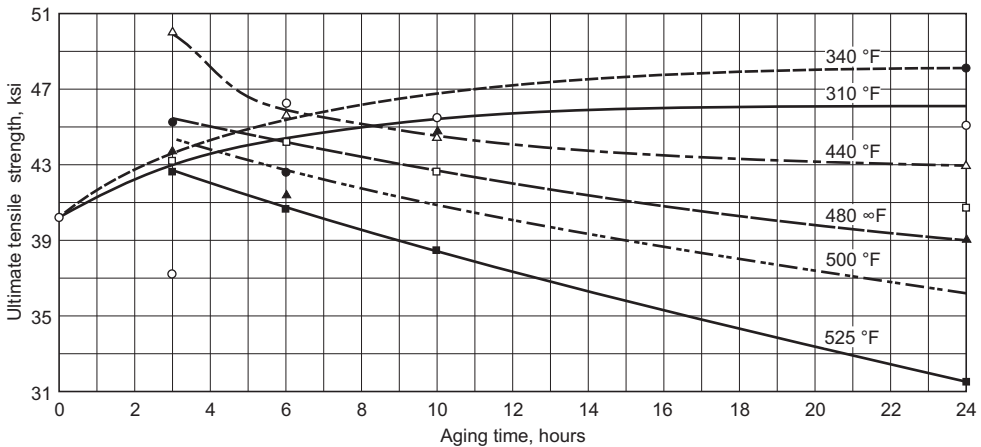


**Fig. D1.54** High-temperature aging characteristics for aluminum alloy 242.0-T4, permanent mold. Solution heat treatment: 6 h at 960 °F, quenched in 110 °F water



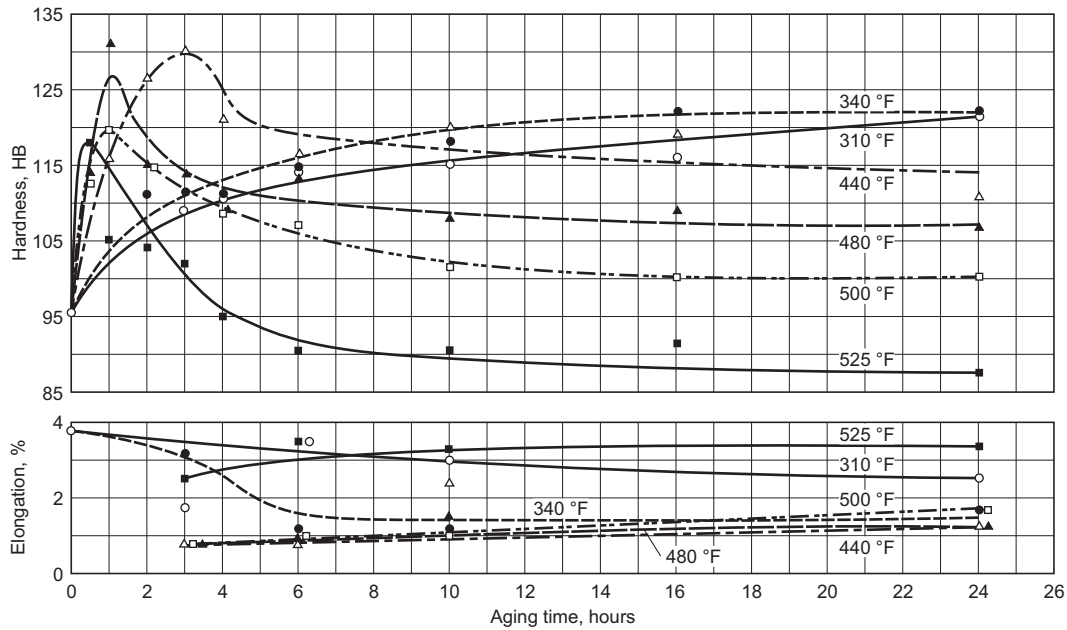


**Fig. D1.55** High-temperature aging characteristics for aluminum alloy 242.0-T4, permanent mold. Solution heat treatment: 6 h at 960 °F, quenched in 110 °F water

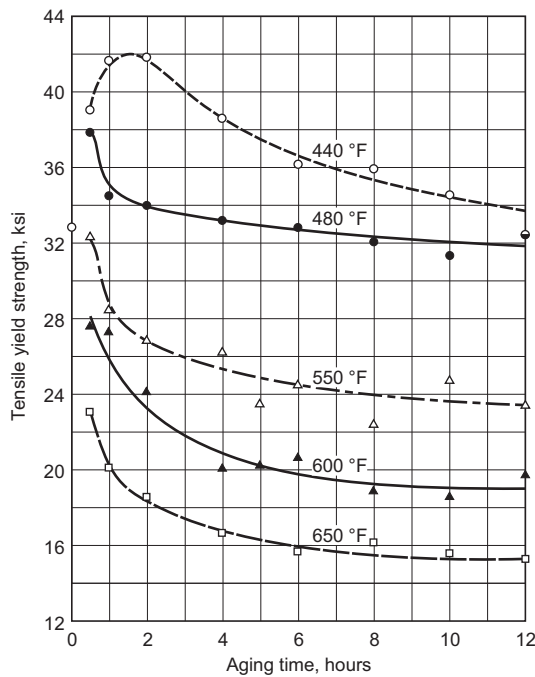


**Fig. D1.56** High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Cooled in still air

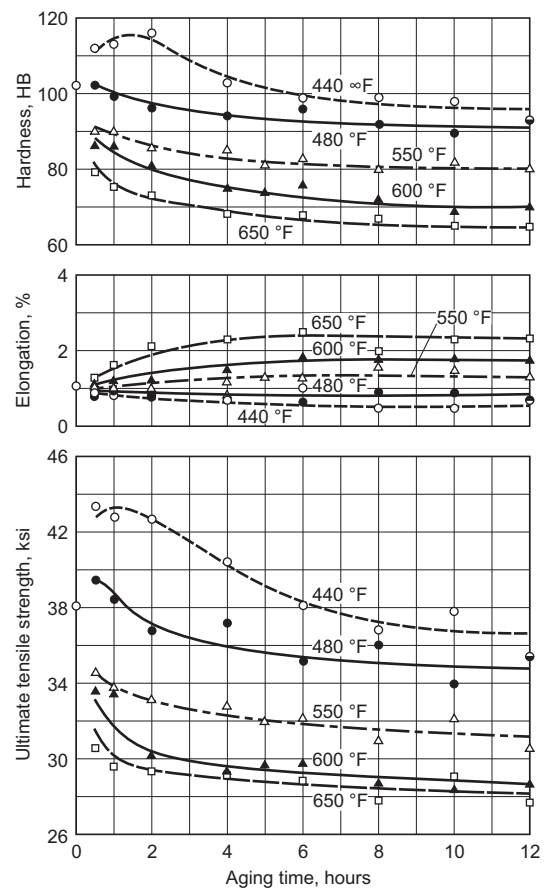


**Fig. D1.57** High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Cooled in still air

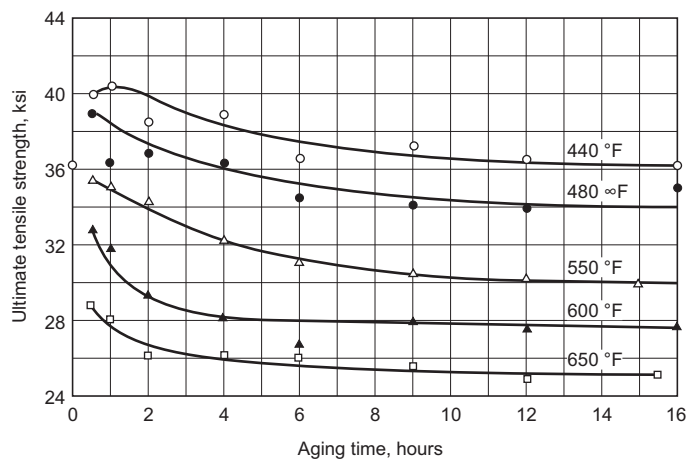


**Fig. D1.58** High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Air blast quench

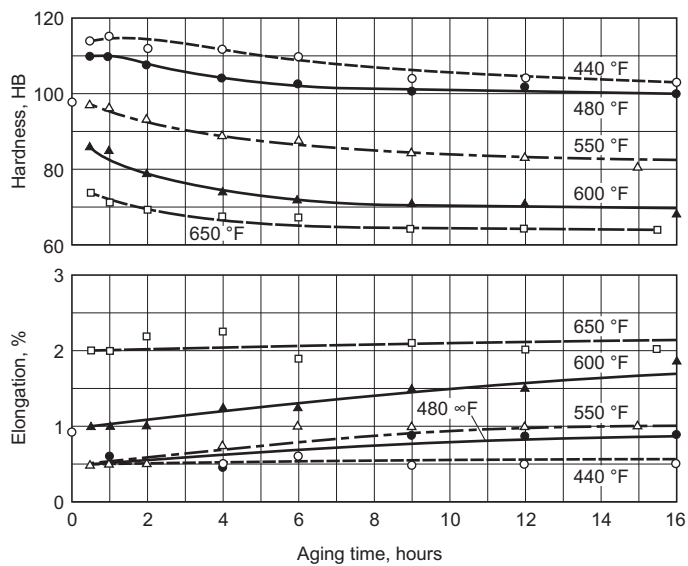


**Fig. D1.59** High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Air blast quench

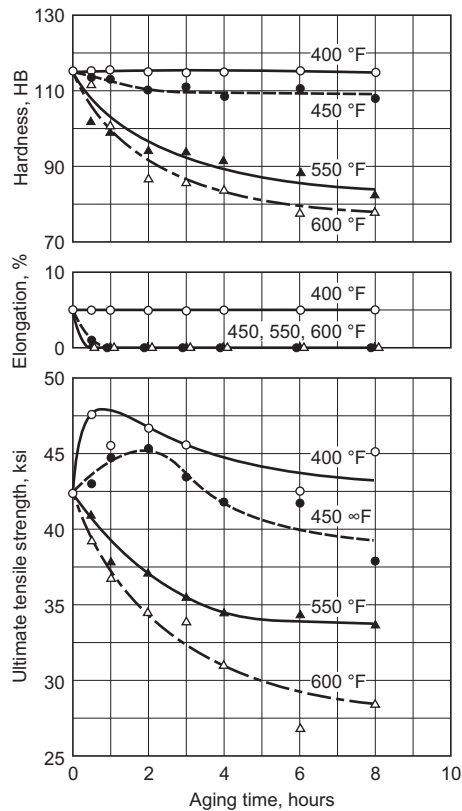


**Fig. D1.60** High-temperature aging characteristics for aluminum alloy 242.0-T4, sand cast. Quenched in boiling water

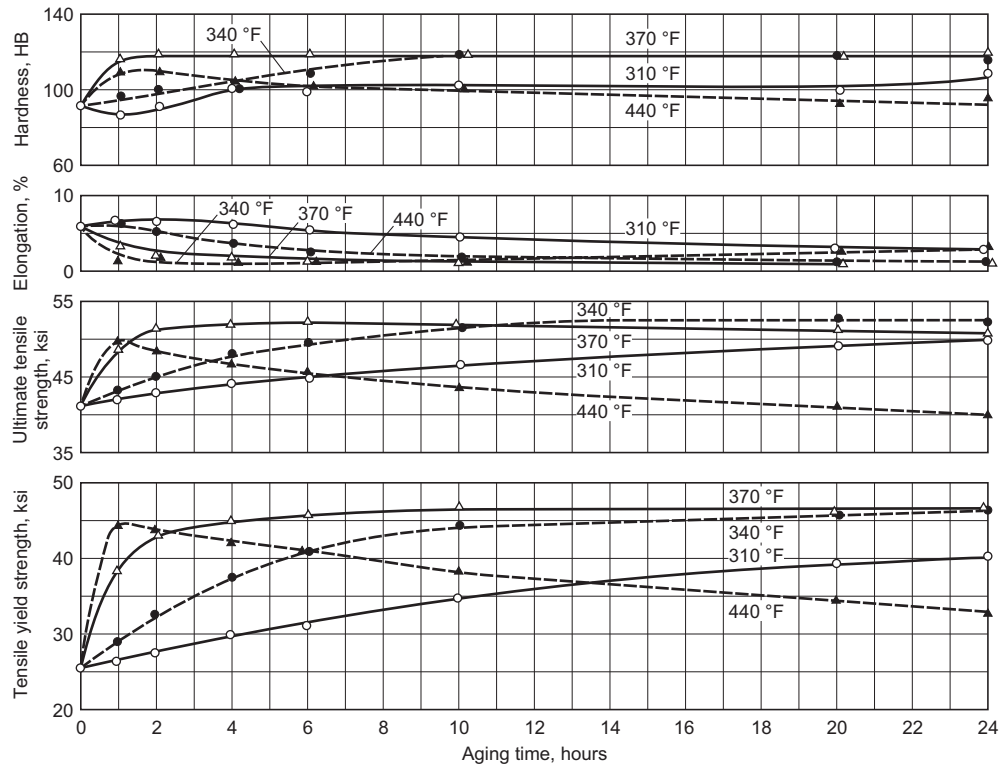


**Fig. D1.61** High-temperature aging characteristics for aluminum alloy C355.0-T4, sand cast. Solution heat treated 15 h at 980 °F, quenched in water at 150 °F. 24 h interval at room temperature. Heat-up times to the aging temperatures varied from 1 h 5 min to 1 h 45 min.

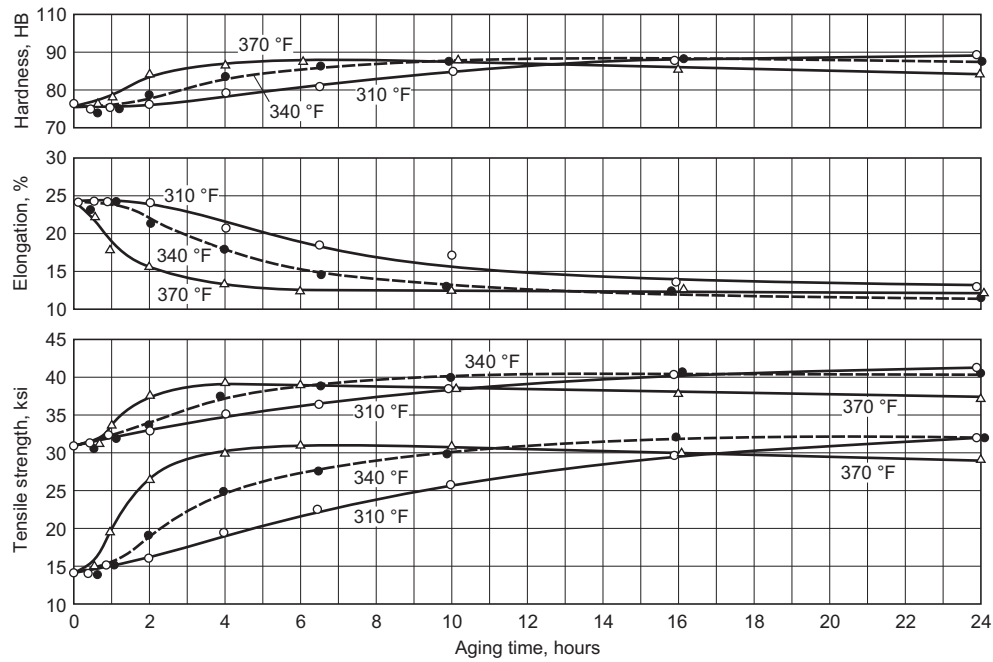


**Fig. D1.62** High-temperature aging characteristics for aluminum alloy A356.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in boiling water. 24 h interval at room temperature

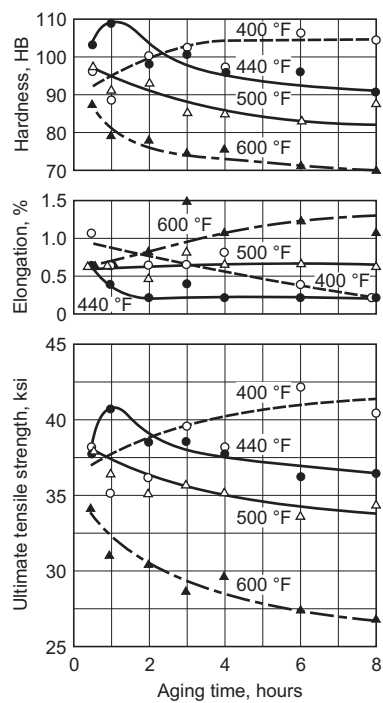


Fig. D1.63 High-temperature aging characteristics for aluminum alloy A242.0-T4, sand cast. Quenched in boiling water

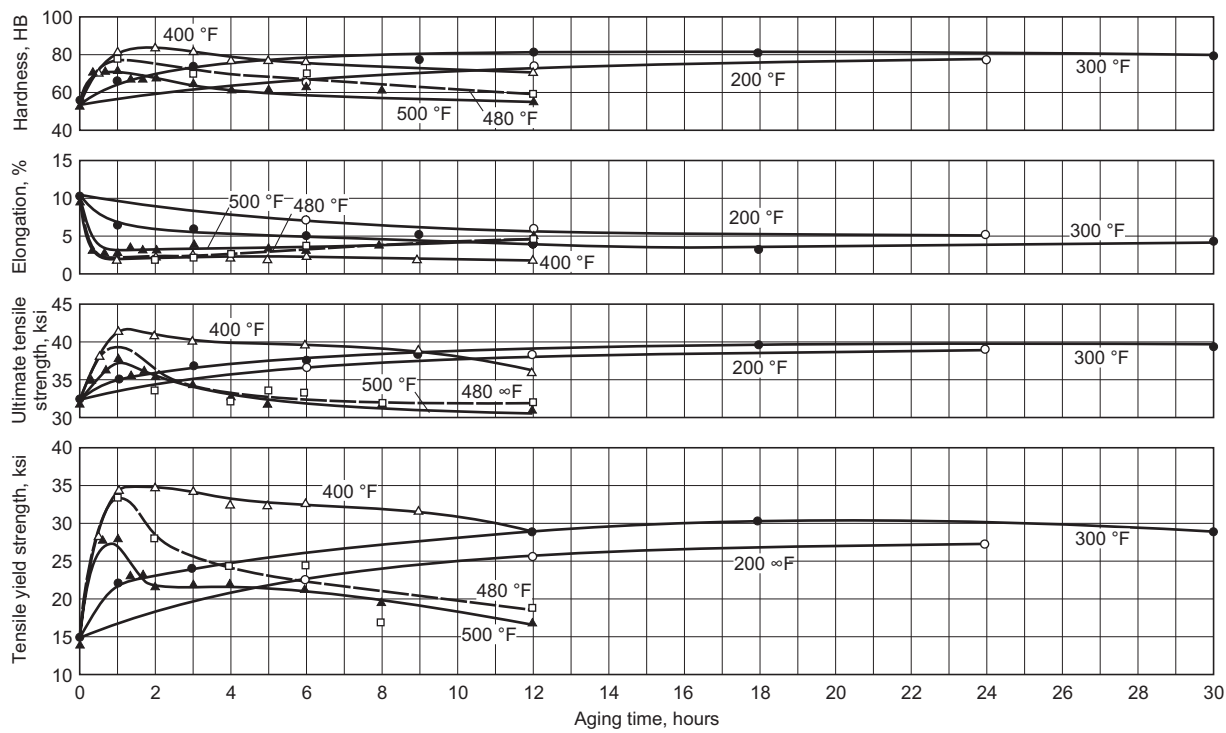


Fig. D1.64 High-temperature aging characteristics for aluminum alloy 295.0-T4, sand cast

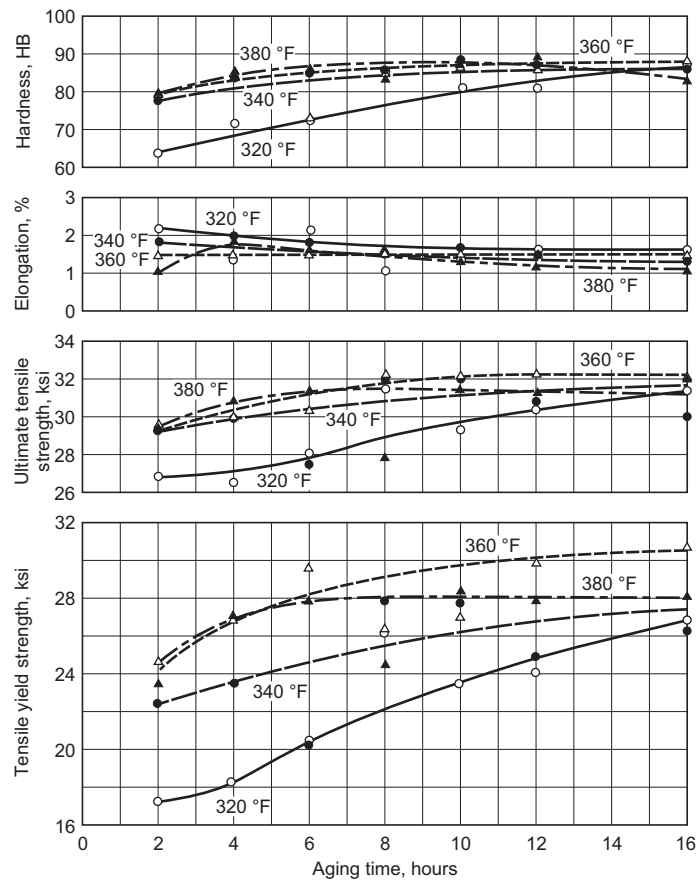


Fig. D1.65 High-temperature aging characteristics for aluminum alloy 319.0-F, sand cast

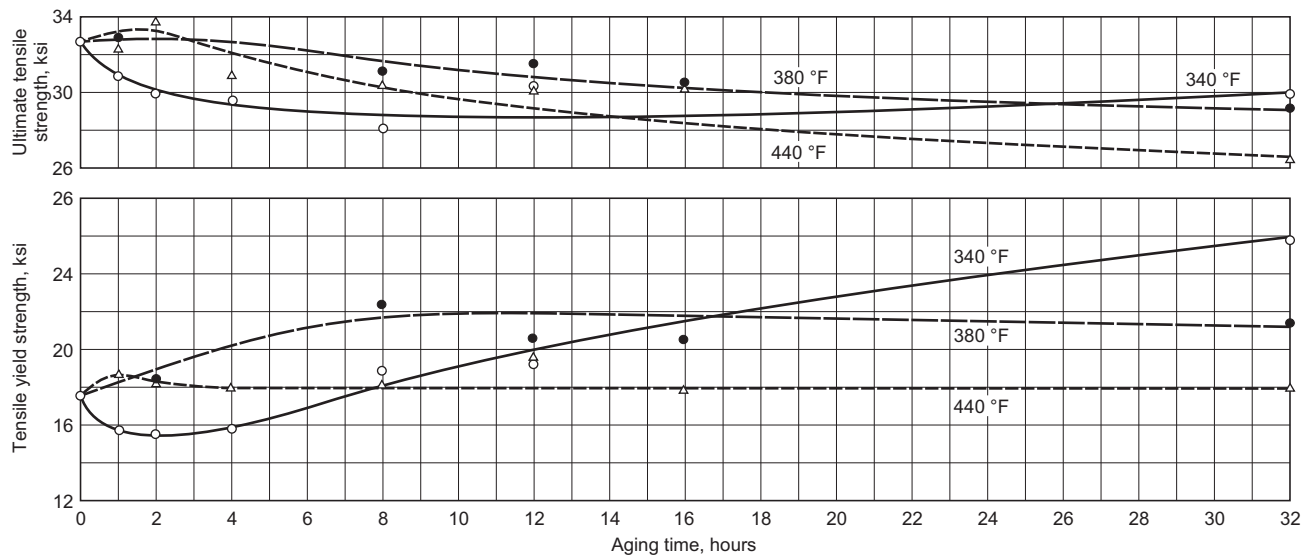


Fig. D1.66 High-temperature aging characteristics for aluminum alloy 319.0-F, permanent mold

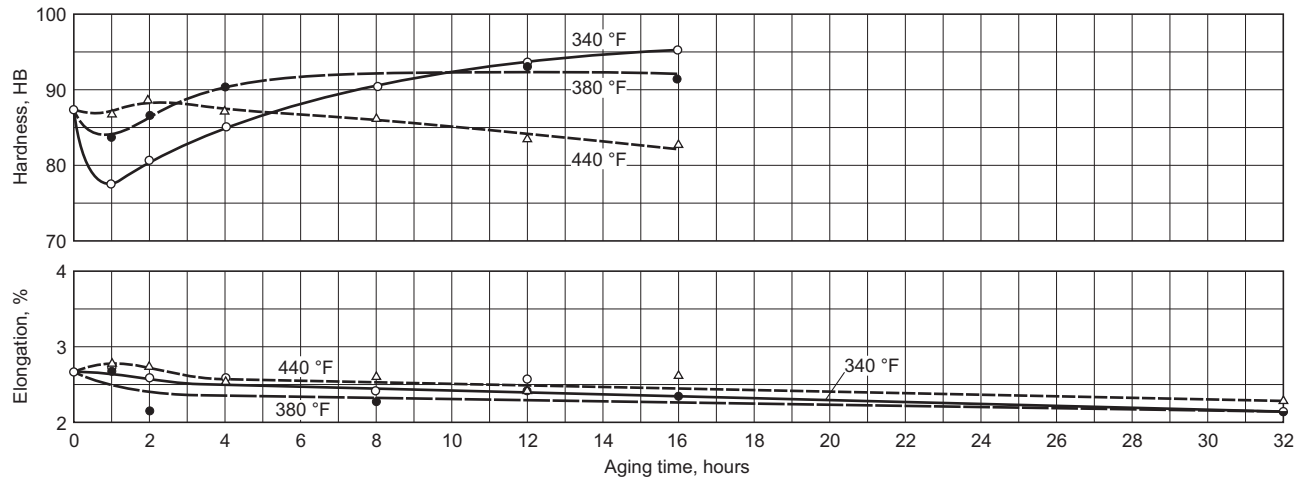


**Fig. D1.67** High-temperature aging characteristics for aluminum alloy 319.0-F, permanent mold

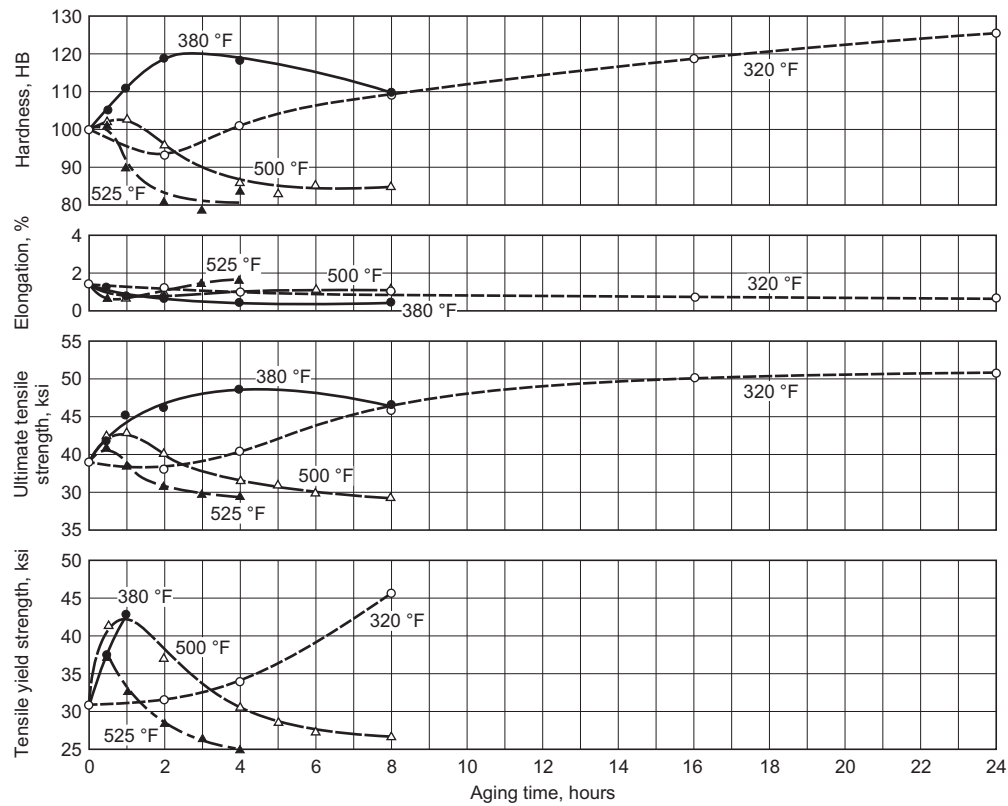


**Fig. D1.68** High-temperature aging characteristics for aluminum alloy 319.0-F, sand cast. Aged 10 days at room temperature. Solution heat treated 12 h at 940 °F, quenched in boiling water



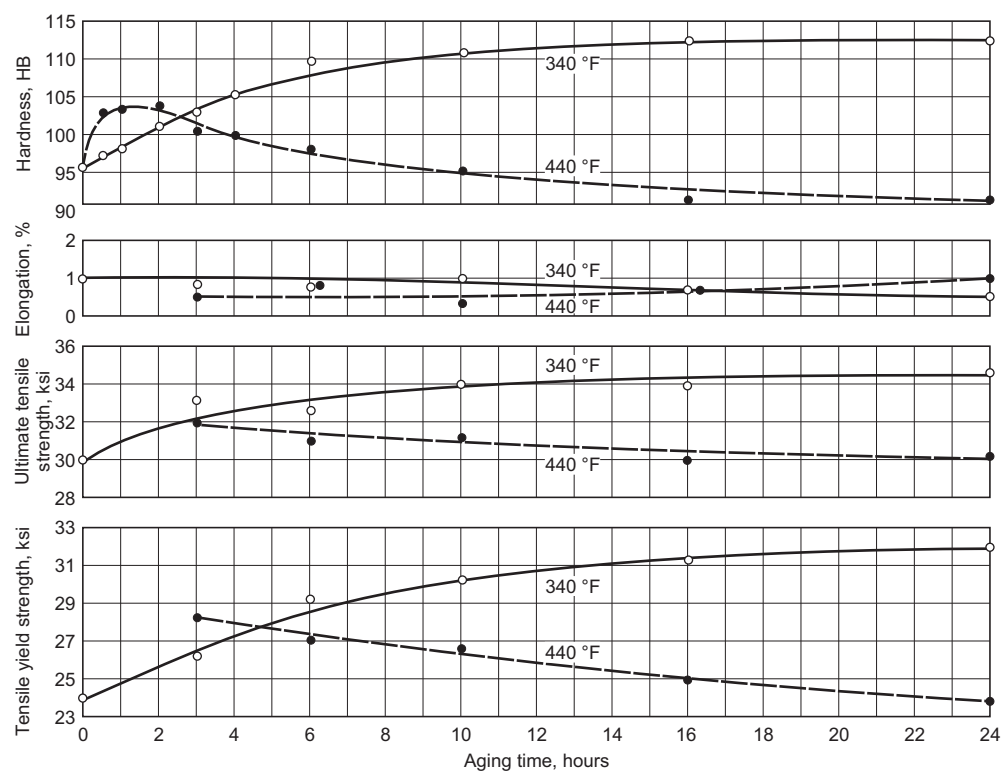


Fig. D1.69 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

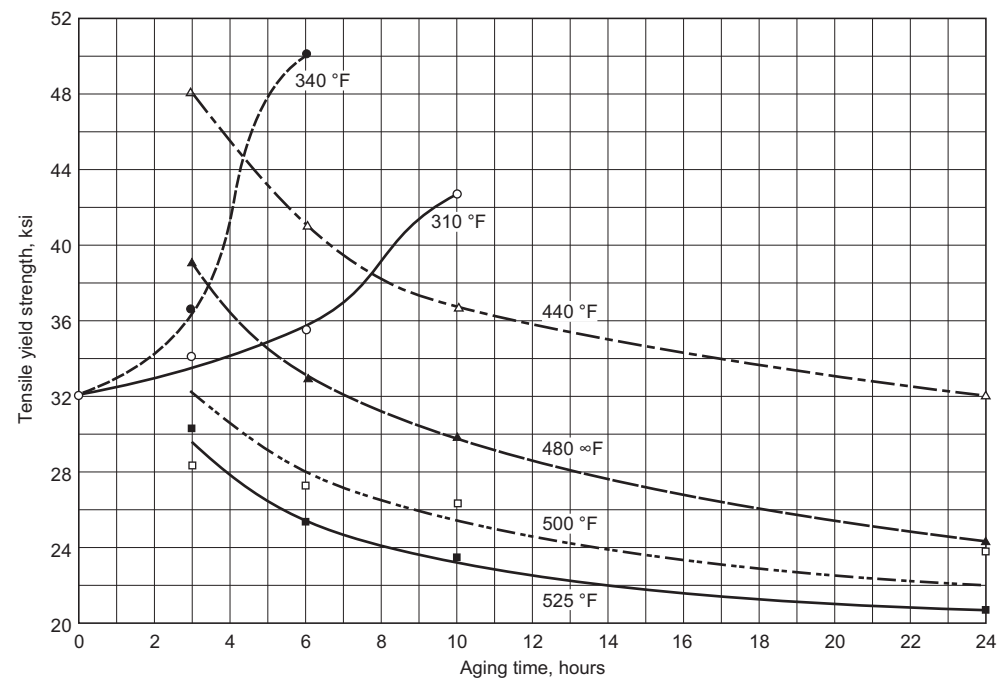


Fig. D1.70 High-temperature aging characteristics for aluminum alloy 333.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

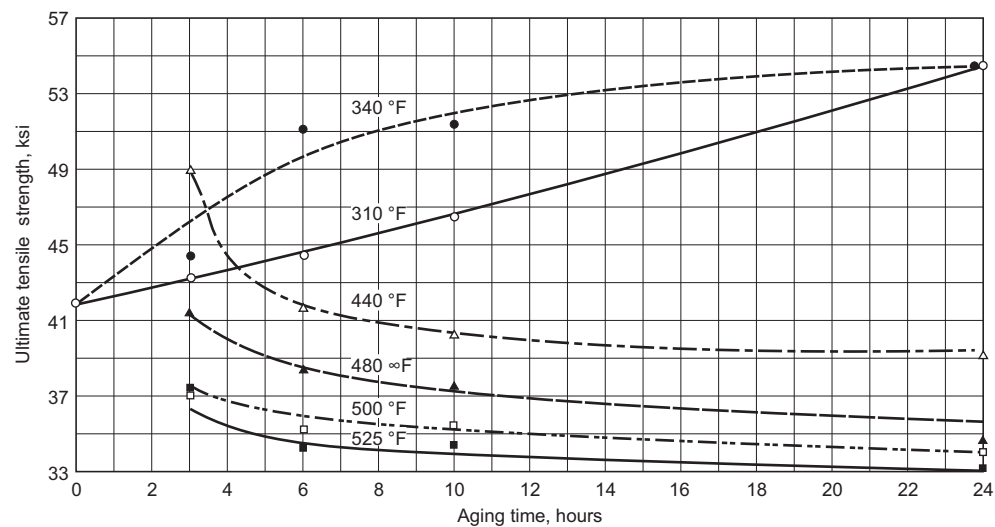


**Fig. D1.71** High-temperature aging characteristics for aluminum alloy 333.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

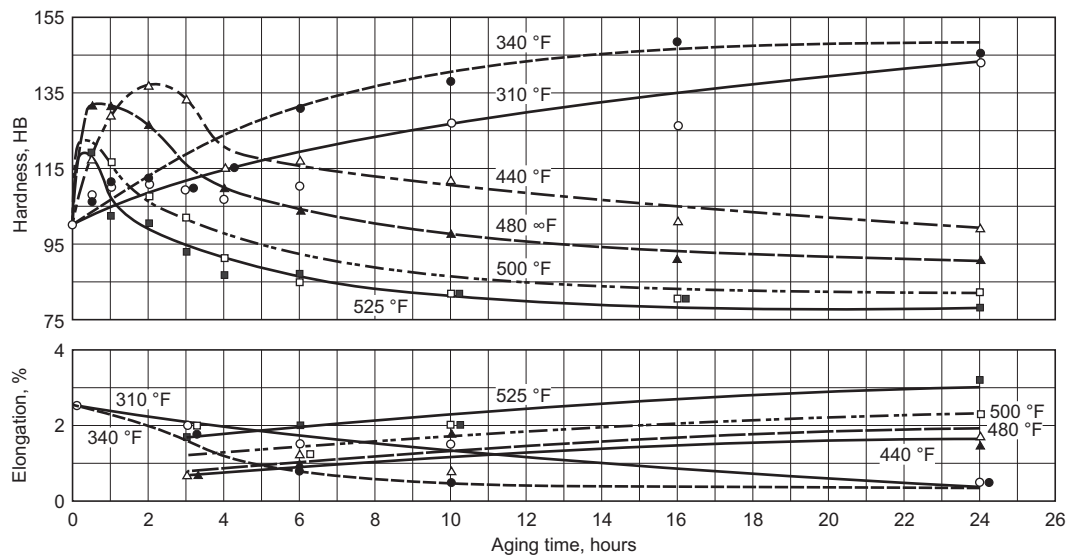


**Fig. D1.72** High-temperature aging characteristics for aluminum alloy 333.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

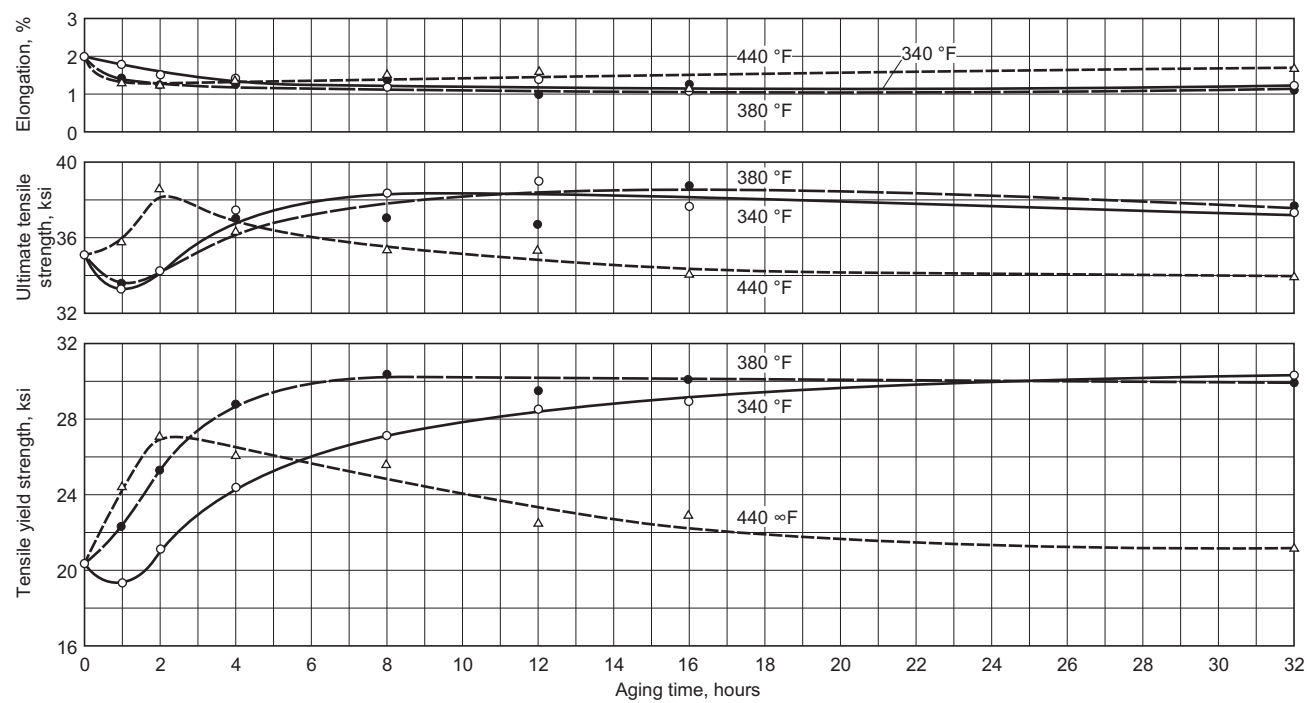


Fig. D1.73 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

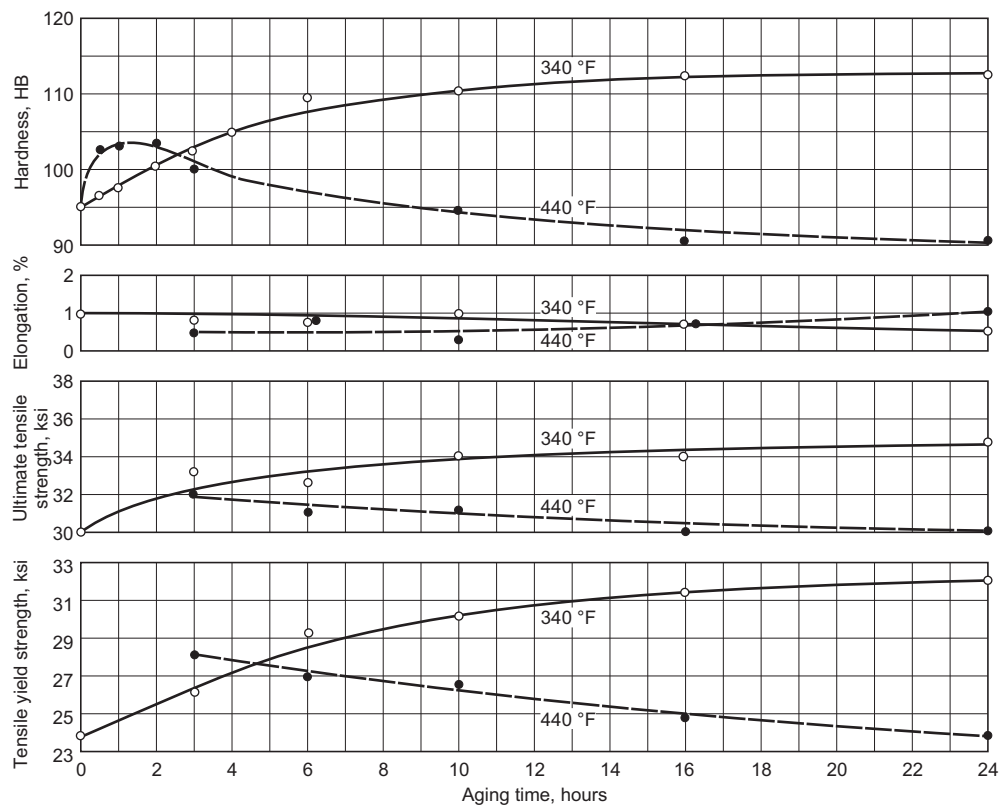


Fig. D1.74 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

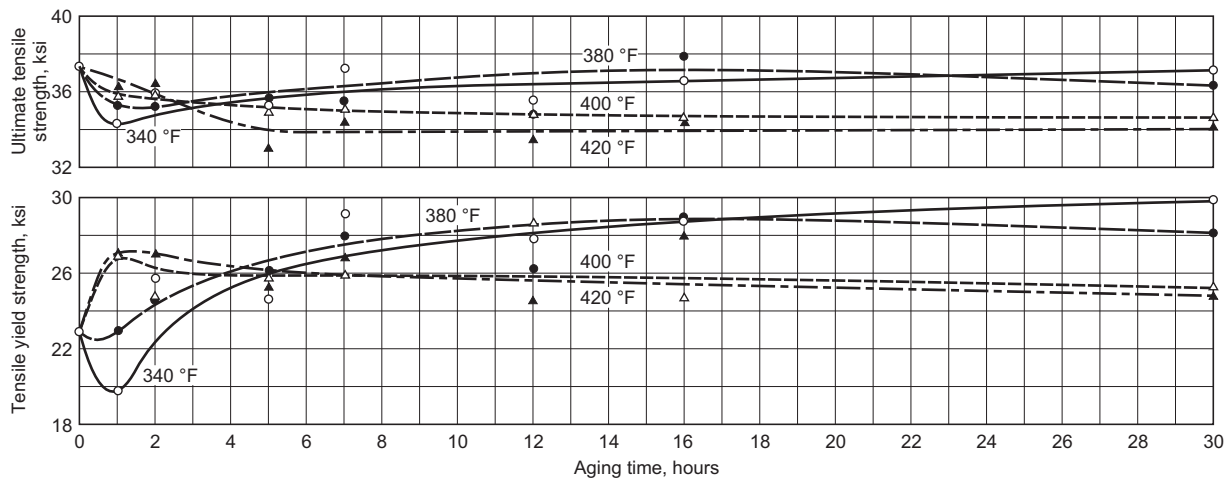


Fig. D1.75 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

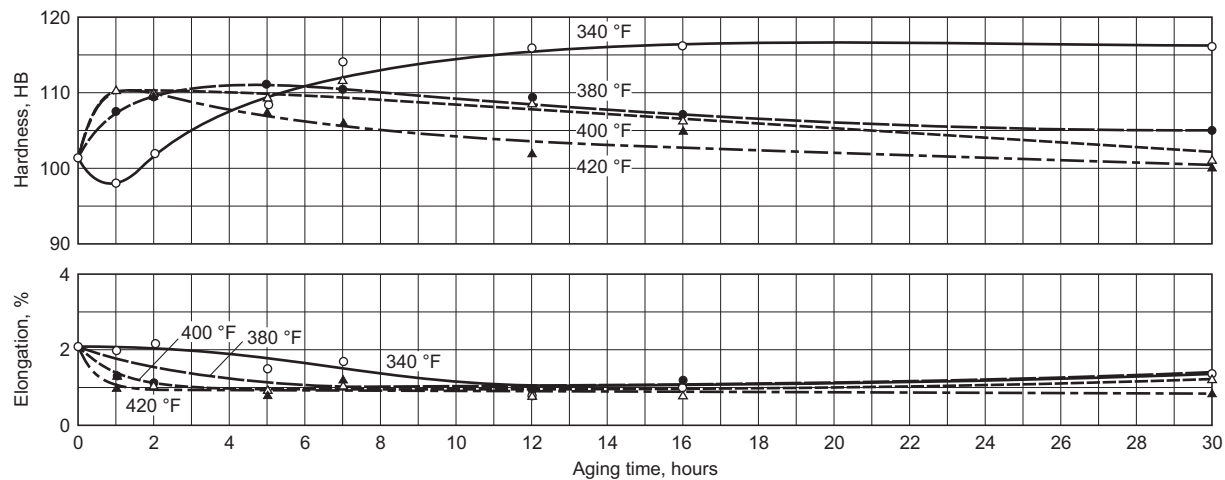


Fig. D1.76 High-temperature aging characteristics for aluminum alloy 333.0-F, permanent mold

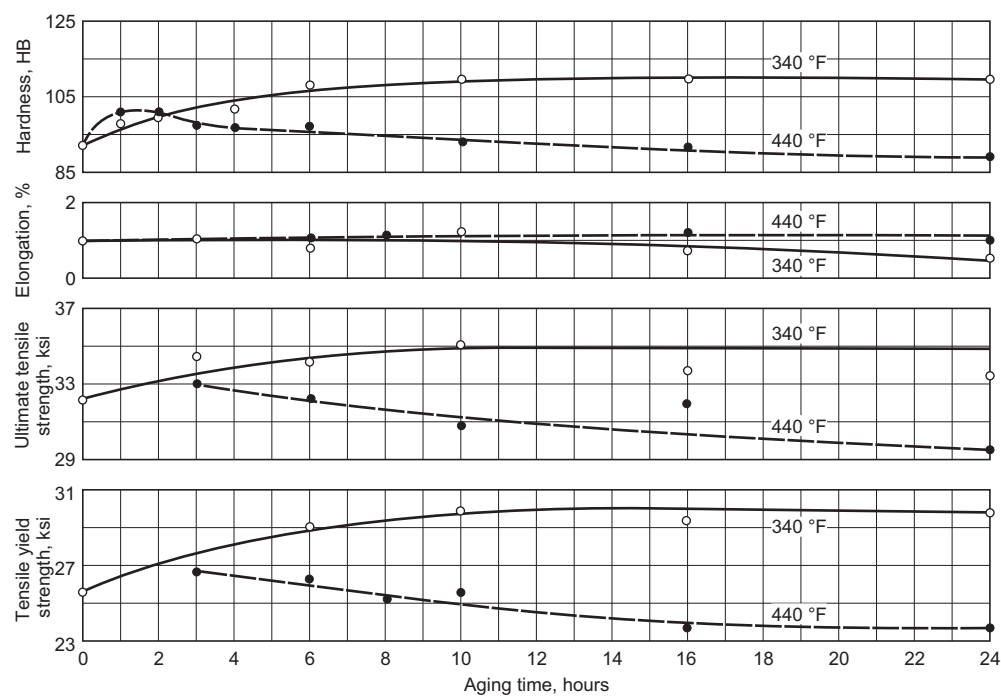


Fig. D1.77 High-temperature aging characteristics for aluminum alloy 336.0-F, permanent mold

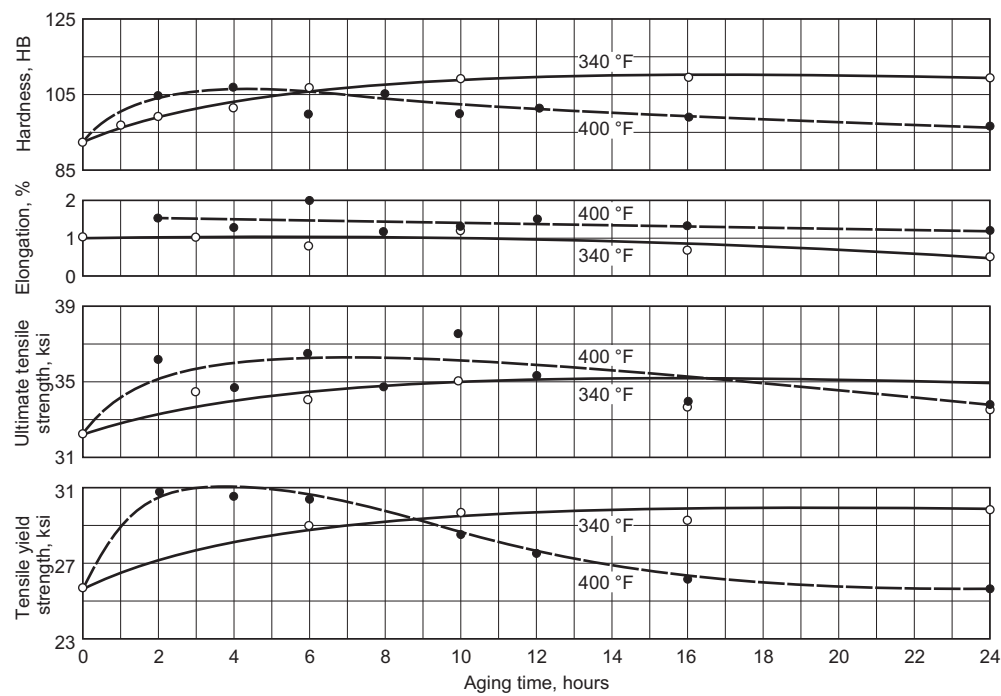


Fig. D1.78 High-temperature aging characteristics for aluminum alloy 336.0-F, permanent mold

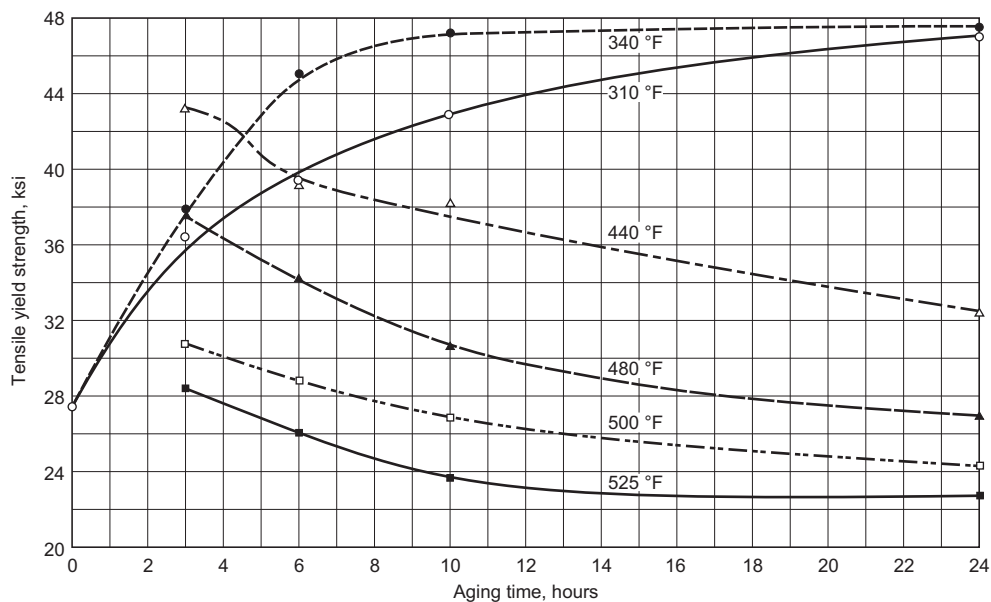


**Fig. D1.79** High-temperature aging characteristics for aluminum alloy 336.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

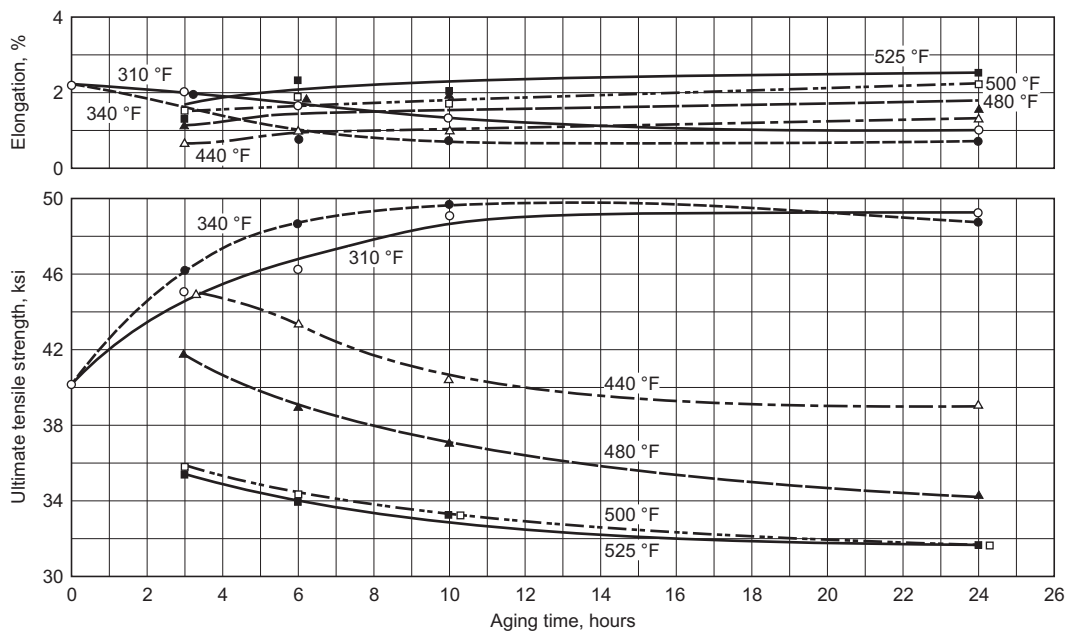


**Fig. D1.80** High-temperature aging characteristics for aluminum alloy 336.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F



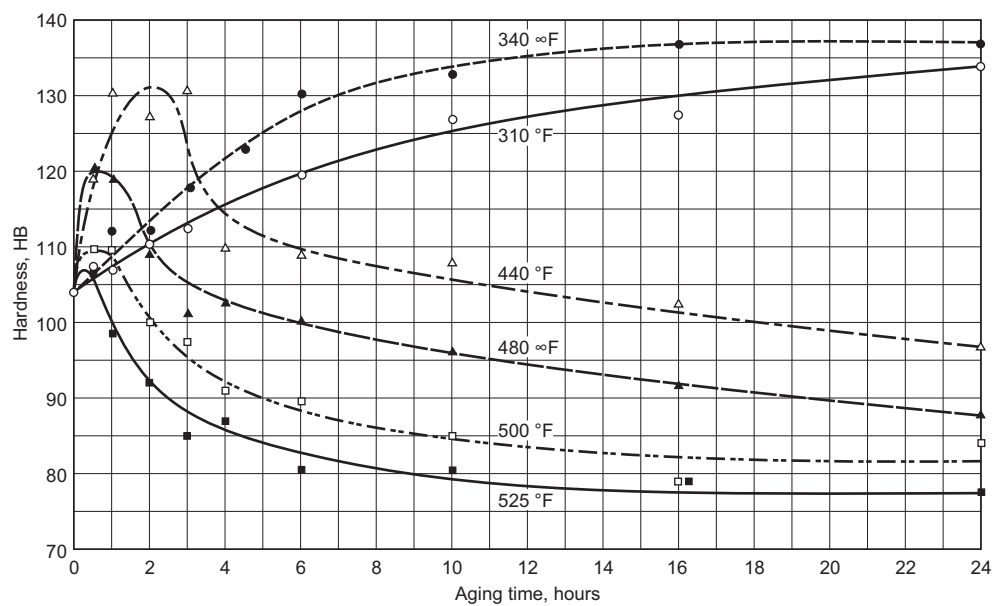


**Fig. D1.81** High-temperature aging characteristics for aluminum alloy 336.0-T4, permanent mold. Solution heat treated 6 h at 960 °F, quenched in water at 110 °F

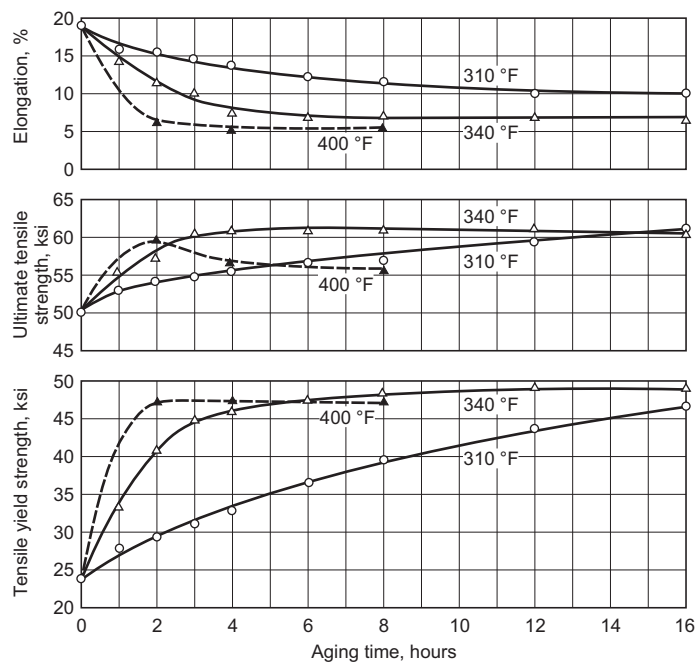


**Fig. D1.82** High-temperature aging characteristics for aluminum alloy 354.0-T4, permanent mold. Solution heat treated 8 h at 980 °F, quenched in room temperature water. Held 4 h at room temperature

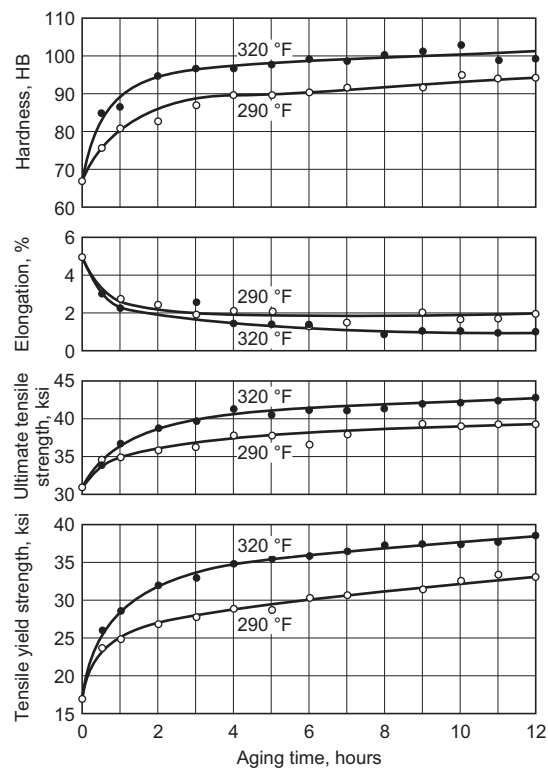


**Fig. D1.83** High-temperature aging characteristics for aluminum alloy 355.0-T4, sand cast

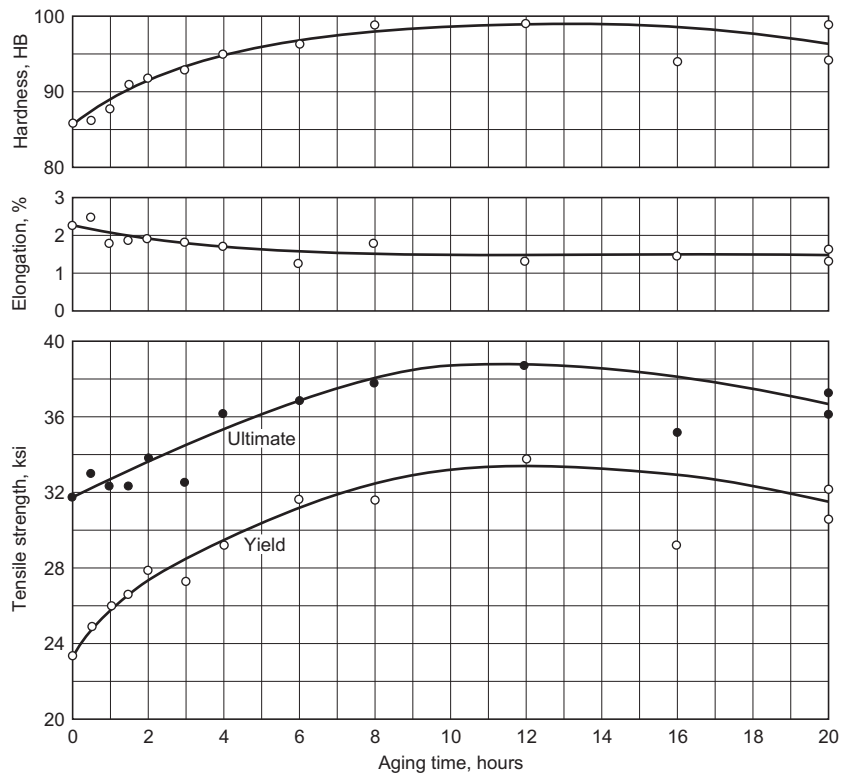


Fig. D1.84 High-temperature aging characteristics for aluminum alloy 355.0-T4, sand cast. Aging at 275 °F with boiling water quench

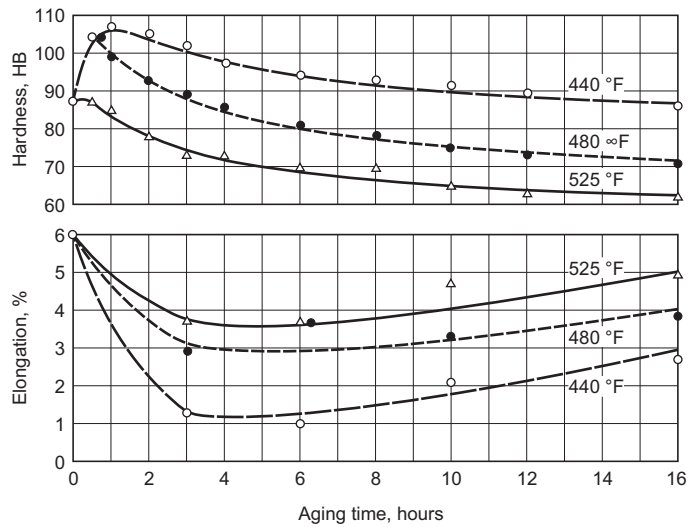


Fig. D1.85 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

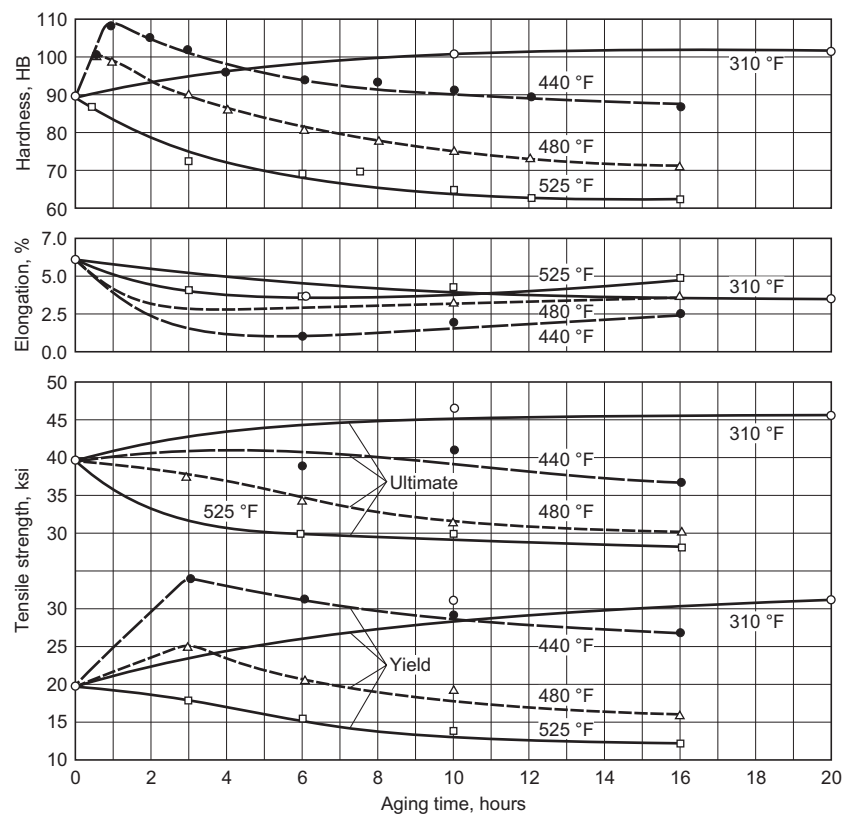


Fig. D1.86 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

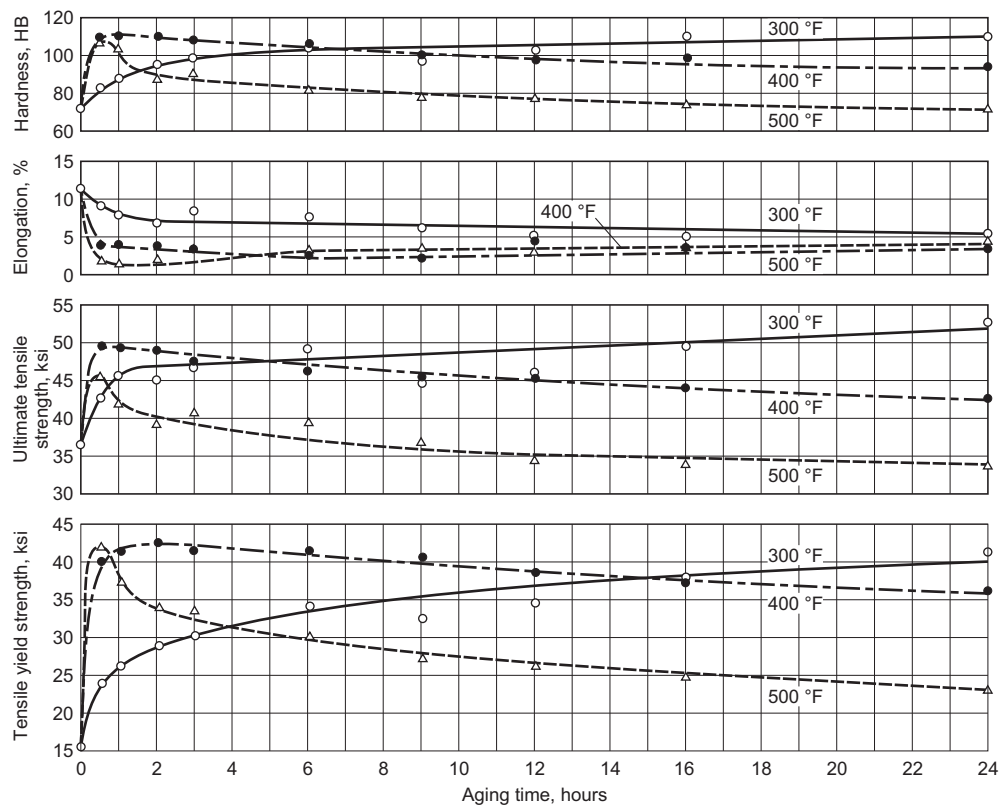


Fig. D1.87 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

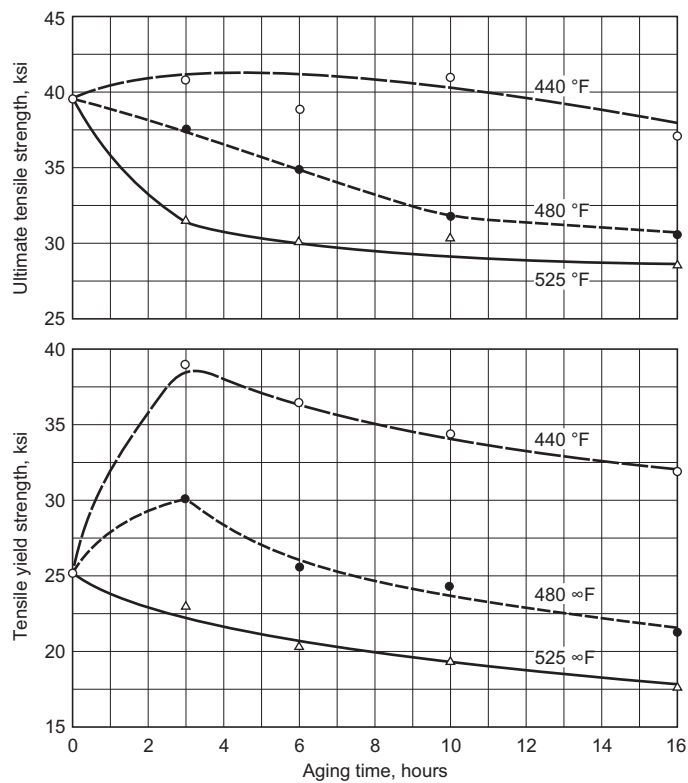


Fig. D1.88 High-temperature aging characteristics for aluminum alloy 355.0-T4, permanent mold

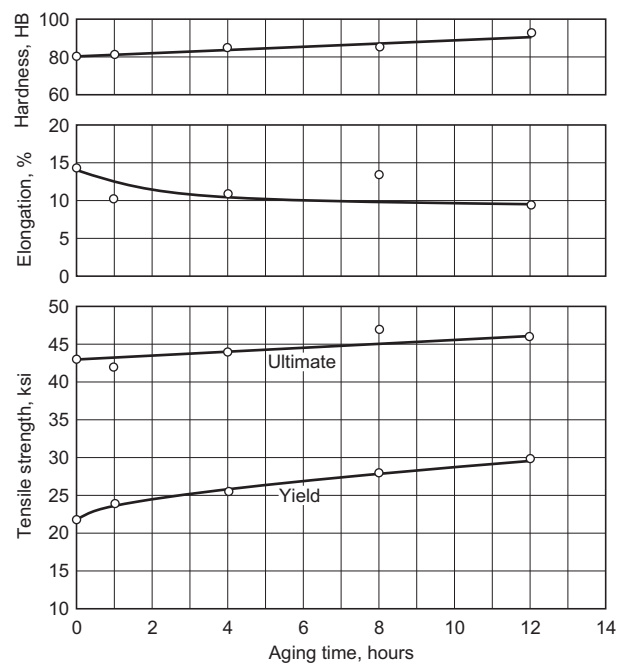


Fig. D1.89 High-temperature aging characteristics for aluminum alloy C355.0-T4, permanent mold. Solution heat treated 8 h at 980 °F, quenched in 200 °F water. Held 16 h at room temperature. Aged at 310 °F

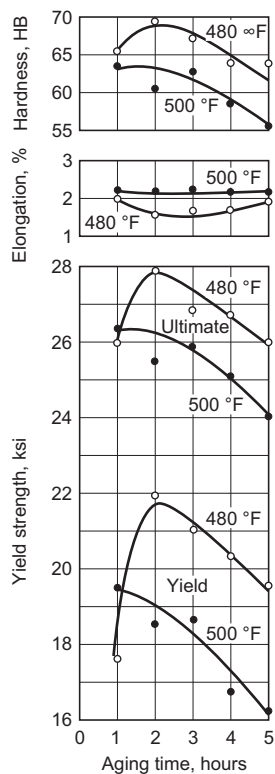


Fig. D1.90 High-temperature aging characteristics for aluminum alloy 356.0-F, sand cast

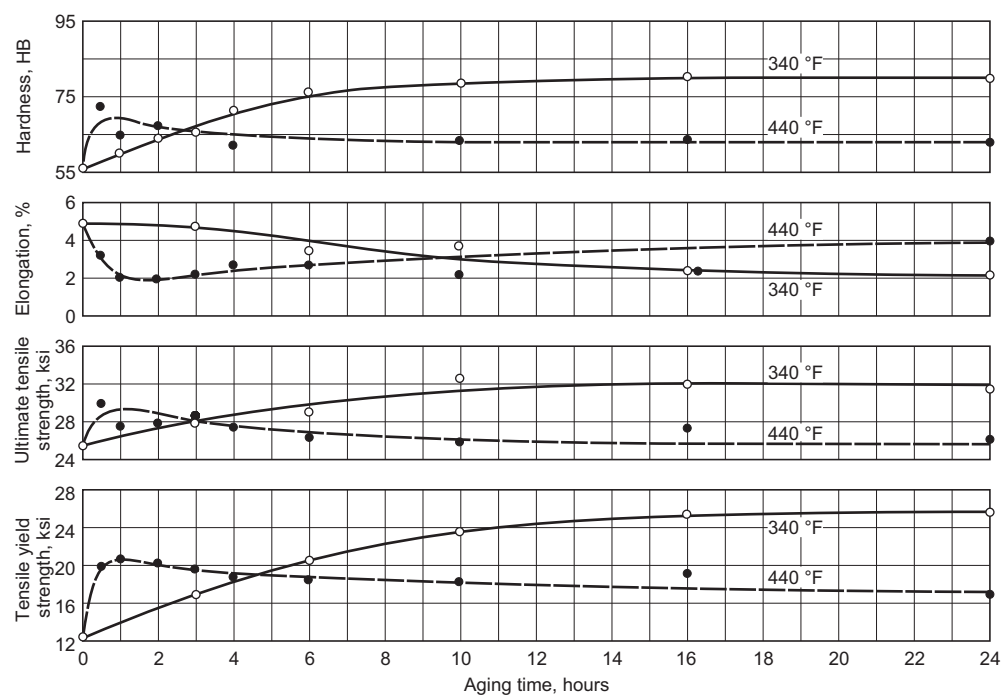


Fig. D1.91 High-temperature aging characteristics for aluminum alloy 356.0-F, permanent mold

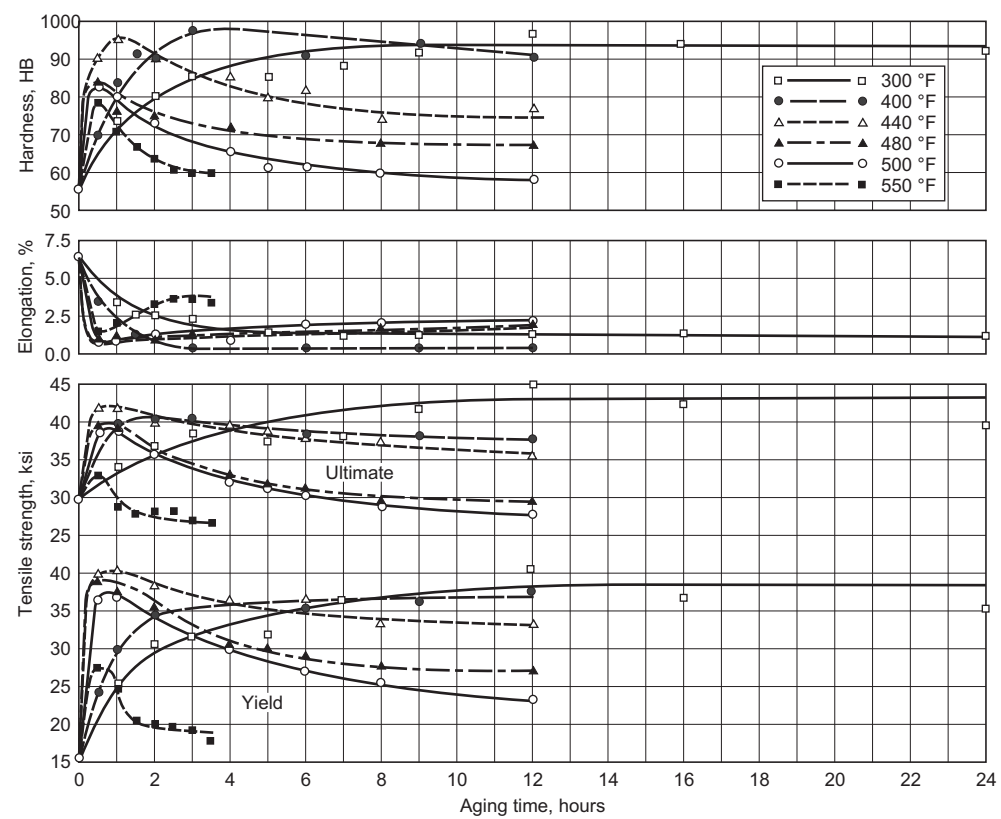


Fig. D1.92 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast

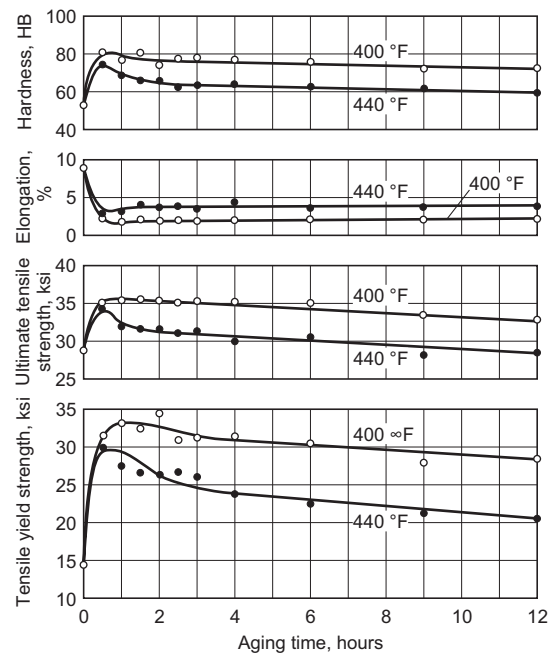


Fig. D1.93 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast

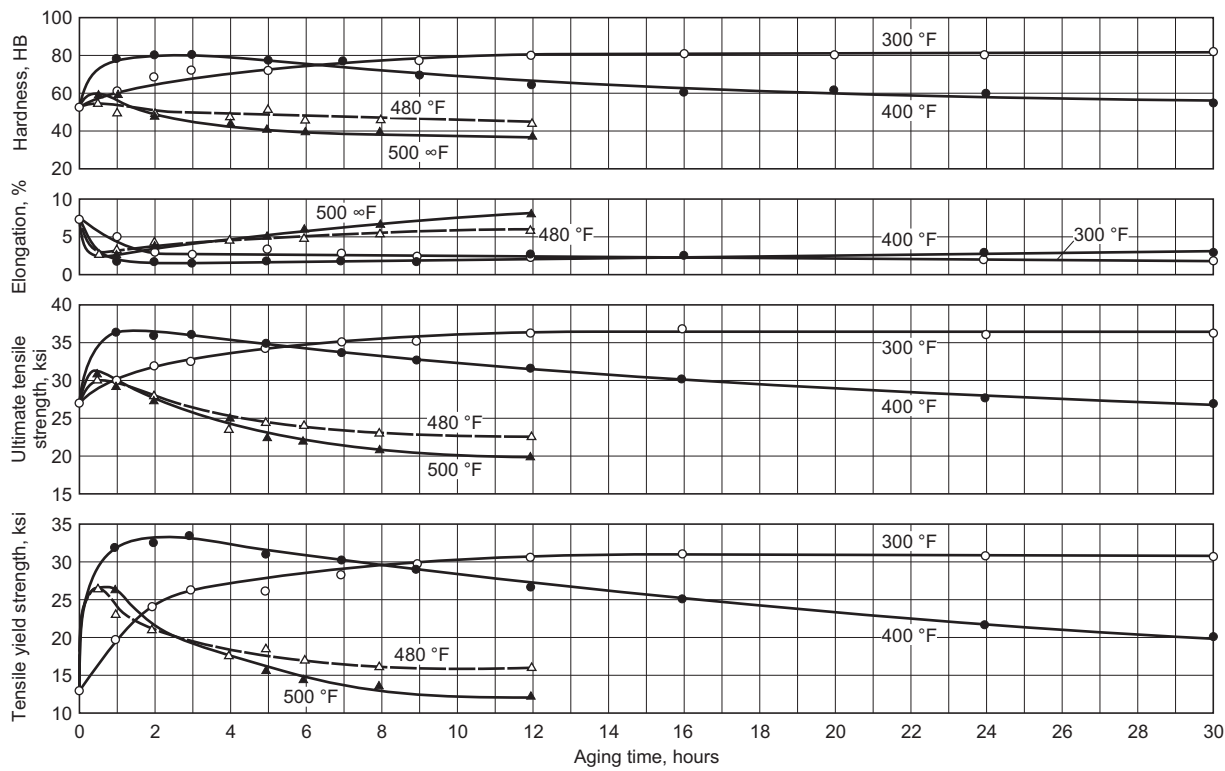


Fig. D1.94 High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast



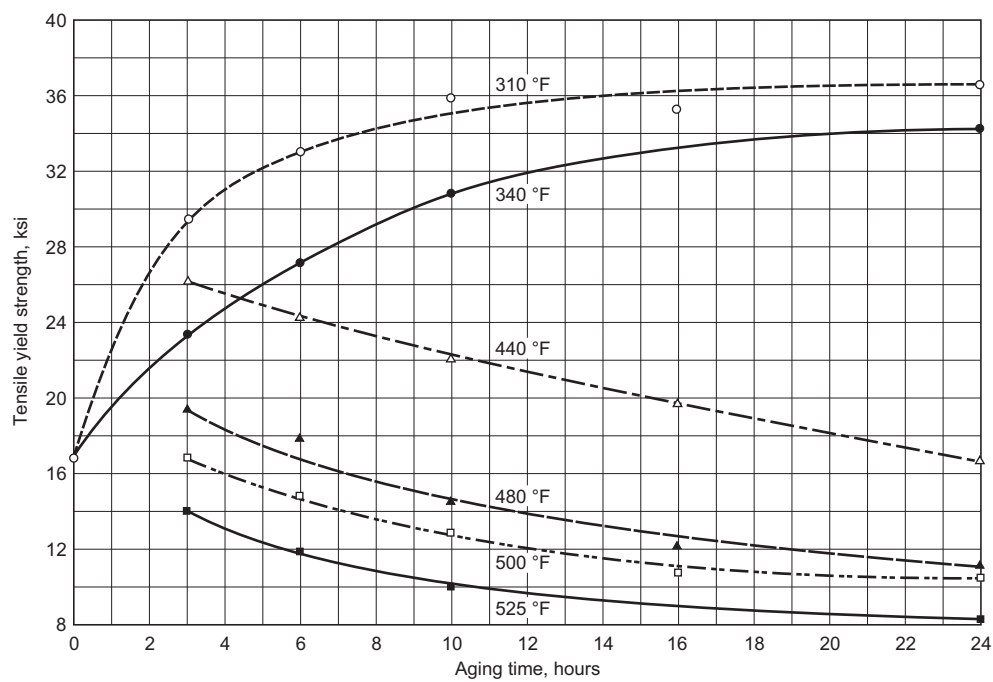


**Fig. D1.95** High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 6 h at 980 °F, quenched in 110 °F water. Specimens were aged 8 months at room temperature prior to artificial aging.

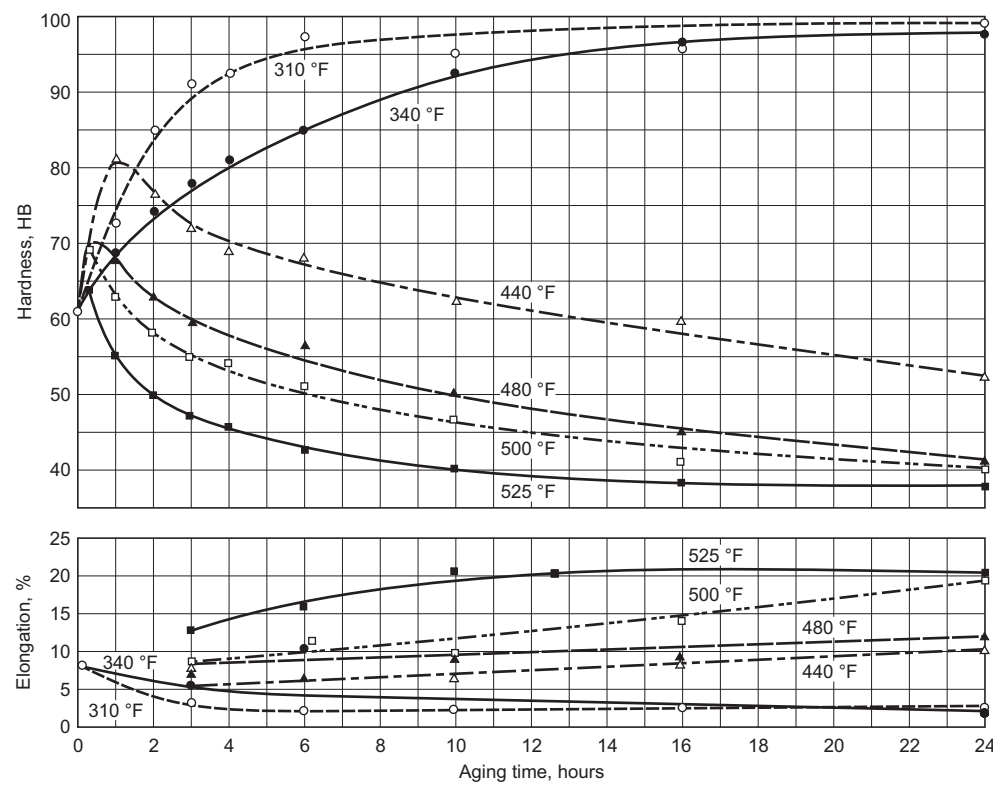


**Fig. D1.96** High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 6 h at 980 °F, quenched in 110 °F water. Specimens were aged 8 months at room temperature prior to artificial aging.

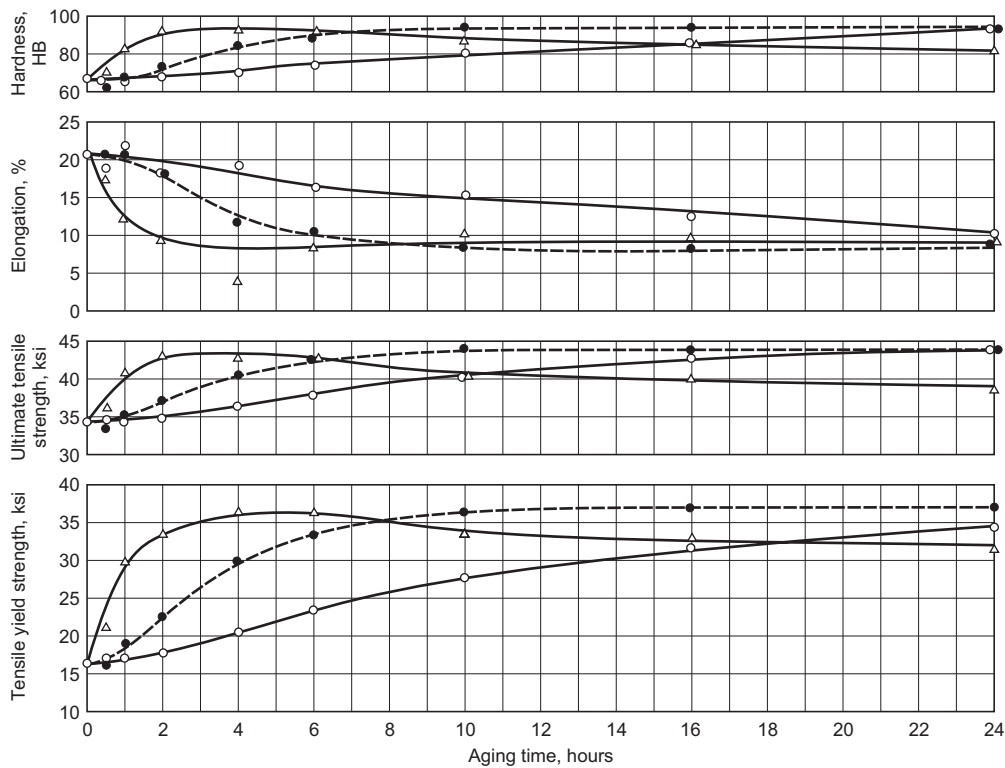


**Fig. D1.97** High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in boiling water. Held 24 h at room temperature

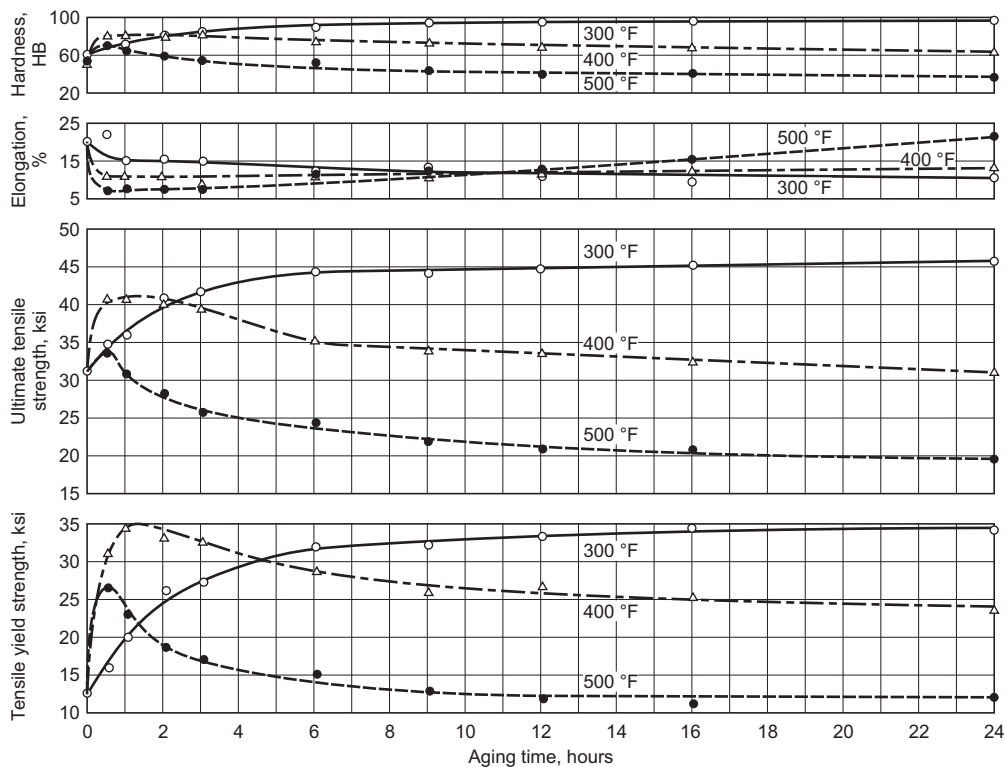


**Fig. D1.98** High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold

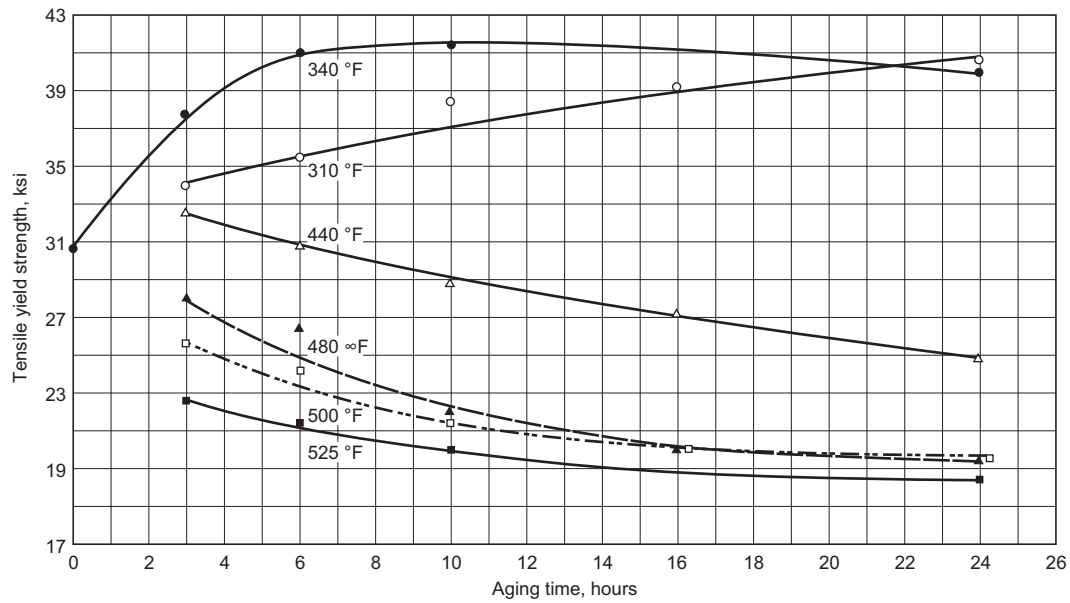


**Fig. D1.99** High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 6 h at 980 °F, quenched in 110 °F water. Specimens were aged 8 months at room temperature prior to artificial aging.

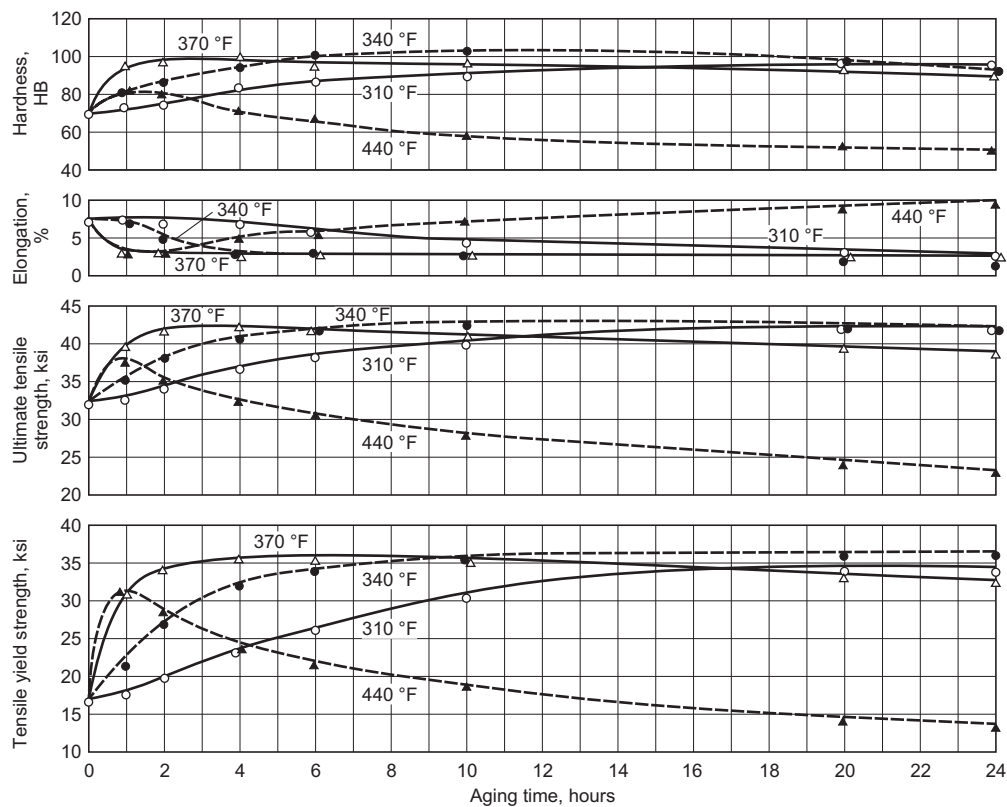


**Fig. D1.100** High-temperature aging characteristics for aluminum alloy 356.0-T4, sand cast. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

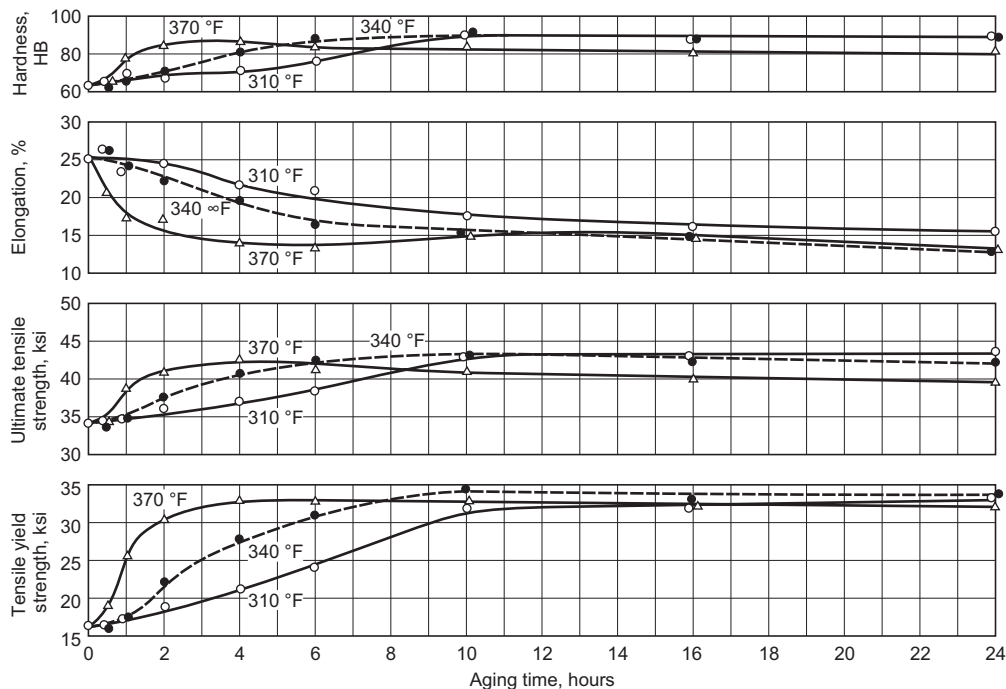


**Fig. D1.101** High-temperature aging characteristics for aluminum alloy 356.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

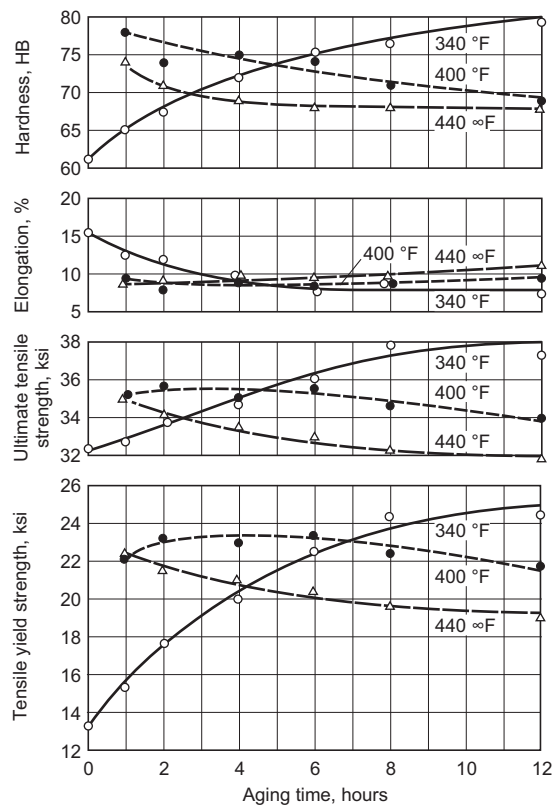


**Fig. D1.102** High-temperature aging characteristics for aluminum alloy A356.0-F, permanent mold

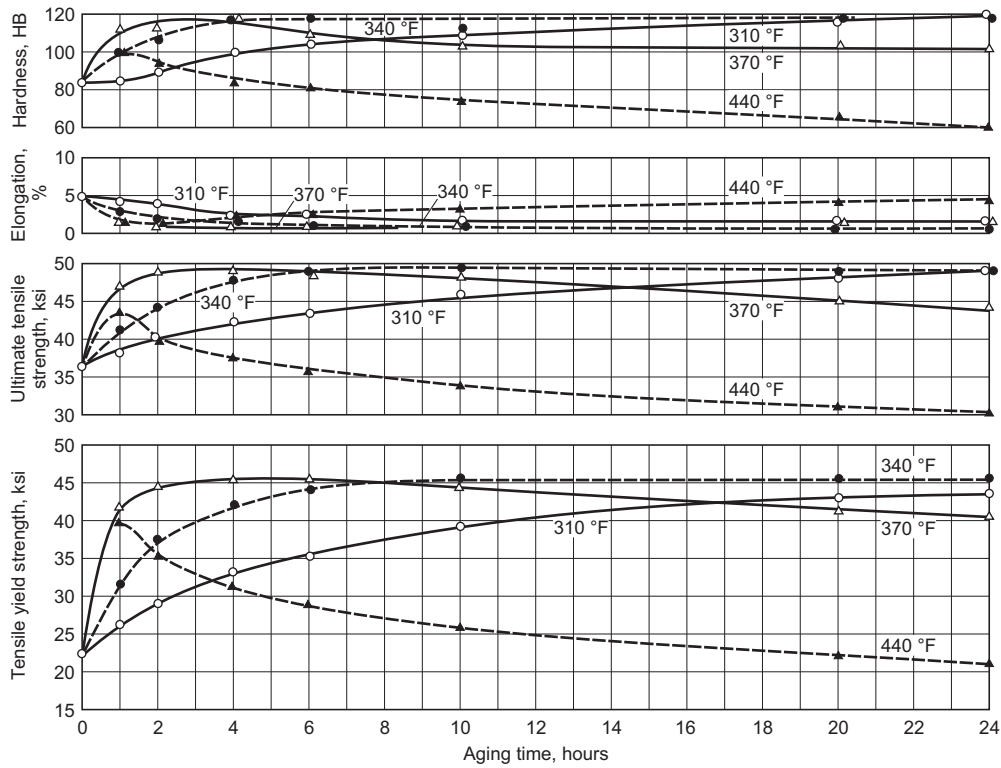


**Fig. D1.103** High-temperature aging characteristics for aluminum alloy 359.0-T4, sand cast. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

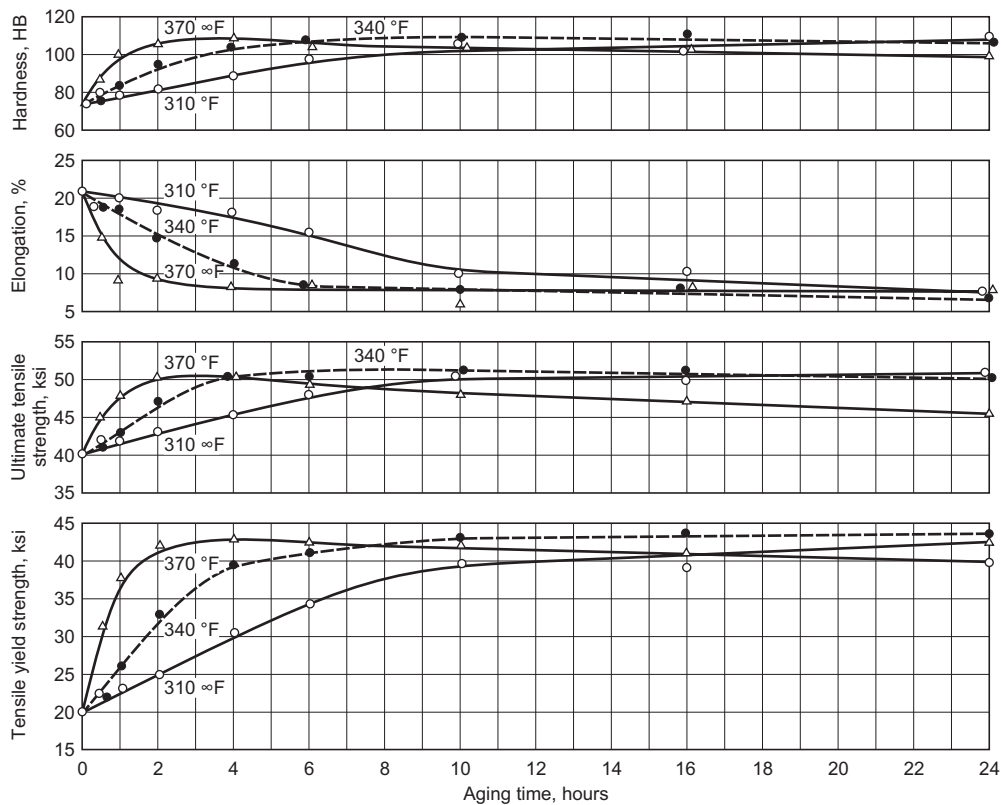


**Fig. D1.104** High-temperature aging characteristics for aluminum alloy 359.0-T4, permanent mold. Solution heat treated 15 h at 1000 °F, quenched in 150 °F water. Held 24 h at room temperature

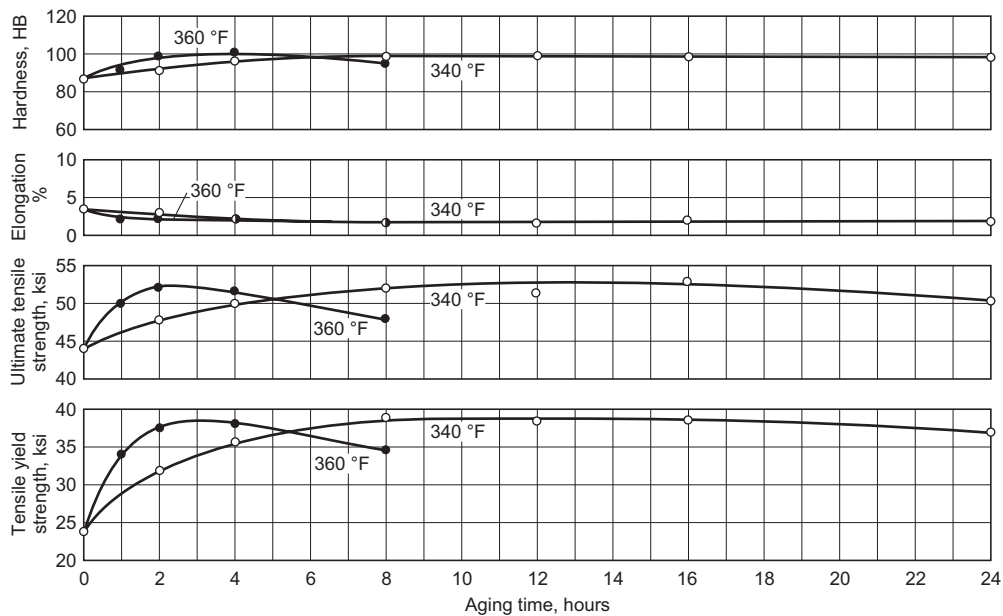


Fig. D1.105 High-temperature aging characteristics for aluminum alloy A360.0-F, die cast

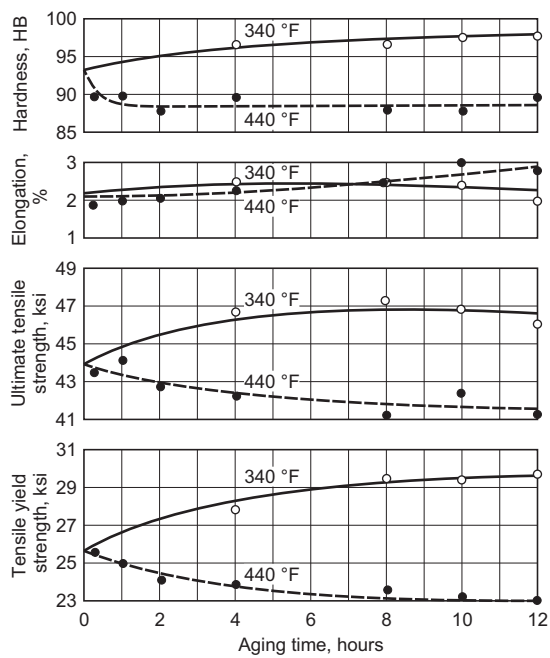


Fig. D1.106 High-temperature aging characteristics for aluminum alloy 380.0-F, die cast



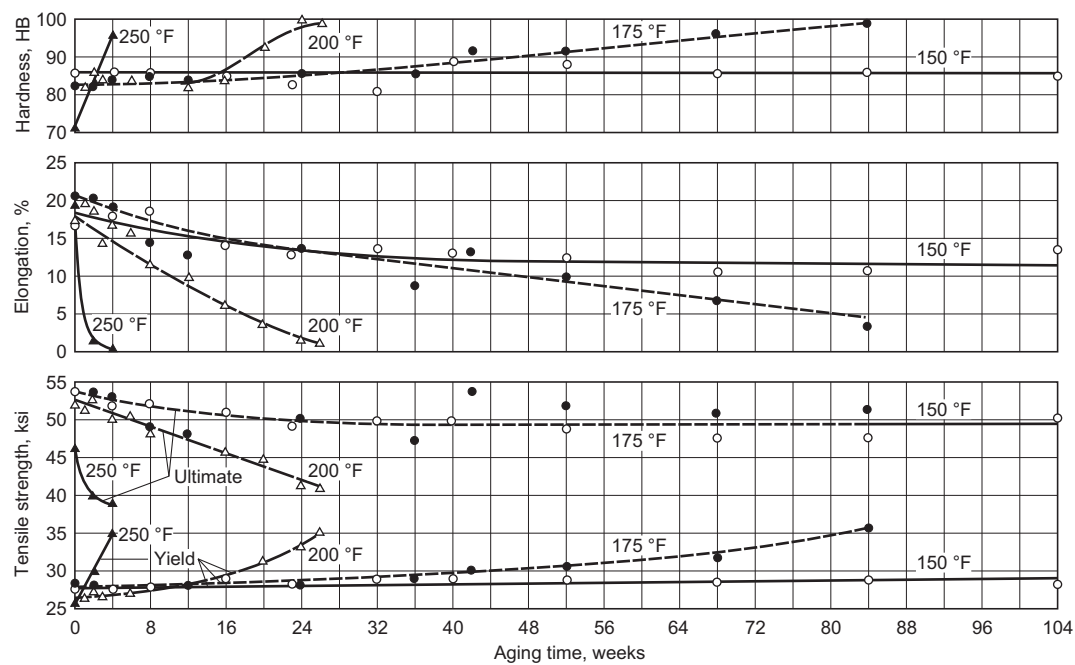


Fig. D1.107 High-temperature aging characteristics for aluminum alloy 520.0-T4. Effect of lower-temperature artificial aging. Tested at room temperature

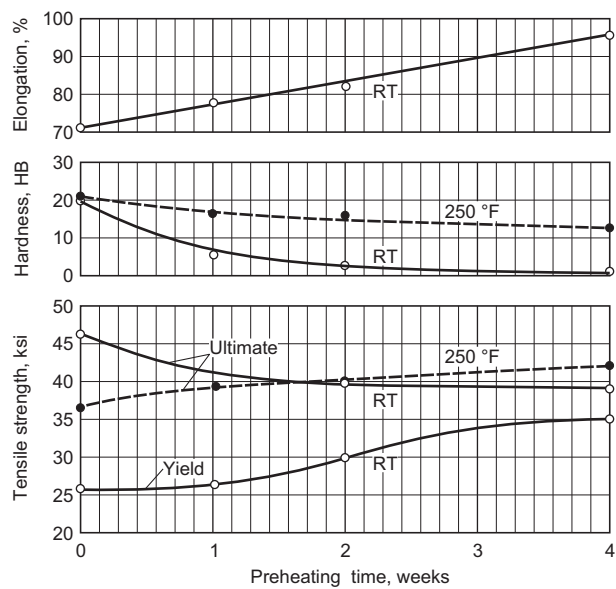


Fig. D1.108 High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of preheating at 250 °F. Tested at room temperature

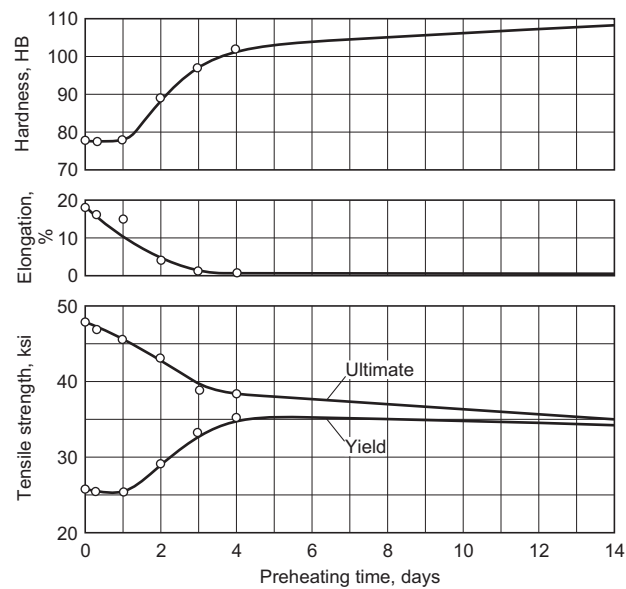


Fig. D1.109 High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of aging at 300 °F. Tested at room temperature

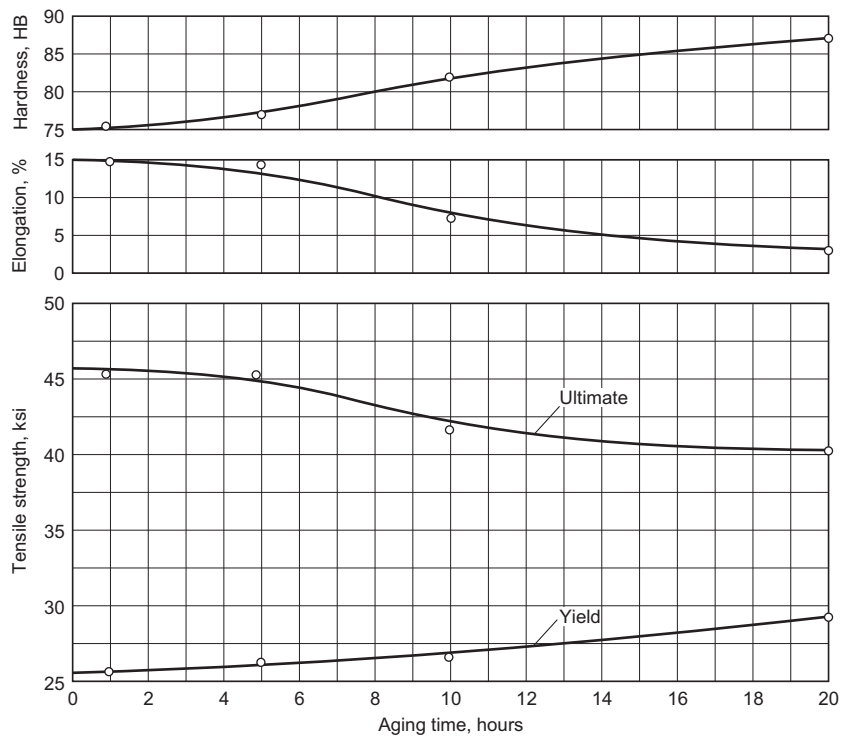


**Fig. D1.110** High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of aging at 325 °F. Tested at room temperature

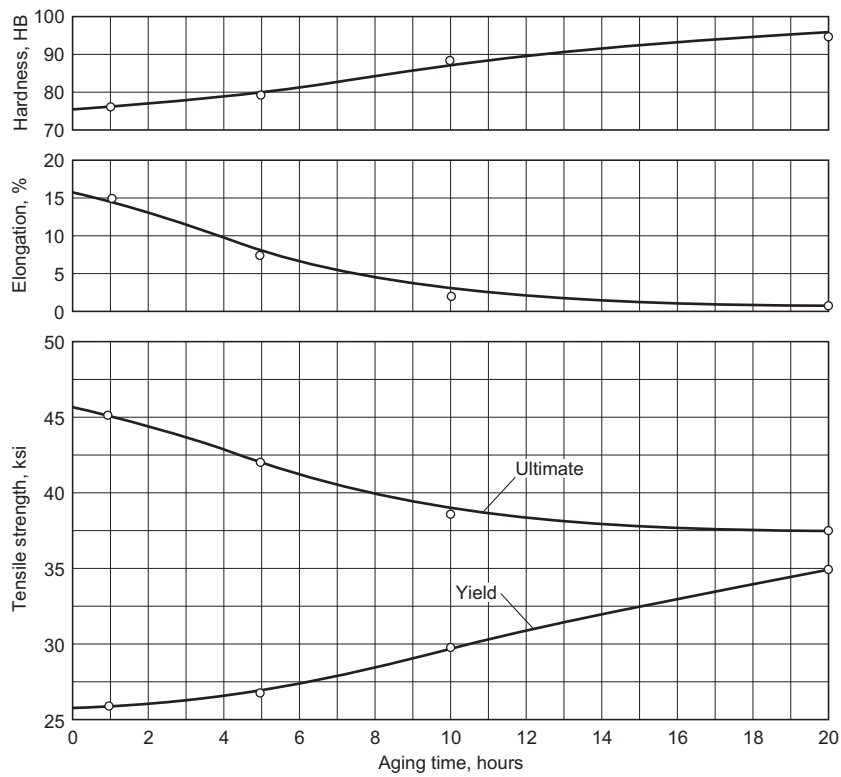


**Fig. D1.111** High-temperature aging characteristics for aluminum alloy 520.0-T4, sand cast. Effect of aging at 350 °F. Tested at room temperature



## DATA SET 2

# Growth Curves

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This data set contains approximately 50 growth curves for a wide range of aluminum casting alloys, providing experimental evidence of permanent dimensional change with time at various temperatures. All of these curves were developed at Alcoa Laboratories Cleveland Casting Research Division.

The purpose in making such measurements is to determine the dimensional changes that must be anticipated during service in applications where close dimensional tolerances are required.

Hardness values shown were the product of corresponding aging response studies in which measurements were made on individual

lots considered representative of the respective alloys and tempers. They have not been normalized to any typical or average compositions for the individual alloys and tempers.

The growth factor is given in units of  $10^{-4}$  in./in.; the values on the axis are to be multiplied by  $10^{-4}$ . This representation is standard industry practice. The growth factor is unitless, so the value is identical in the SI system.

Brinell hardness (HB) was recorded in many of these tests. Hardness testing employed a 4.9 kN (500 kgf) load with a 10 mm ball, in accordance with ASTM E 10.

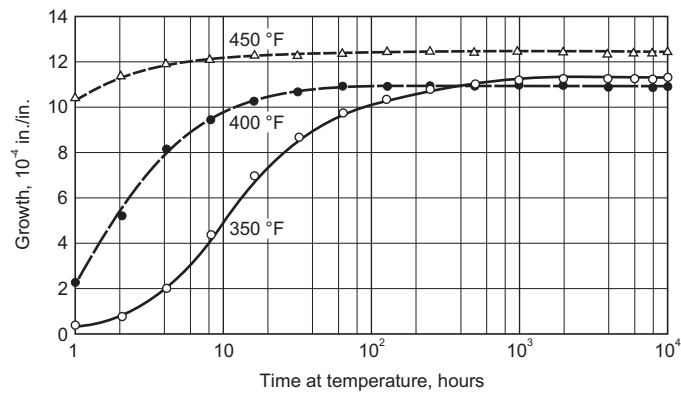


**Fig. D2.1** Growth curves for aluminum alloy 238.0-F, permanent mold. Test specimen: 1.125 diam × 12 in. rod

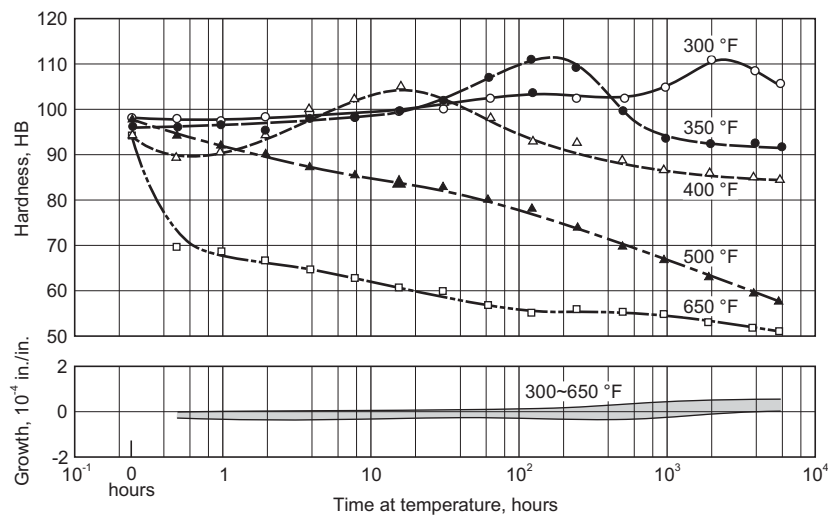


**Fig. D2.2** Growth and hardness curves for aluminum alloy 242.0-F, permanent mold. Test specimen 1.125 diam × 12 in. rod

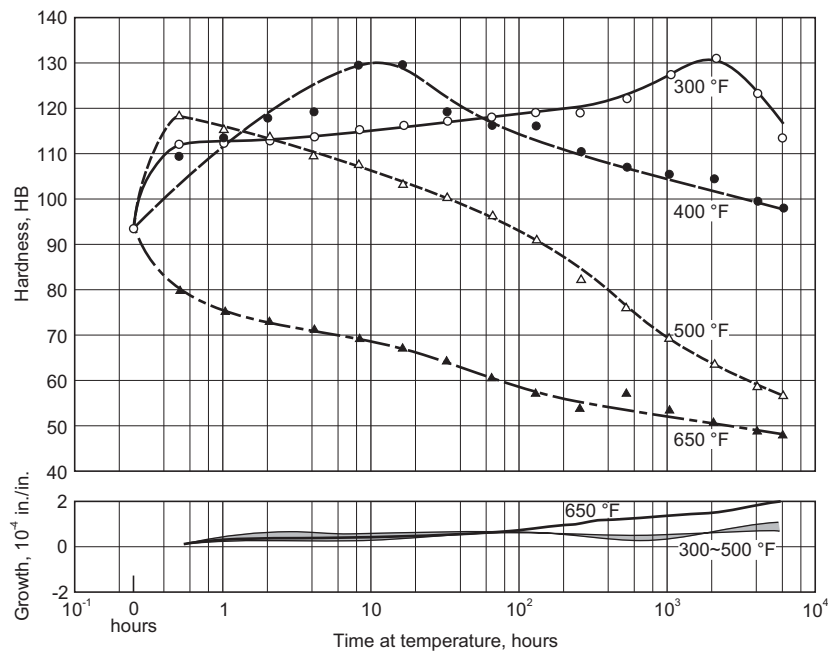


**Fig. D2.3** Growth and hardness curves for aluminum alloy 242.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

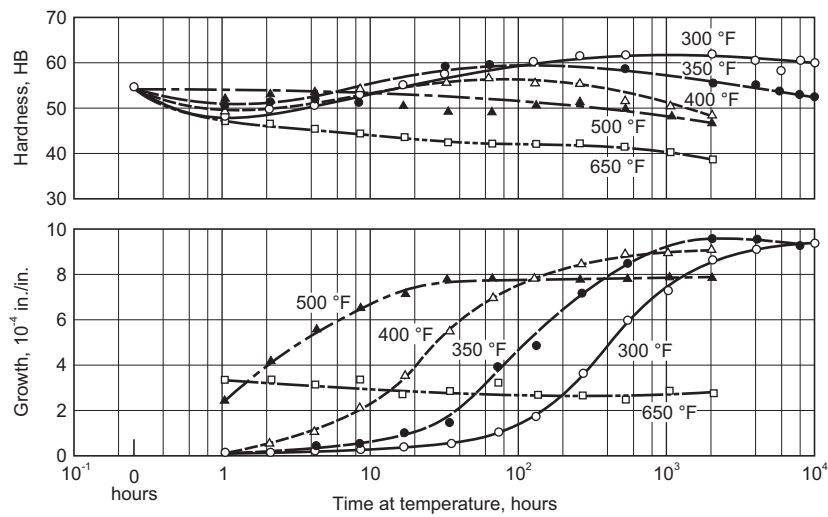


**Fig. D2.4** Growth and hardness curves for aluminum alloy 295.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

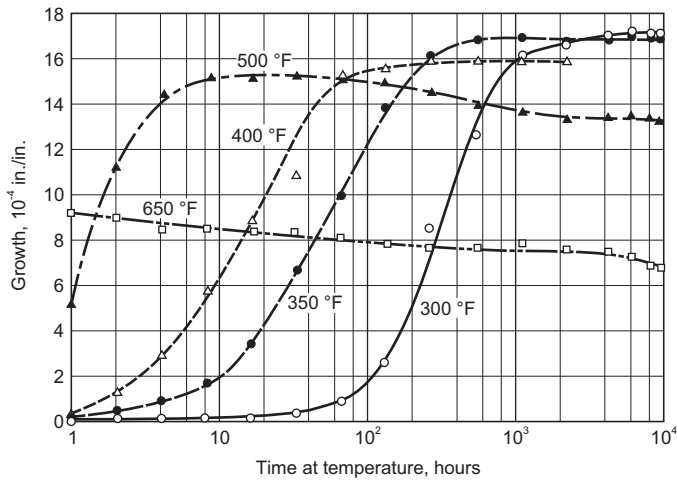


**Fig. D2.5** Growth curves for aluminum alloy 295.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

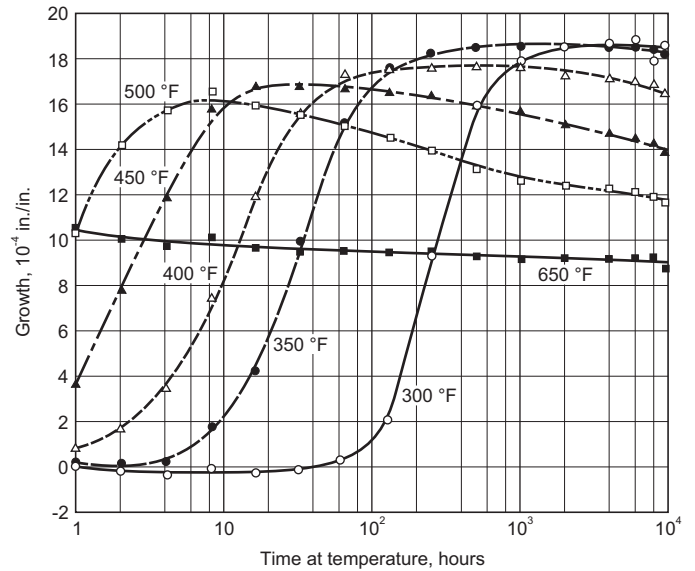


**Fig. D2.6** Growth curves for aluminum alloy B295.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 950 °F, boiling water quench

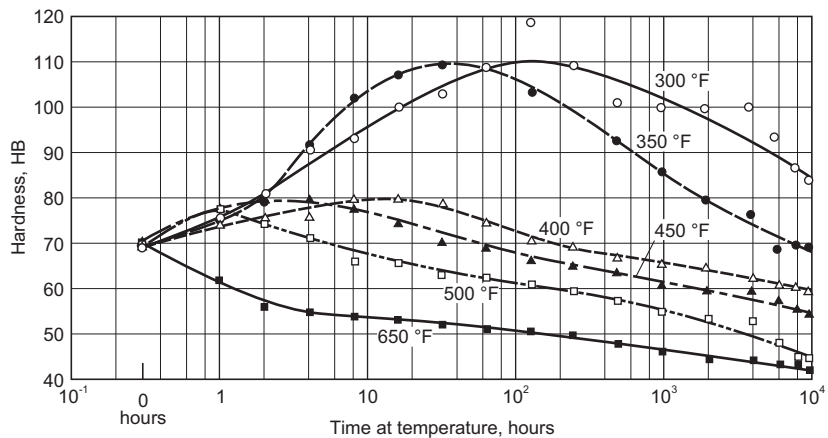


**Fig. D2.7** Hardness curves for aluminum alloy B295.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 940 °F, boiling water quench



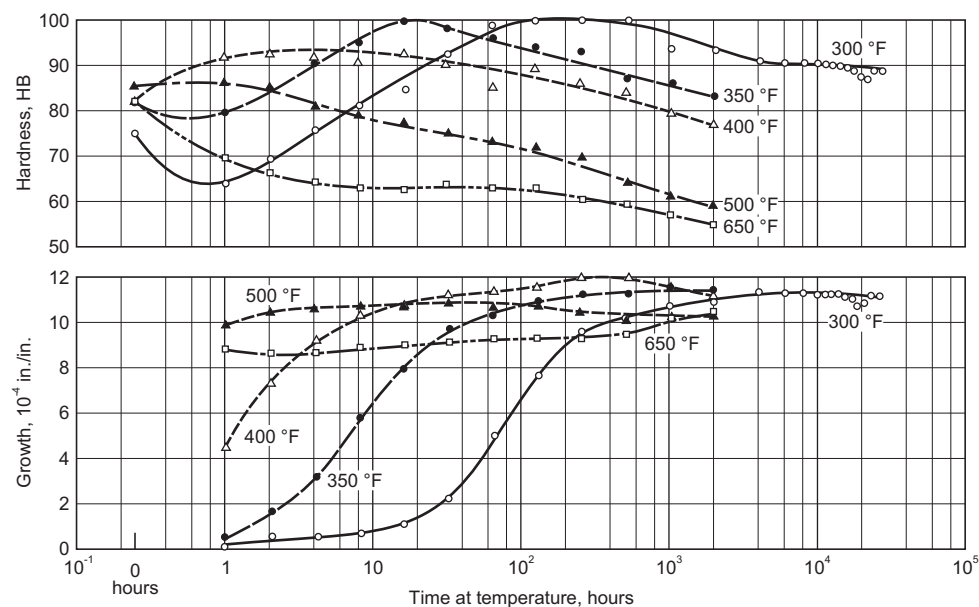


**Fig. D2.8** Growth and hardness curves for aluminum alloy 319.0-F, permanent mold. Specimen: 1.125 diam × 12 in. rod

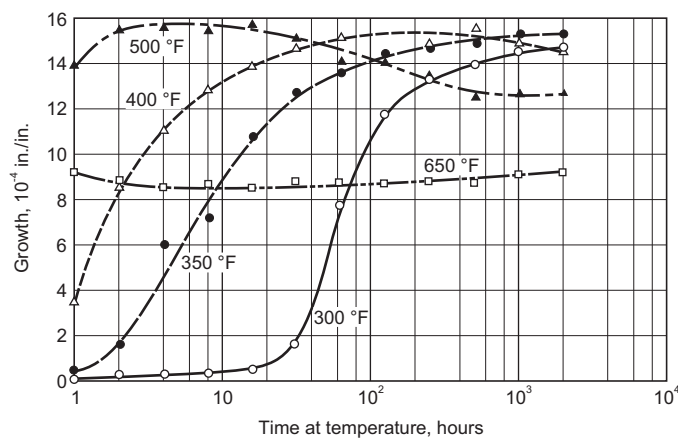


**Fig. D2.9** Growth curves for aluminum alloy 319.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

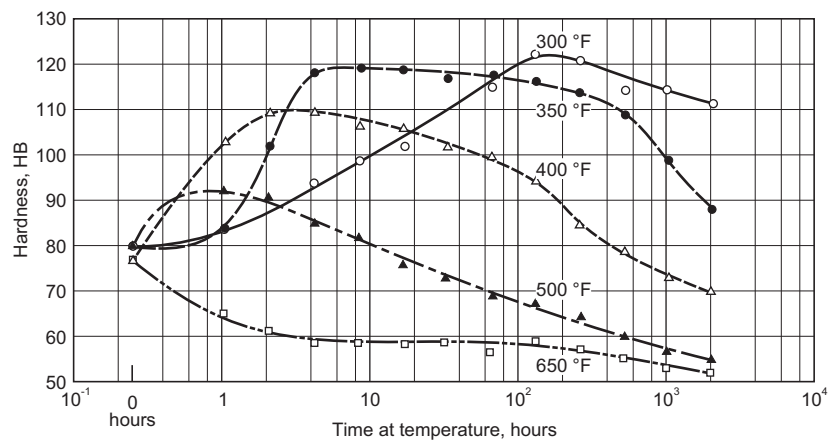


**Fig. D2.10** Hardness curves for aluminum alloy 319.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

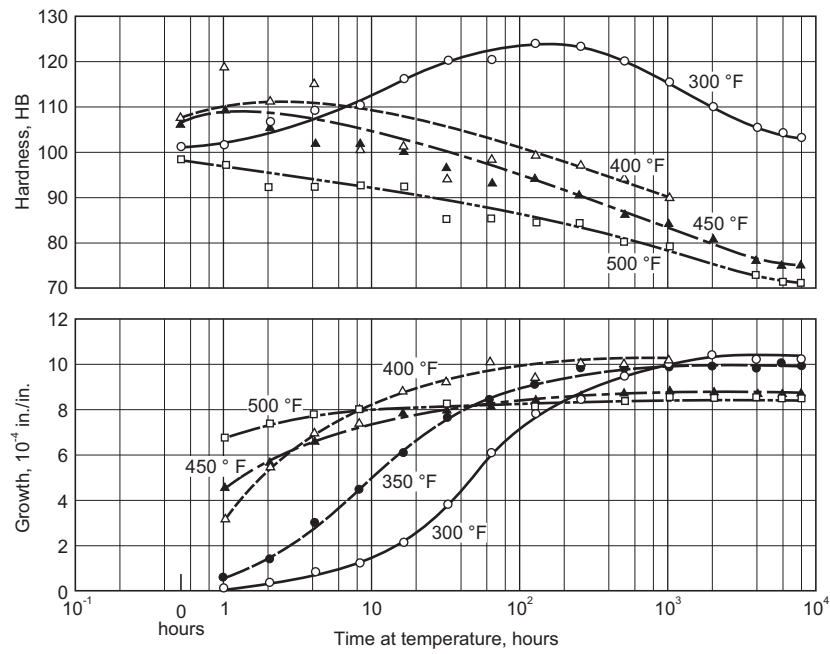


**Fig. D2.11** Growth and hardness curves for aluminum alloy 332.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

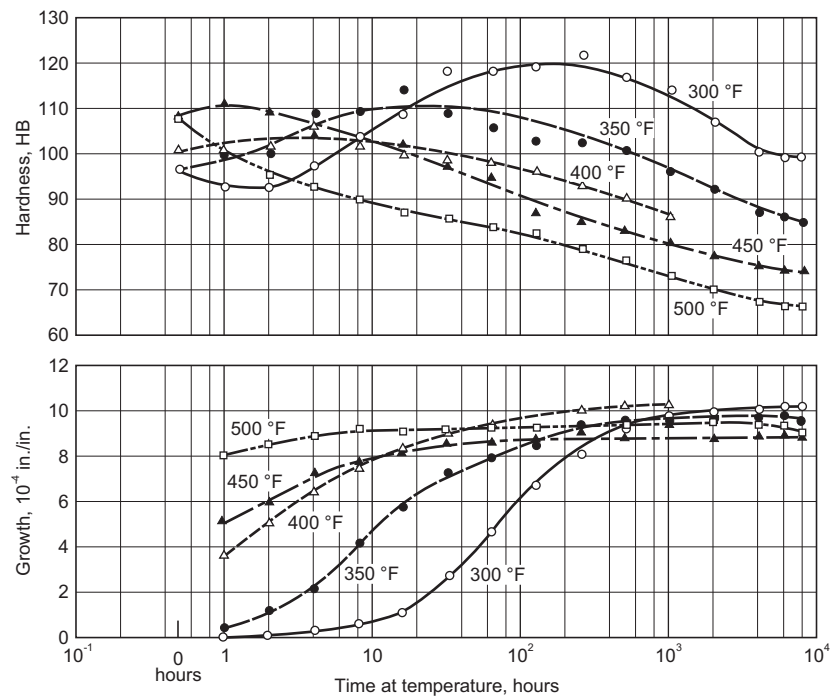


**Fig. D2.12** Growth and hardness curves for aluminum alloy 333.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

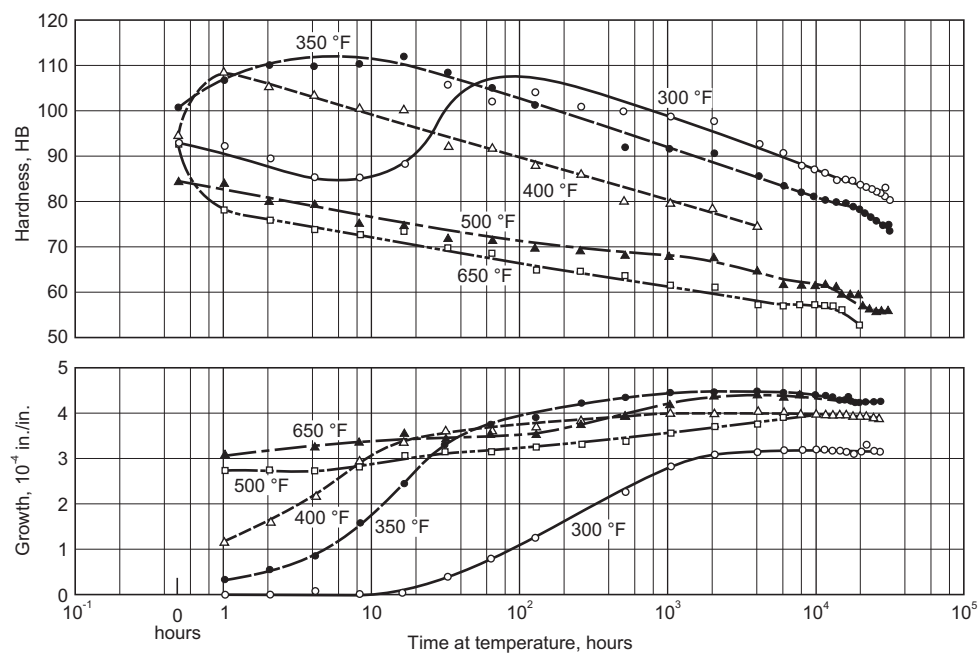


Fig. D2.13 Growth and hardness curves for aluminum alloy 336.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

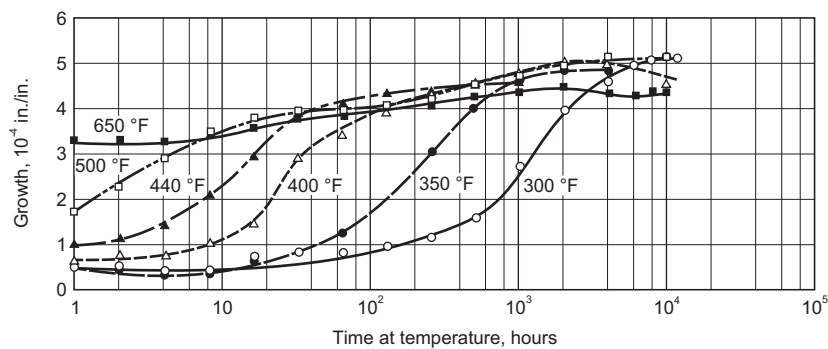


Fig. D2.14 Growth curves for aluminum alloy 336.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 950 °F, boiling water quench

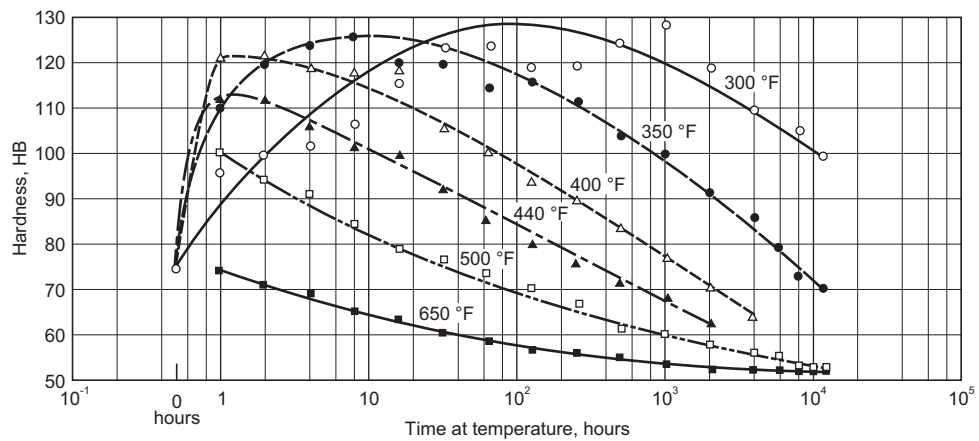


Fig. D2.15 Hardness curves for aluminum alloy 336.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 950 °F, boiling water quench

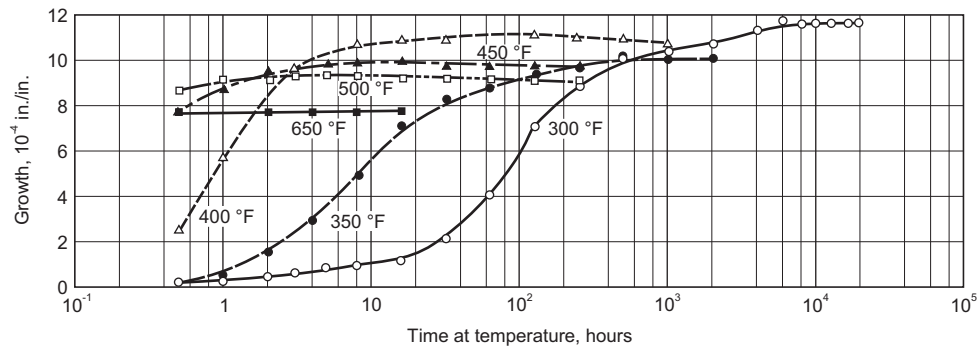


**Fig. D2.16** Growth curves for aluminum alloy 355.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

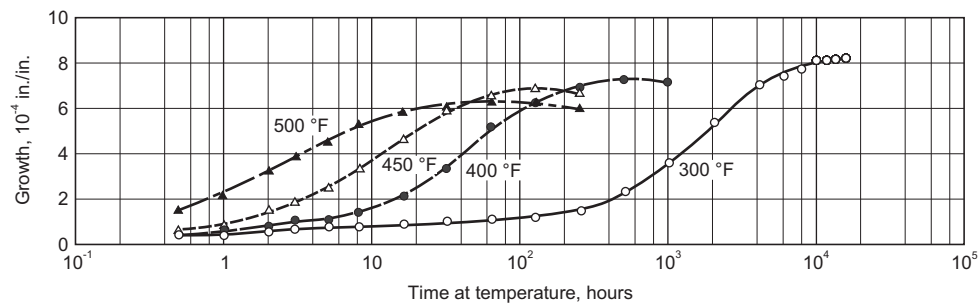


**Fig. D2.17** Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 940 °F, boiling water quench

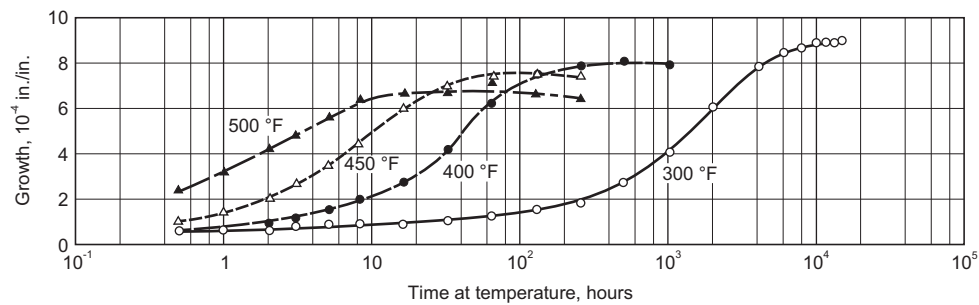


**Fig. D2.18** Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 960 °F, boiling water quench

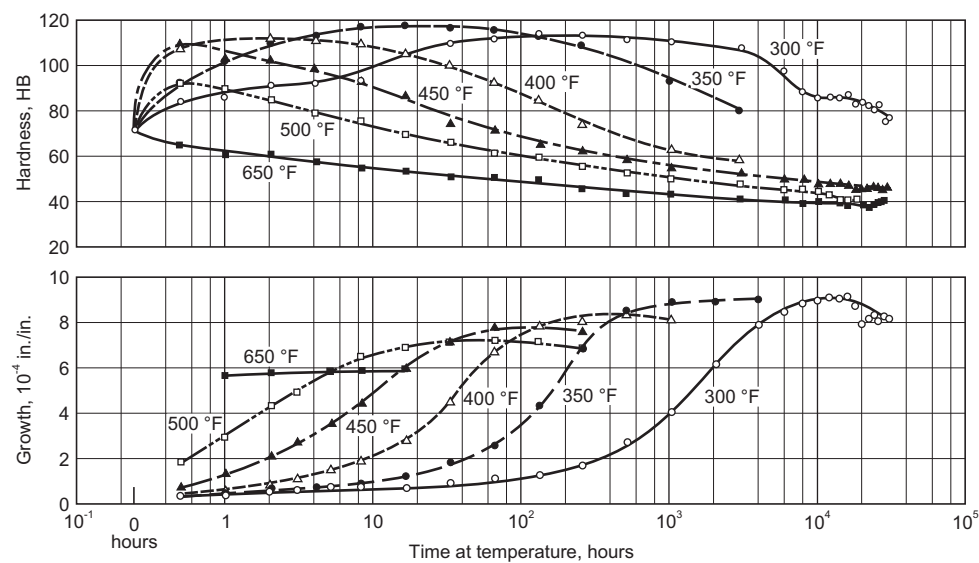


**Fig. D2.19** Growth and hardness curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 980 °F, boiling water quench

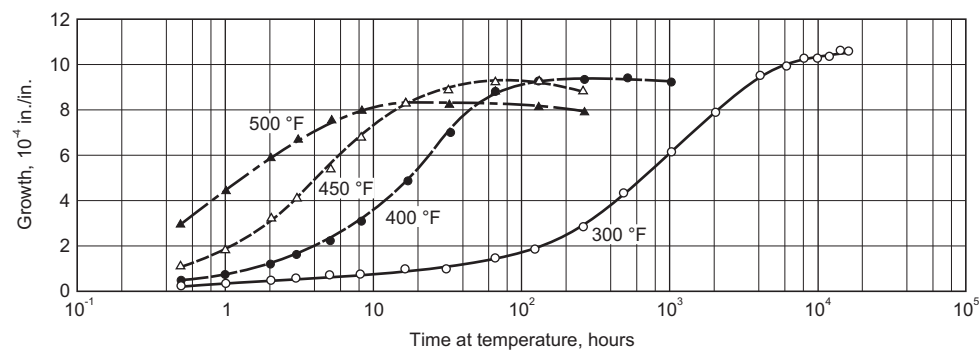


**Fig. D2.20** Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 1000 °F, boiling water quench

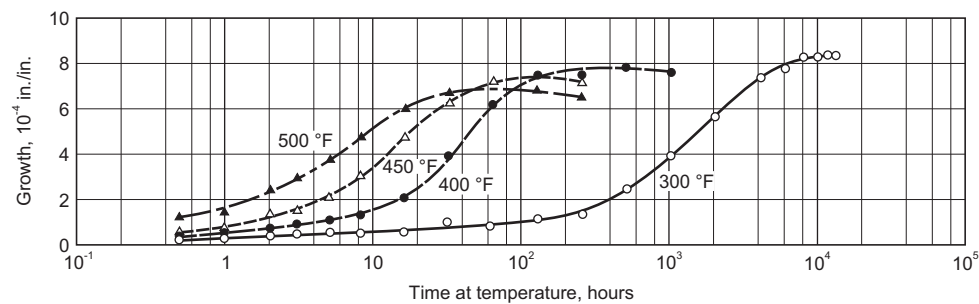


**Fig. D2.21** Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam × 12 in. rod. Treatment: 12 h at 940 °F, cold water quench

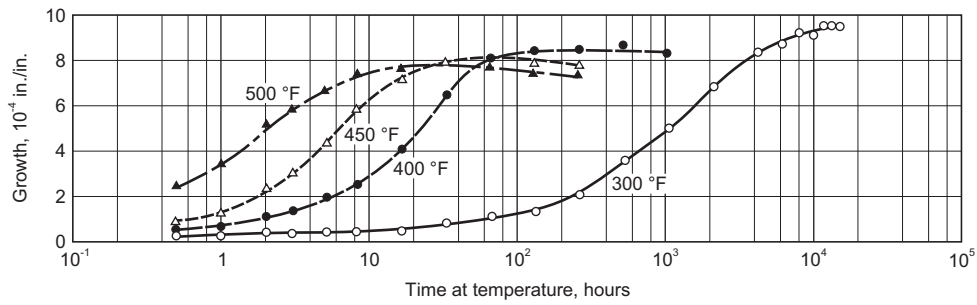


**Fig. D2.22** Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 960 °F, cold water quench

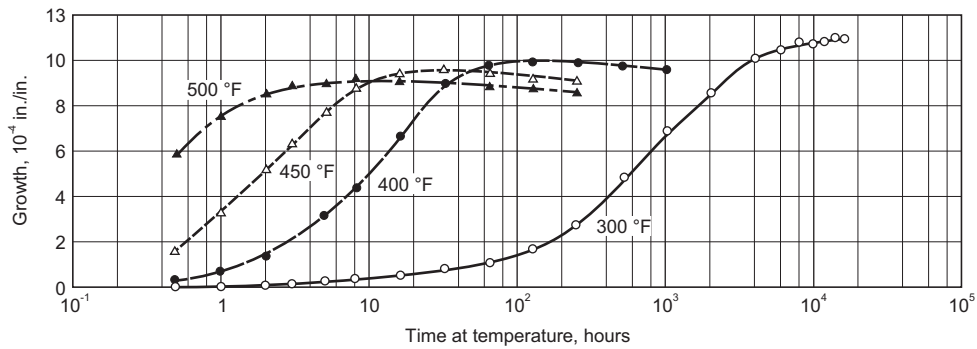


**Fig. D2.23** Growth curves for aluminum alloy 355.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 1000 °F, cold water quench

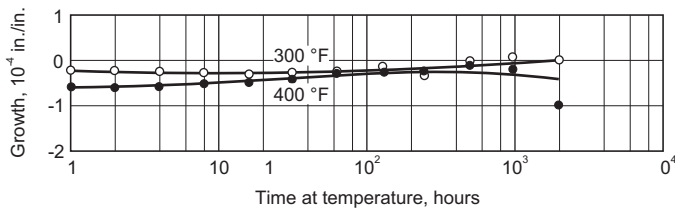


**Fig. D2.24** Growth curves for aluminum alloy 355.0-T51, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 8 h at 440 °F

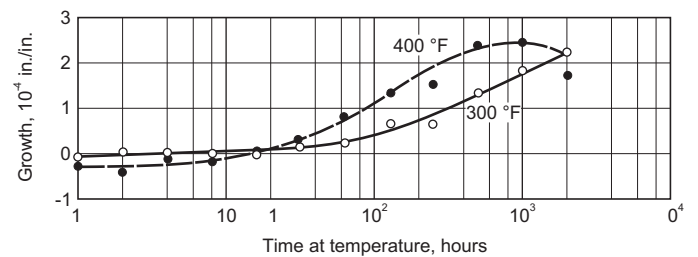


**Fig. D2.25** Growth curves for aluminum alloy 355.0-T7, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 5 h at 700 °F plus 12 h at 850 °F, boiling water quench, 8 h at 440 °F



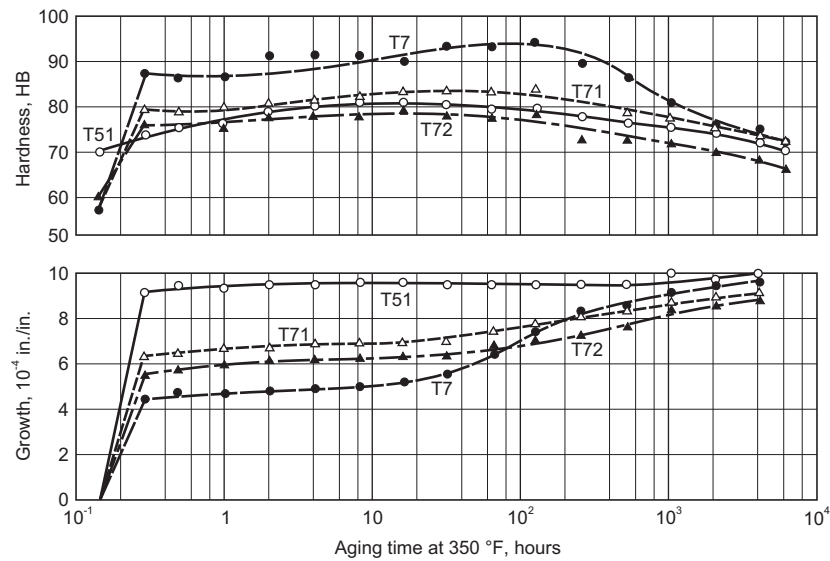


**Fig. D2.26** Growth and hardness curves for aluminum alloy 355.0 with various commercial tempers and aging at 350 °F, permanent mold. Zero hour data is as-cast. Data at 0.3 h is after the commercial heat treatment. Data for aging at 350 °F is then given. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: T51, 8 h at 440 °F; T7, 980 °F, boiling water quench, 5 h at 540 °F; T71, 980 °F, boiling water quench, 5 h at 480 °F; T72, 980 °F boiling water quench, 5 h at 500 °F

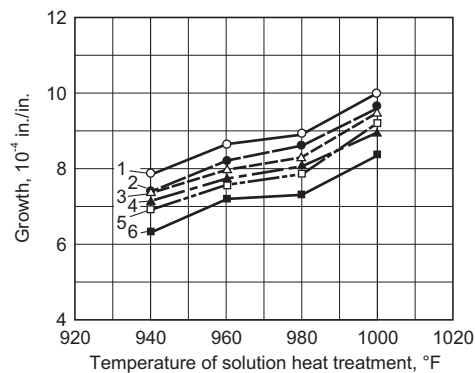


**Fig. D2.27** Maximum growth of aluminum alloy 355.0-T4 under various conditions of solution heat treatment and quench: Curve 1, cold water quench, aging at 400 °F. Curve 2, cold water quench, aging at 450 °F. Curve 3, boiling water quench, aging at 400 °F. Curve 4, cold water quench, aging at 500 °F. Curve 5, boiling water quench, aging at 450 °F. Curve 6, boiling water quench, aging at 500 °F. Permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

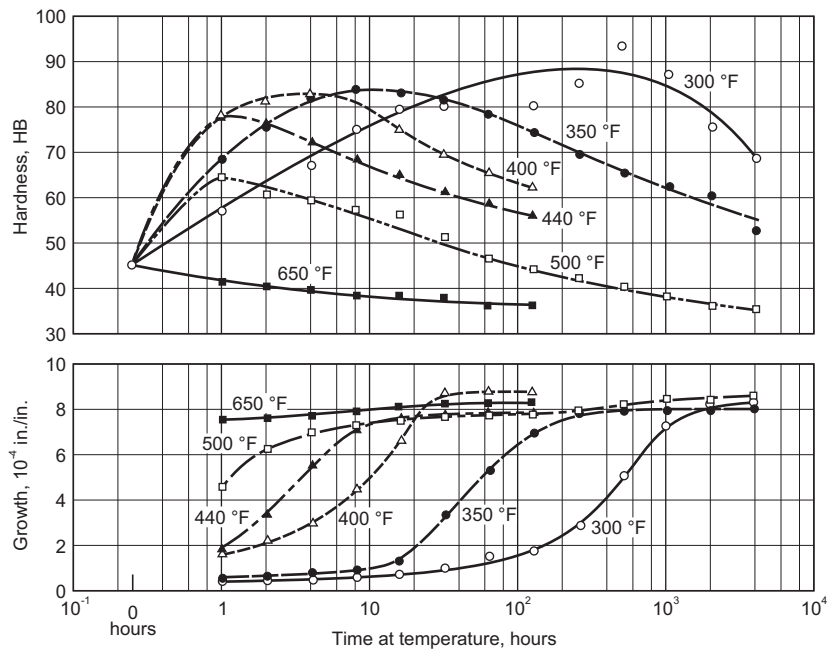


**Fig. D2.28** Growth and hardness curves for aluminum alloy 356.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 980 °F, boiling water quench

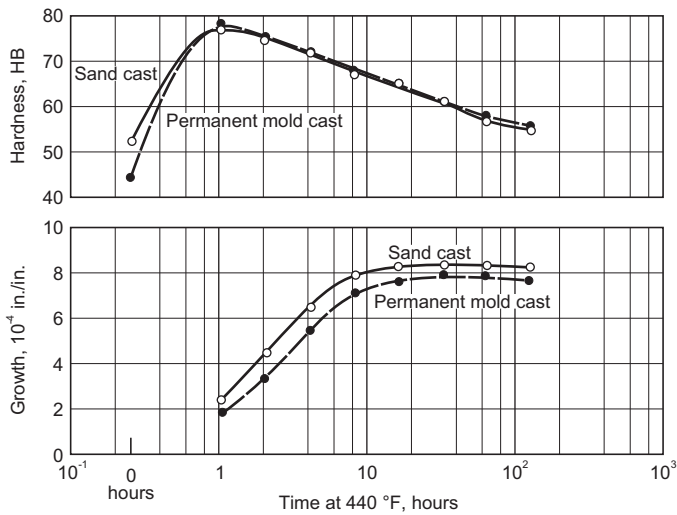


**Fig. D2.29** Growth and hardness curves for aluminum alloy 356.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 980 °F, boiling water quench. Comparison of sand cast and permanent mold

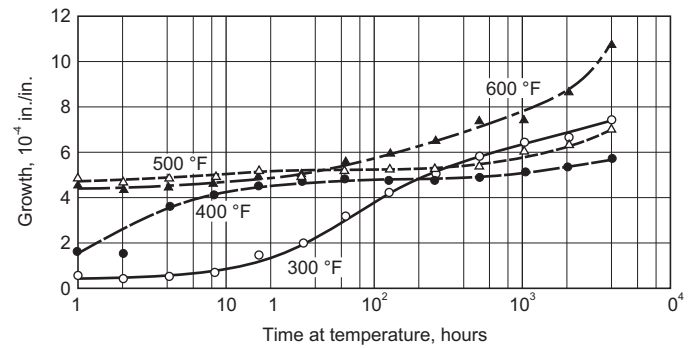


**Fig. D2.30** Growth curves for aluminum alloy 360.0-F, die cast. Specimen:  $\frac{3}{16}$  in. thick plate

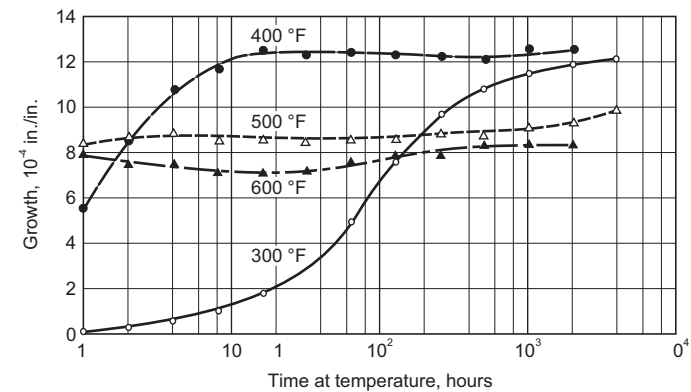


**Fig. D2.31** Growth curves for aluminum alloy 380.0-F, die cast. Specimen:  $\frac{3}{16}$  in. thick plate

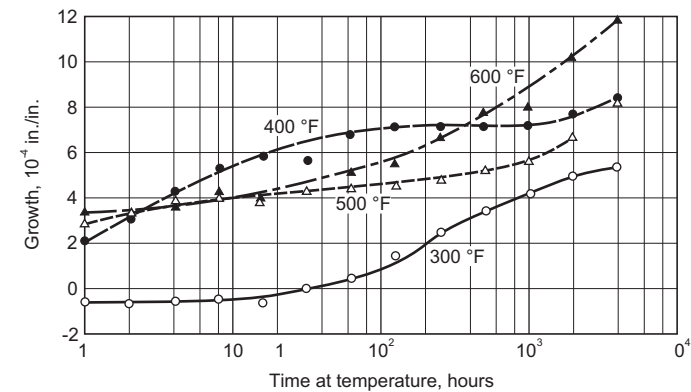


**Fig. D2.32** Growth curves for aluminum alloy 384.0-F, die cast. Specimen:  $\frac{5}{16}$  in. thick plate

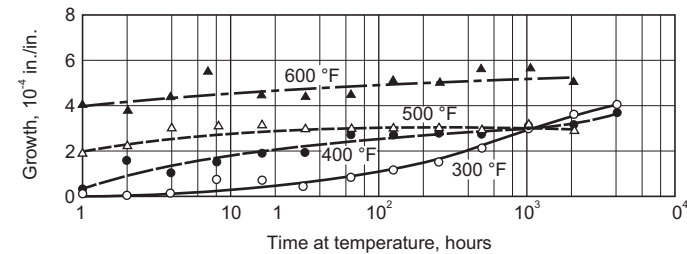


**Fig. D2.33** Growth curves for aluminum alloy 413.0-F, die cast. Specimen:  $\frac{3}{16}$  in. thick plate

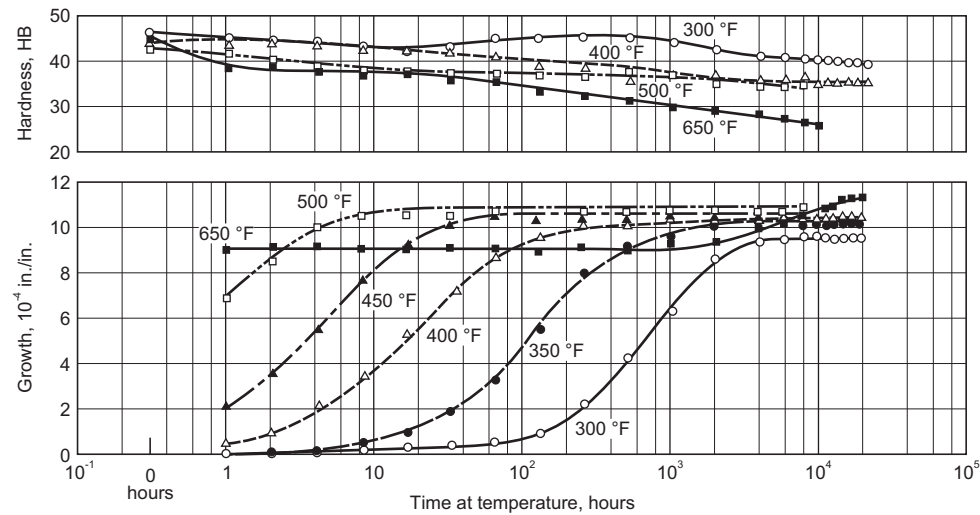


**Fig. D2.34** Growth and hardness curves for aluminum alloy 443.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

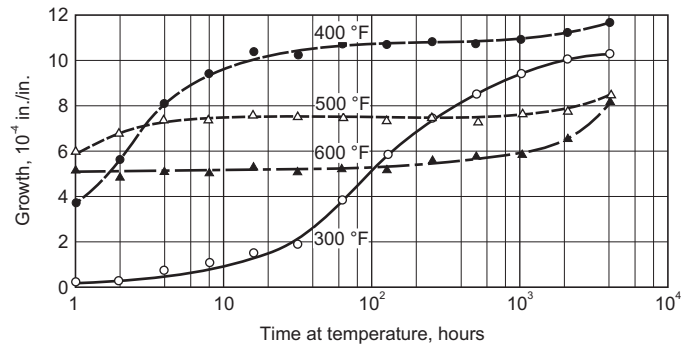


**Fig. D2.35** Growth curves for aluminum alloy 443.0-F, die cast. Specimen:  $\frac{3}{16}$  in. thick plate

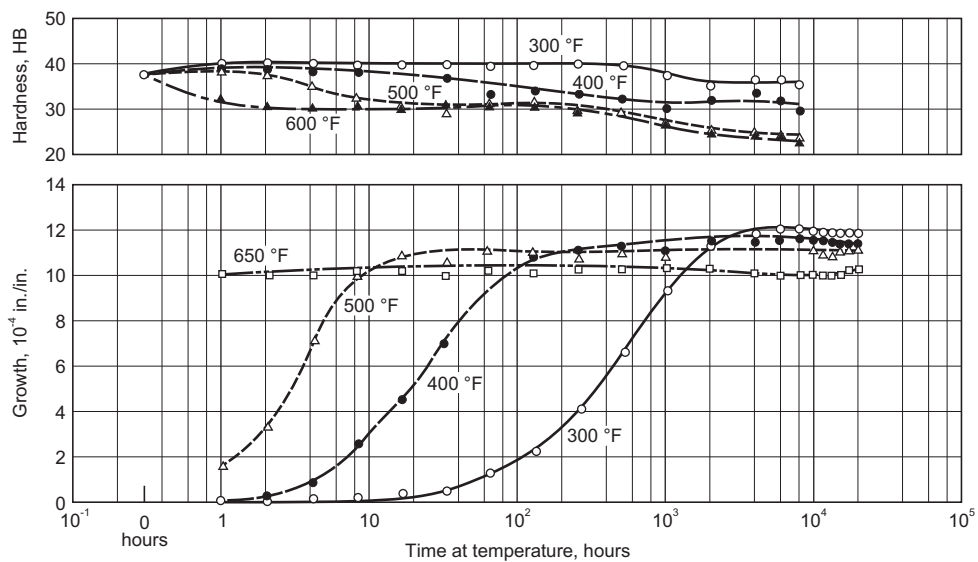


**Fig. D2.36** Growth and hardness curves for aluminum alloy 443.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 1000 °F, boiling water quench

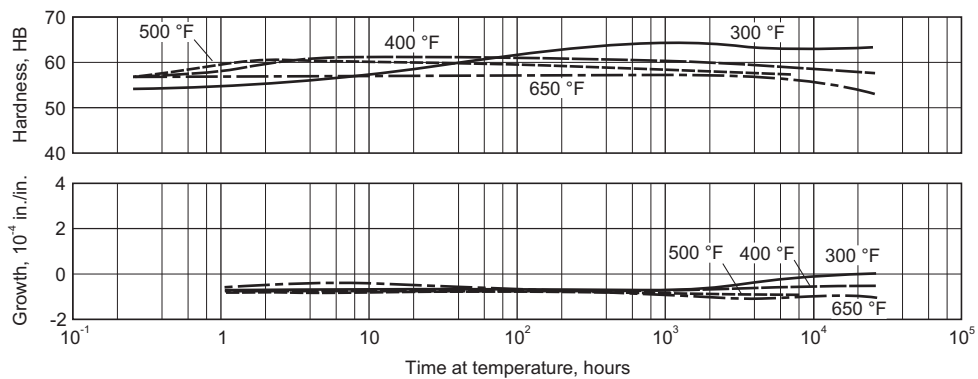


**Fig. D2.37** Growth and hardness curves for aluminum alloy 514.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

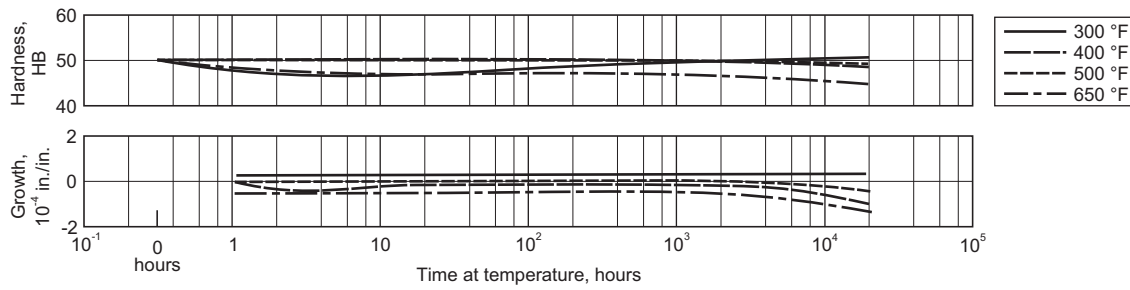


**Fig. D2.38** Growth and hardness curves for aluminum alloy 514.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 825 °F, boiling water quench

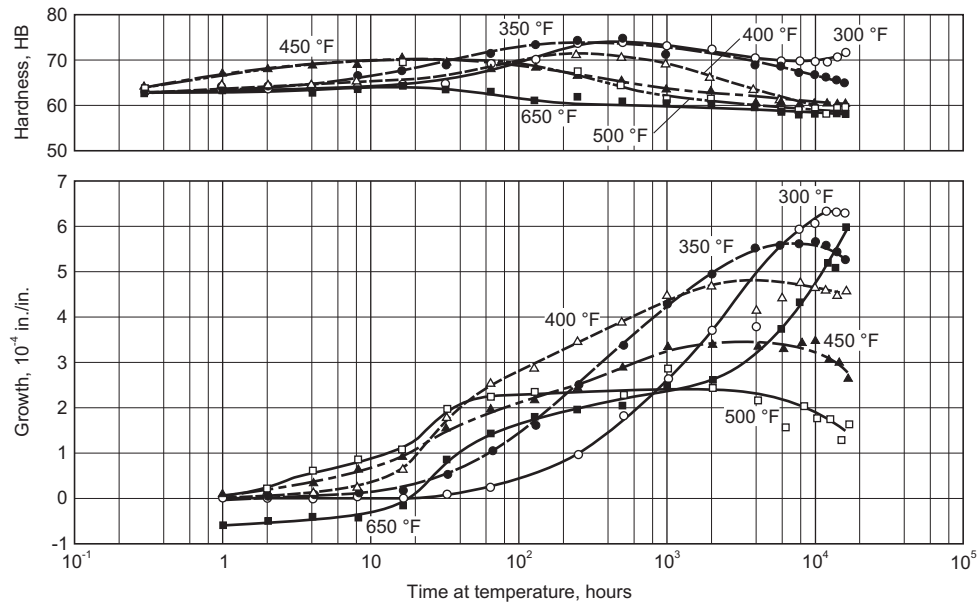


**Fig. D2.39** Growth and hardness curves for aluminum alloy 516.0-F, sand cast. Specimen: 1.125 diam  $\times$  12 in. rod

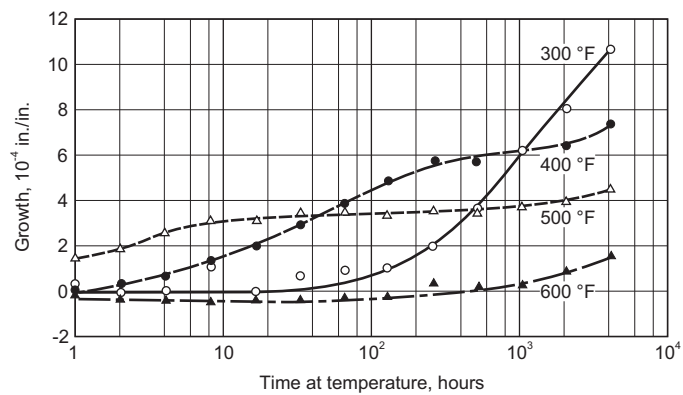


**Fig. D2.40** Growth curves for aluminum alloy 518.0-F, die cast. Specimen:  $\frac{3}{16}$  in. thick plate

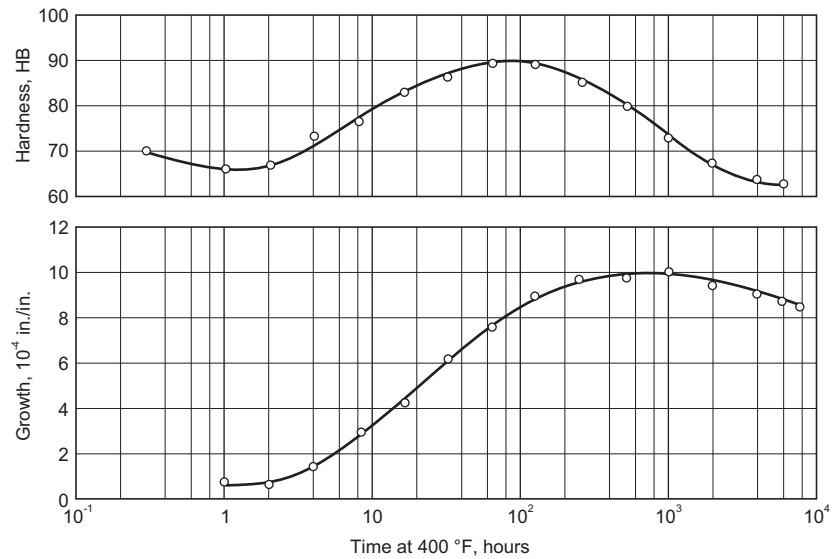


**Fig. D2.41** Growth and hardness curves for aluminum alloy 520.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

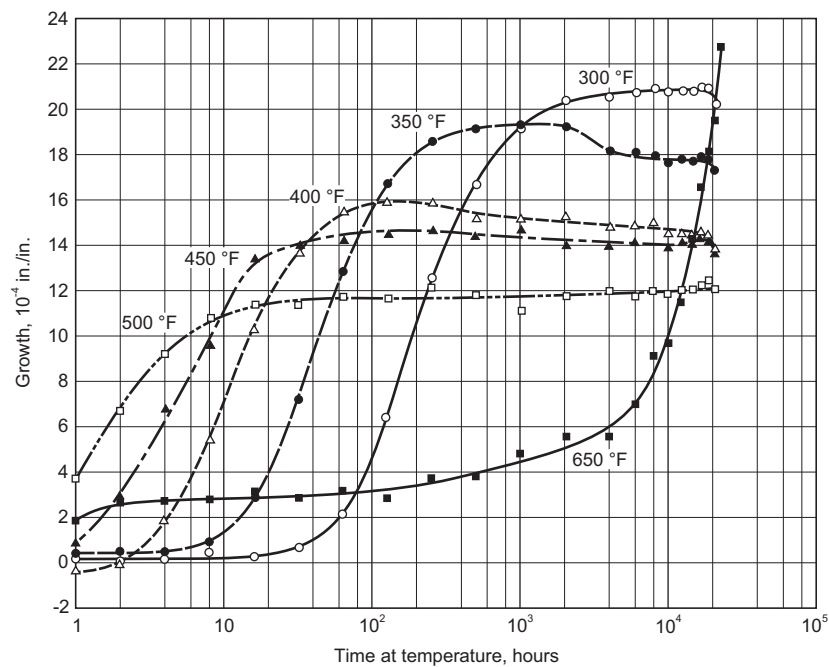


**Fig. D2.42** Growth curves for aluminum alloy 520.0-T4, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 825 °F, boiling water quench

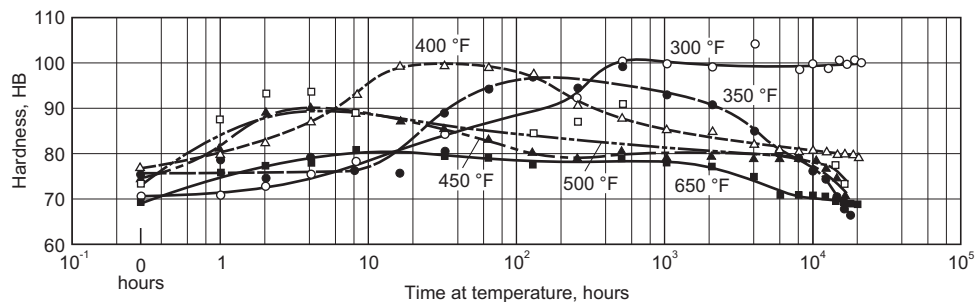


**Fig. D2.43** Hardness curves for aluminum alloy 520.0-T4, permanent mold. Hardness curve. Specimen: 1.125 diam  $\times$  12 in. rod. Treatment: 12 h at 825 °F, boiling water quench



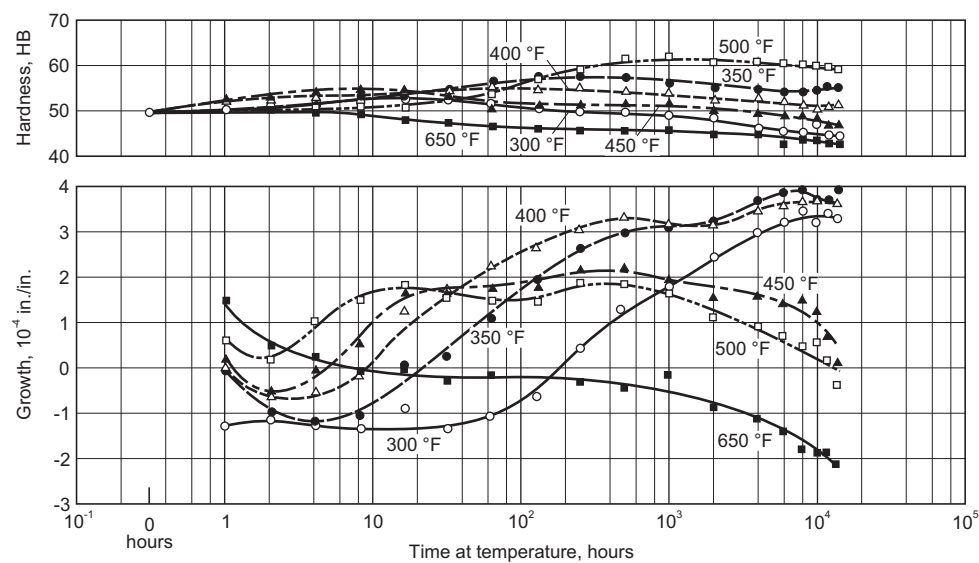


Fig. D2.44 Growth and hardness curves for aluminum alloy 850.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

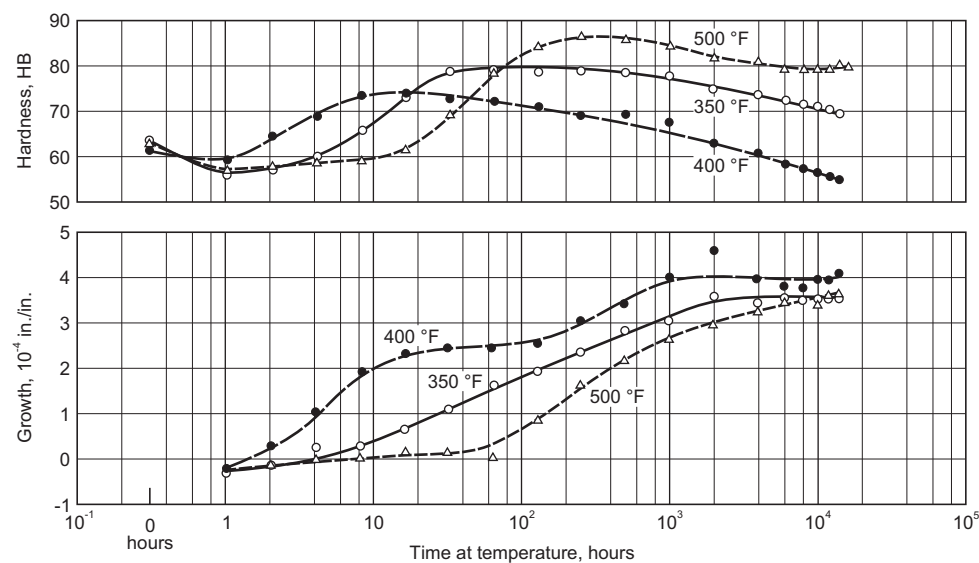


Fig. D2.45 Growth and hardness curves for aluminum alloy B850.0-F, permanent mold. Specimen: 1.125 diam  $\times$  12 in. rod

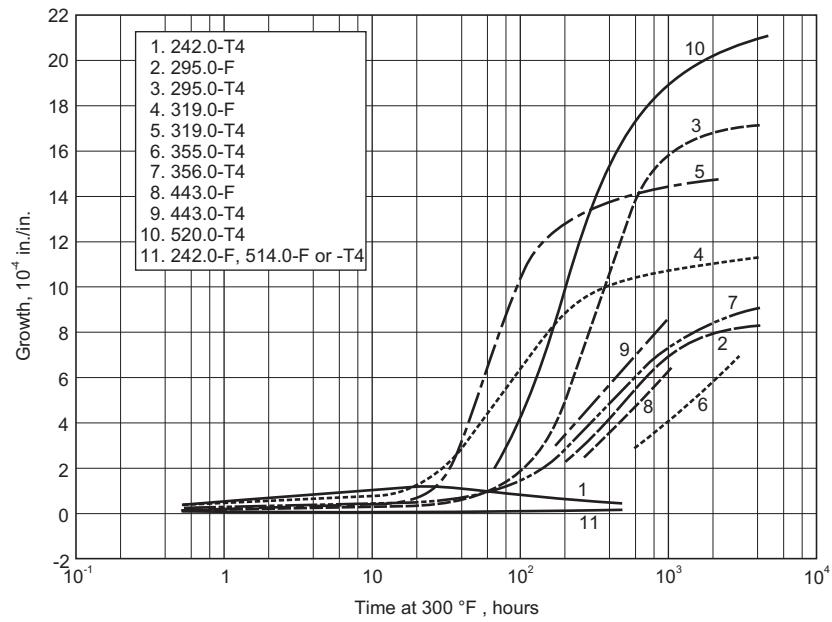


**Fig. D2.46** Summary of the growth of various casting alloys at 300 °F

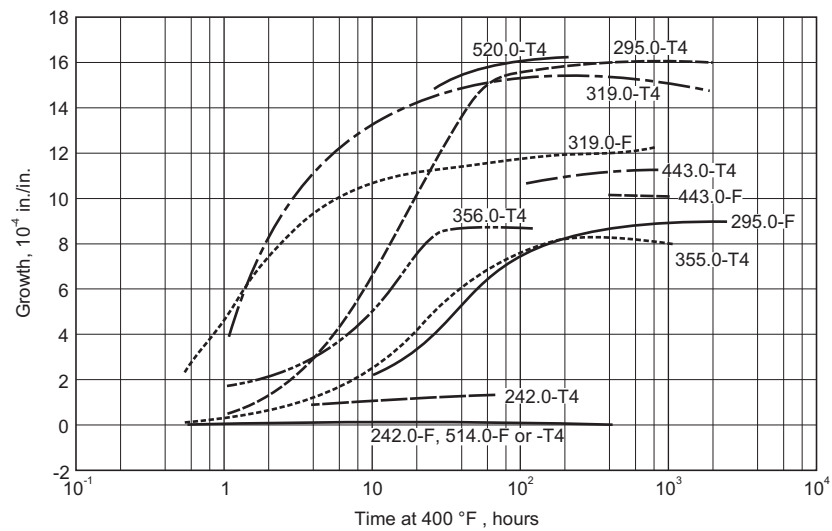


**Fig. D2.47** Summary of the growth of various casting alloys at 400 °F

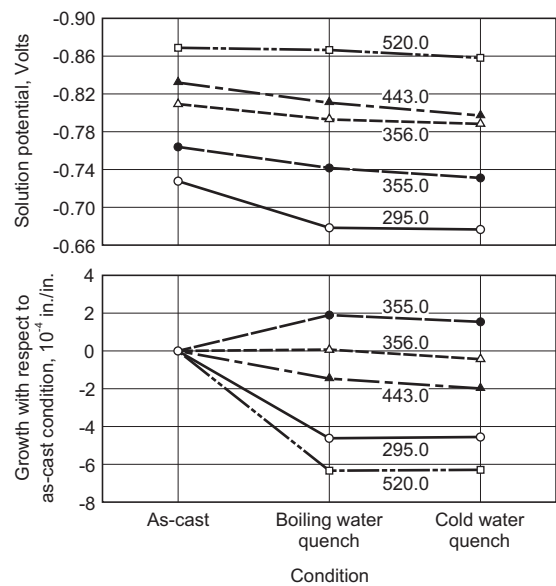


**Fig. D2.48** Changes in dimension and in solution potential that occur when chill cast specimens of five aluminum alloys were given solution heat treatment

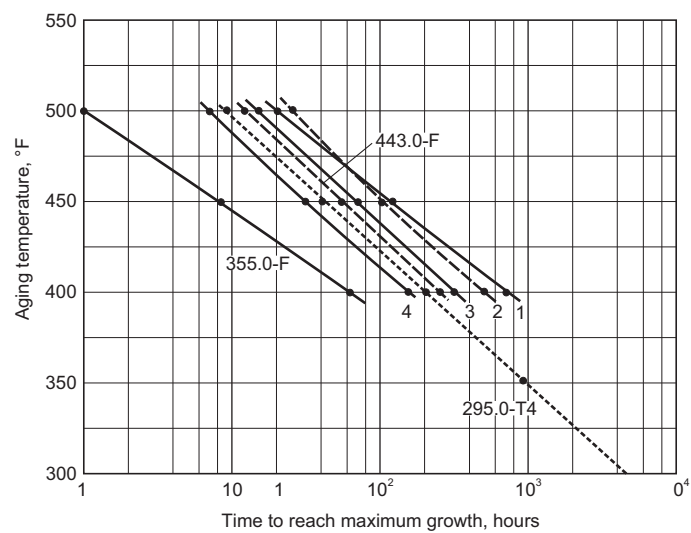


**Fig. D2.49** Relationship between aging temperature and the time to reach maximum growth. Curves 1 through 4 are all 355.0. Curve 1, 940 °F, boiling water quench; curve 2, 940 °F, cold water quench; curve 3, 1000 °F, boiling water quench; curve 4, 1000 °F, cold water quench

## DATA SET 3

# Stress-Strain Curves

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This collection of stress-strain curves is representative of the behavior of several cast alloys under tensile or compressive loads. The curves are arranged by alloy designation.

The curves are from the *Atlas of Stress-Strain Curves*, published by ASM International (Ref 1). The original source of and, when available, some background on the data are indicated on each figure.

Compressive tangent modulus curves, which represent the slope of the compressive stress-strain curve, are given for some alloys.

The effects of cyclic loading are given on several curves. The cyclic curves are constructed by connecting the points that represent the tips of stabilized hysteresis loops. The curves given indicate the occurrence of cyclic hardening.

### REFERENCE

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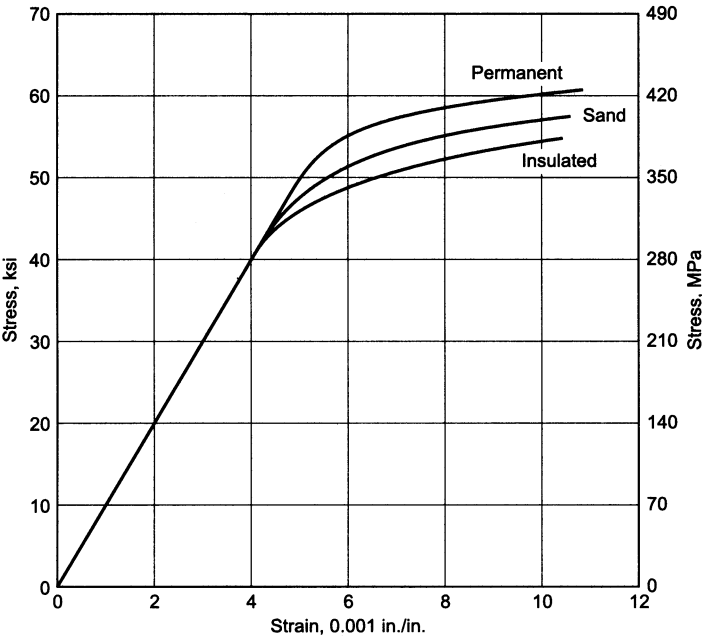


**Fig. D3.1 201.0-T6 aluminum casting, tensile stress-strain curves, various casting processes**

Effect of casting process. Heat treatment: 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 20 h at 154 °C (310 °F), air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 450 MPa (65.2 ksi); tensile yield strength, 402 MPa (58.3 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 394 MPa (57.1 ksi); tensile yield strength, 372 MPa (53.9 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 359 MPa (52.1 ksi); tensile yield strength, 349 MPa (50.6 ksi). UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 67

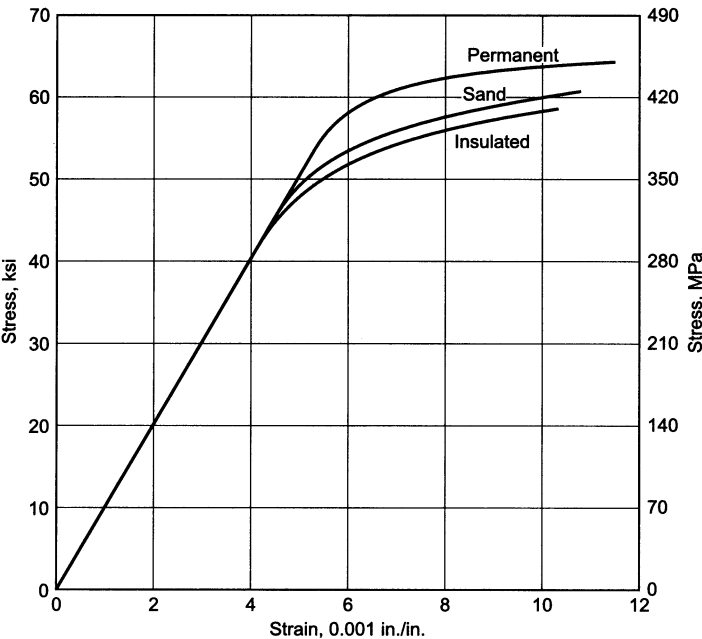


**Fig. D3.2 201.0-T6 aluminum casting, compressive stress-strain curves, various casting processes**

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 20 h at 154 °C (310 °F), air cooled. Average compressive yield strength: permanent mold castings, 433 MPa (62.8 ksi); sand castings, 396 MPa (57.5 ksi); insulated mold castings, 382 MPa (55.4 ksi). UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 67

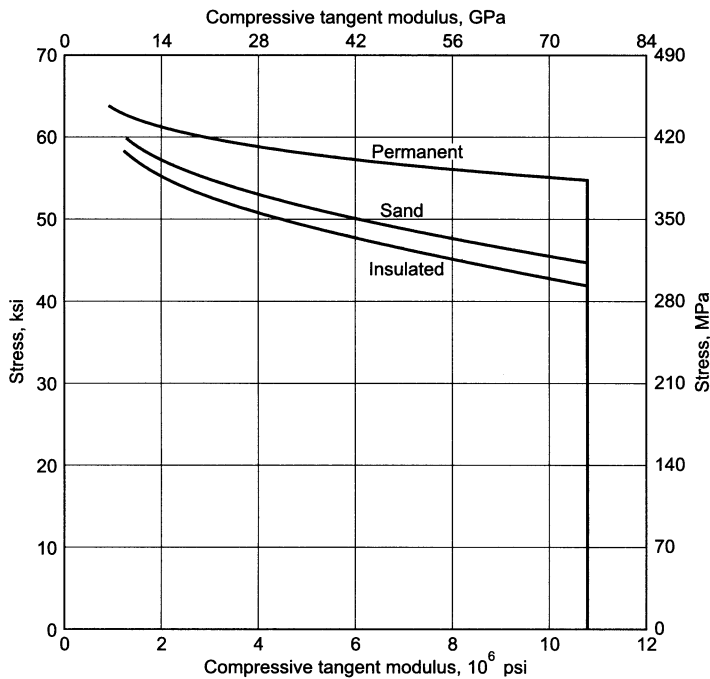


**Fig. D3.3 201.0-T6 aluminum casting, compressive tangent modulus curves, various casting processes**

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 20 h at 154 °C (310 °F), air cooled. UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 68

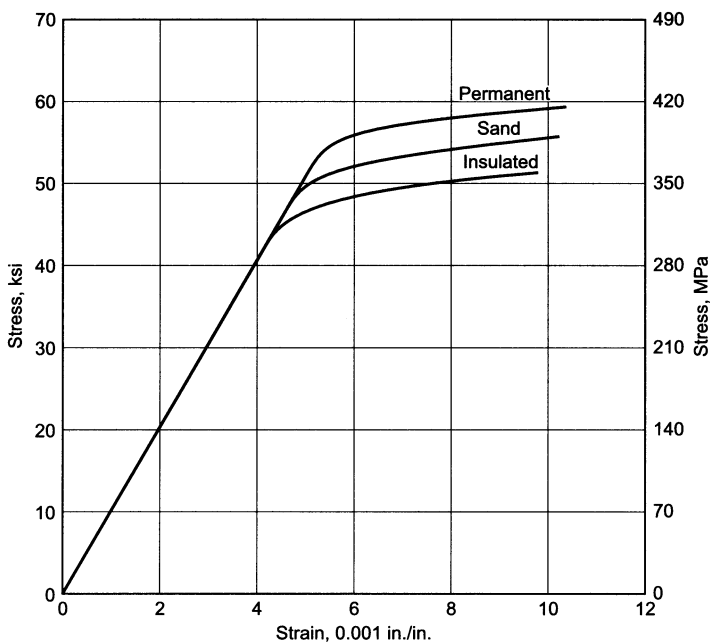


**Fig. D3.4 201.0-T7 aluminum casting, tensile stress-strain curves, various casting processes**

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 5 h at 188 °C (370 °F), air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 439 MPa (63.7 ksi); tensile yield strength, 403 MPa (58.5 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 385 MPa (55.8 ksi); tensile yield strength, 374 MPa (54.2 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 345 MPa (50.6 ksi); tensile yield strength, 344 MPa (49.9 ksi). UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 67



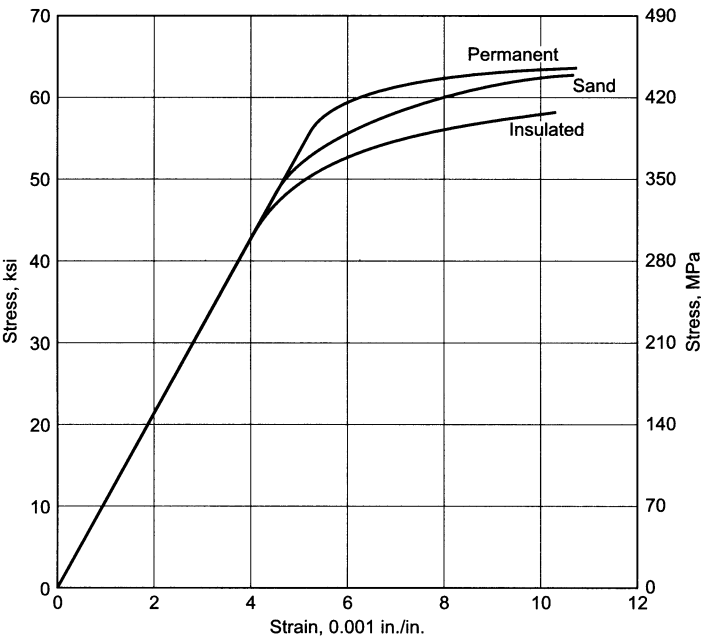


**Fig. D3.5 201.0-T7 aluminum casting, compressive stress-strain curves, various casting processes**

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 5 h at 188 °C (370 °F), air cooled. Average compressive yield strength: permanent mold castings, 429 MPa (62.2 ksi); sand castings, 407 MPa (59.1 ksi); insulated mold castings, 377 MPa (54.7 ksi). UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 67

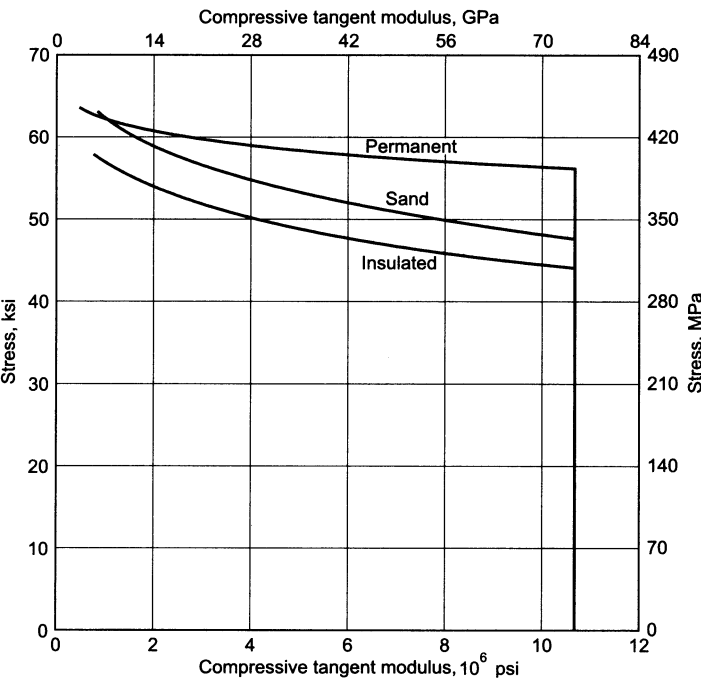


**Fig. D3.6 201.0-T7 aluminum casting, compressive tangent modulus curves, various casting processes**

Effect of casting process is illustrated. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 5 h at 188 °C (370 °F), air cooled. UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 68

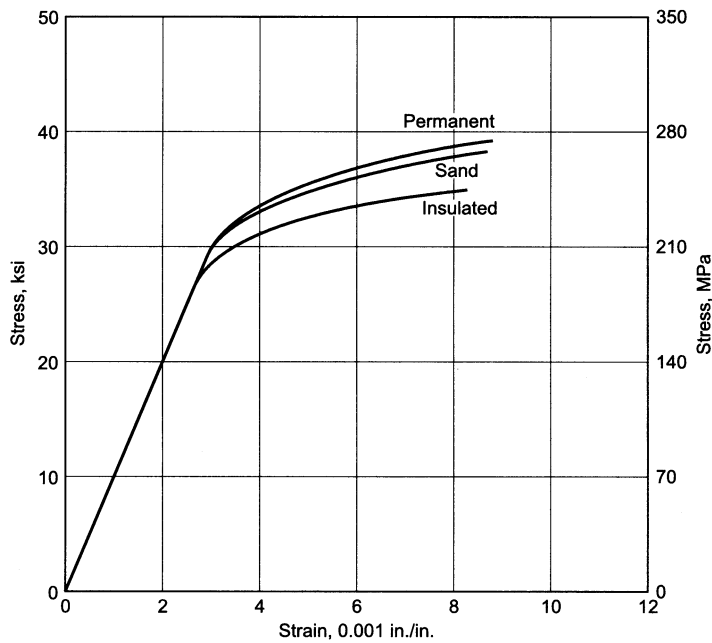


**Fig. D3.7 201.0-T43 aluminum casting, tensile stress-strain curves, various casting processes**

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 0.5 h at 154 °C (310 °F), air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 407 MPa (59.0 ksi); tensile yield strength, 250 MPa (36.2 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 356 MPa (51.7 ksi); tensile yield strength, 243 MPa (35.3 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 273 MPa (39.6 ksi); tensile yield strength, 225 MPa (32.6 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 67

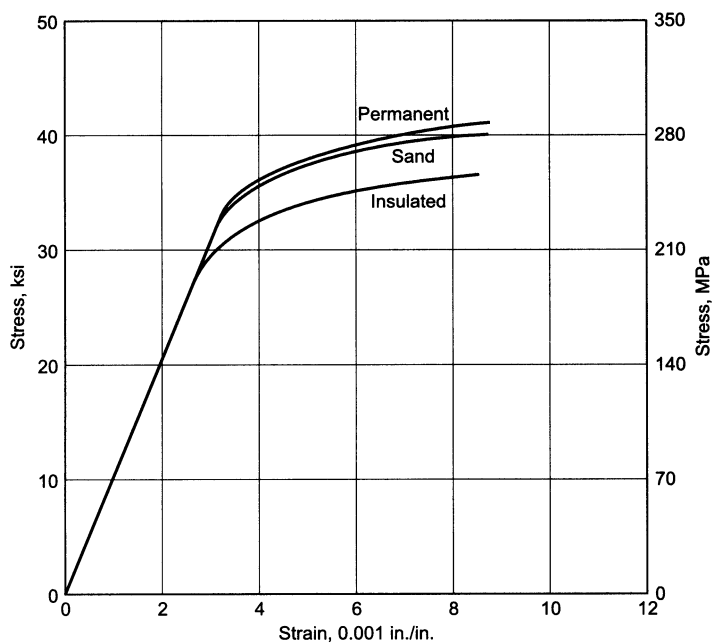


**Fig. D3.8 201.0-T43 aluminum casting, compressive stress-strain curves, various casting processes**

Effect of casting process. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 0.5 h at 154 °C (310 °F), air cooled. Average compressive yield strength: permanent mold castings, 272 MPa (39.4 ksi); sand castings, 266 MPa (38.6 ksi); insulated mold castings, 238 MPa (34.5 ksi). UNS A02010

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 67

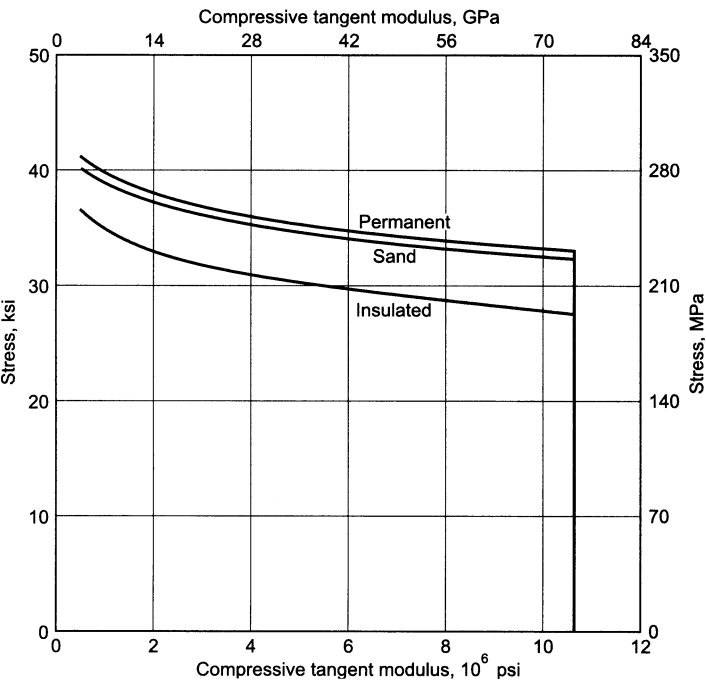


**Fig. D3.9 201.0-T43 aluminum casting, compressive tangent modulus curves, various casting processes**

Effect of casting process is illustrated. Heat treatment, 2 h at 504–521 °C (940–970 °F), 14 h at 529 °C (985 °F), water quench, 24 h at room temperature, plus 0.5 h at 154 °C (310 °F), air cooled. UNS A02010

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 68

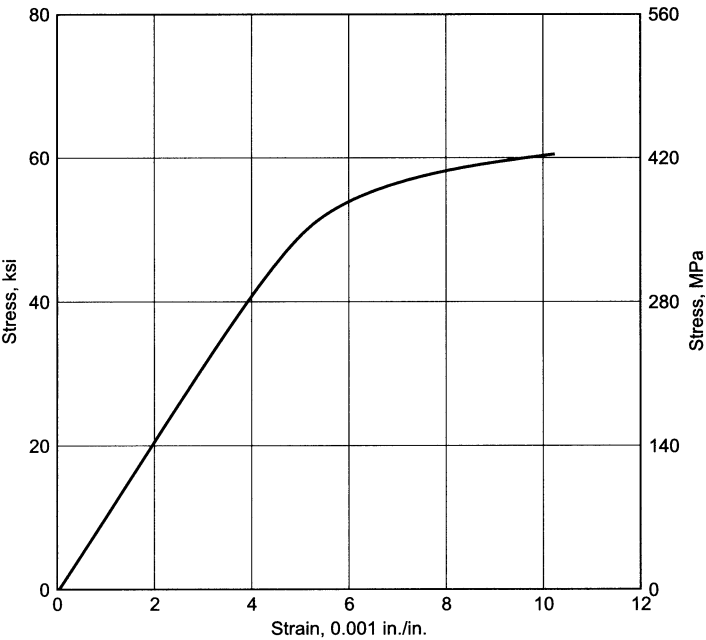


**Fig. D3.10 A201.0-T7 aluminum casting, typical tensile stress-strain curve**

Designated area, at room temperature. Ramberg-Osgood parameter,  $n(\text{tension}) = 14$ . S basis design properties (originally presented in ksi) for strength class 1 and 2, designated area within casting: ultimate tensile strength, 414 MPa (60 ksi); tensile yield strength, 345 MPa (50 ksi); compressive yield strength, 352 MPa (51 ksi). UNS A12010

Source: MIL-HDBK-5H, Dec 1998, p 3-463, 3-465

**Fig. D3.11 242.0-T5 aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic**

Al-Cu-Ni-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A02420

Source: John Deere Materials Data, Deere & Co., Moline, IL, p C13

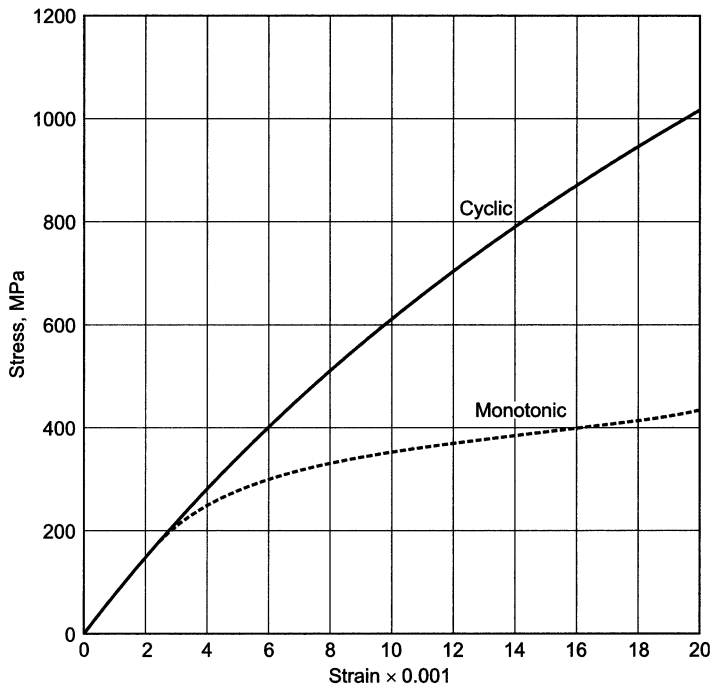
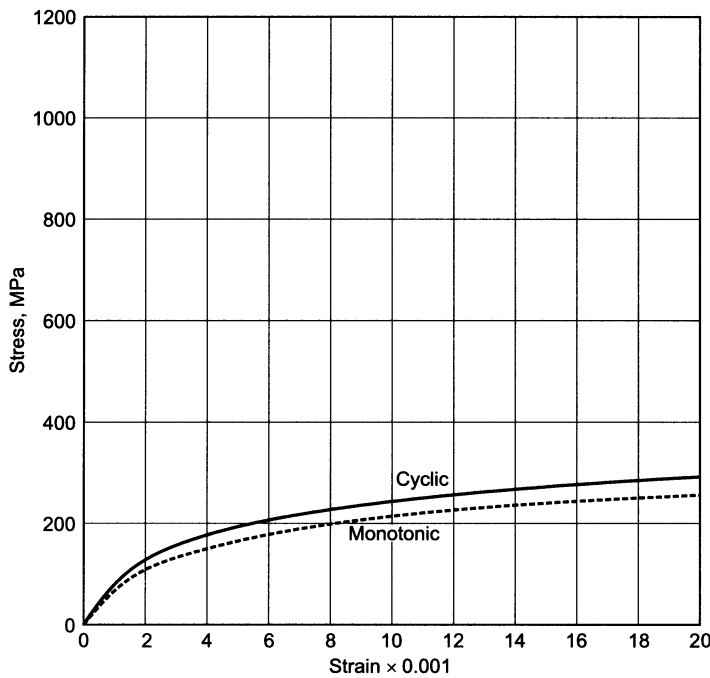


**Fig. D3.12 A332.0-T5 (PC) aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic**

Al-Si-Ni-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A13320 replaced by UNS A03360

Source: John Deere Materials Data, Deere & Co., Moline, IL, p D14



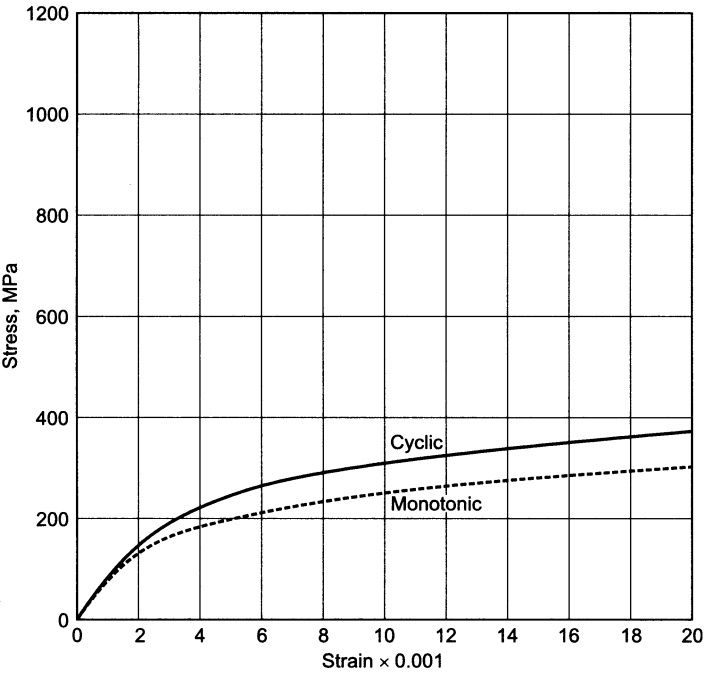


**Fig. D3.13 E332.0-T5 aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic**

Al-Si-Ni-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices

Source: John Deere Materials Data, Deere & Co., Moline, IL, p F13

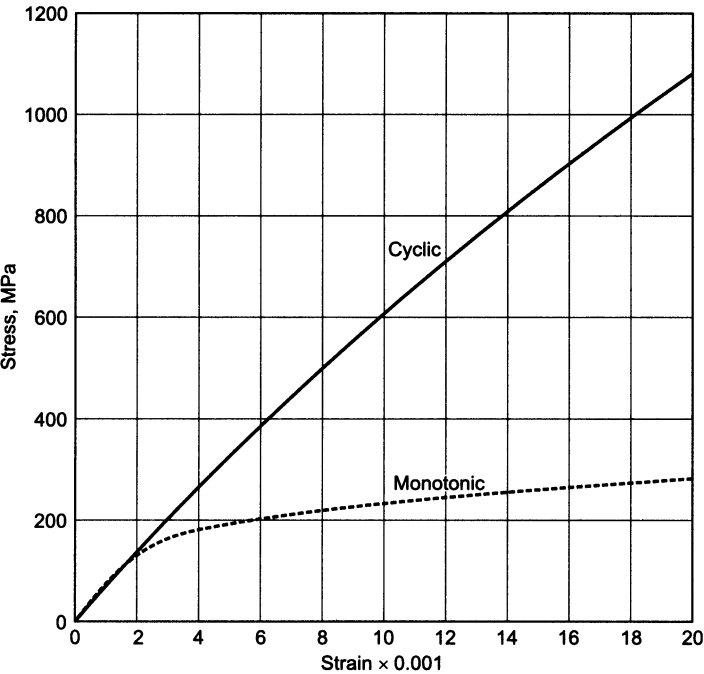


**Fig. D3.14 F332.0-T5 (SR) aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic**

Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A63320 replaced by UNS A03320

Source: John Deere Materials Data, Deere & Co., Moline, IL, p A14

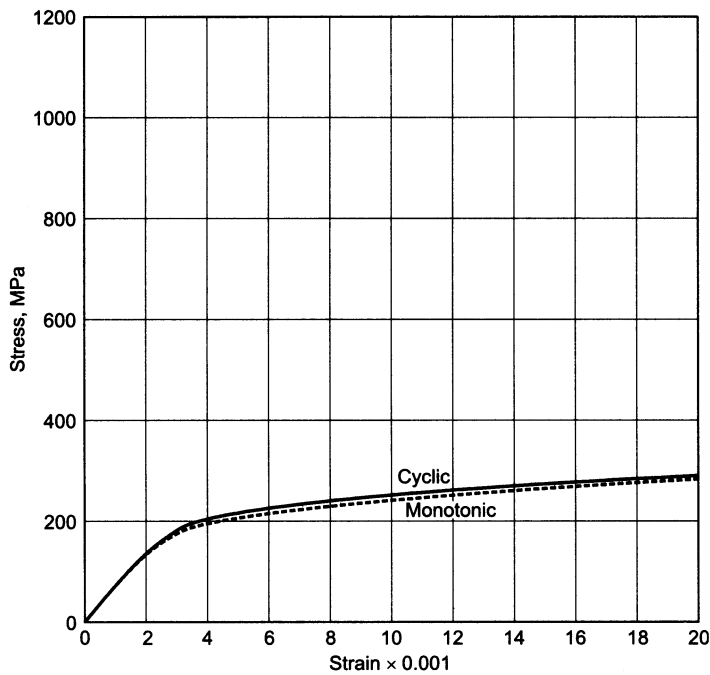


**Fig. D3.15 354.0-T5 aluminum permanent mold casting, tensile stress-strain curves, monotonic and cyclic**

354.0-T5 casting material, Al-Si-Cu-Mg system. Tested at room temperature. Reference ASTM E 466 for cyclic force-controlled constant-amplitude fatigue test practices. UNS A03540

Source: John Deere Materials Data, courtesy of Deere & Co., Moline, IL, p E12

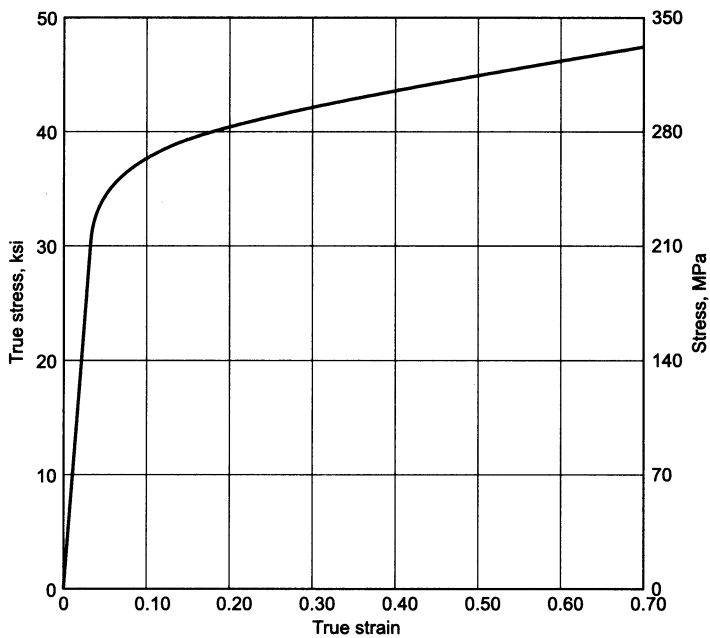


**Fig. D3.16 C355.0-T61 aluminum casting, tensile uniaxial true stress-strain curve**

Specimen size: 6.25 mm (0.250 in.) diam, 31.75 mm (1.25 in.) gage length. UNS A33550

Source: J. Mattavi, "Low Cycle Fatigue Behavior Under Biaxial Strain Distribution," TP-67-16-T, Hamilton Standard, Sept 1967. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 70



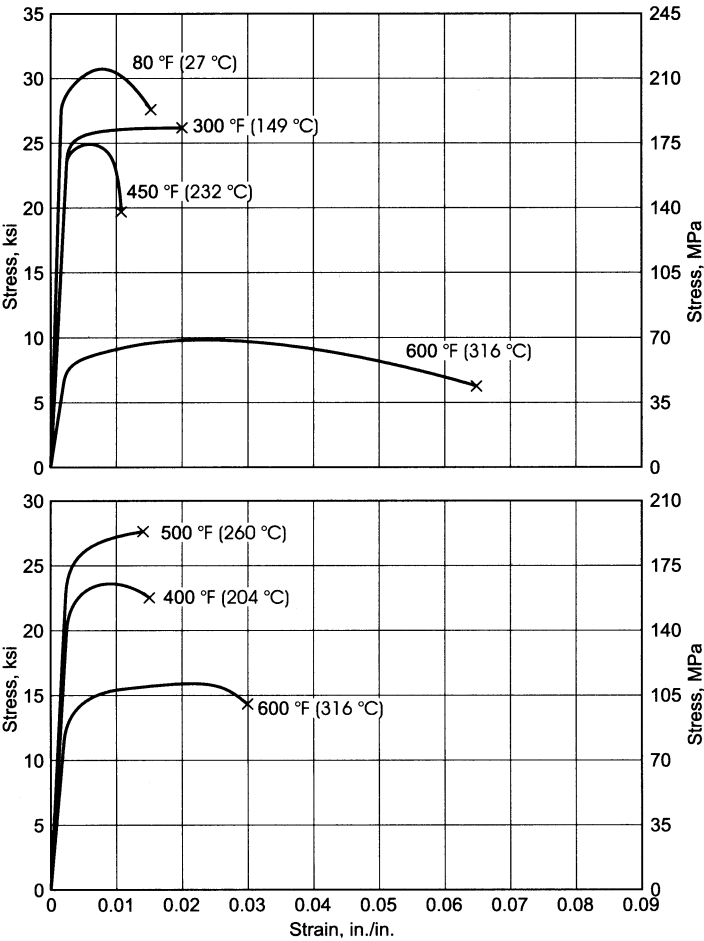


**Fig. D3.17 356.0-T6 aluminum casting, tensile stress-strain curves at several temperatures**

Effect of strain rate and temperature. Strain rate is  $1.0\text{ s}^{-1}$ . Hold times at given temperatures: 1800 s (top); 10 s (bottom). Material was solution heat treated at  $540\text{ }^{\circ}\text{C}$  ( $1000\text{ }^{\circ}\text{F}$ ), water quenched, and aged at  $154\text{ }^{\circ}\text{C}$  ( $310\text{ }^{\circ}\text{F}$ ) for 3 h. UNS A03560

Source: H.E. Dedman, E.J. Wheelan, and E.J. Kattus, "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating," WADC TR-58-440, Southern Research Institute, Part 1, Nov 1958. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 2, CINDAS/Purdue University, 1994, p 71

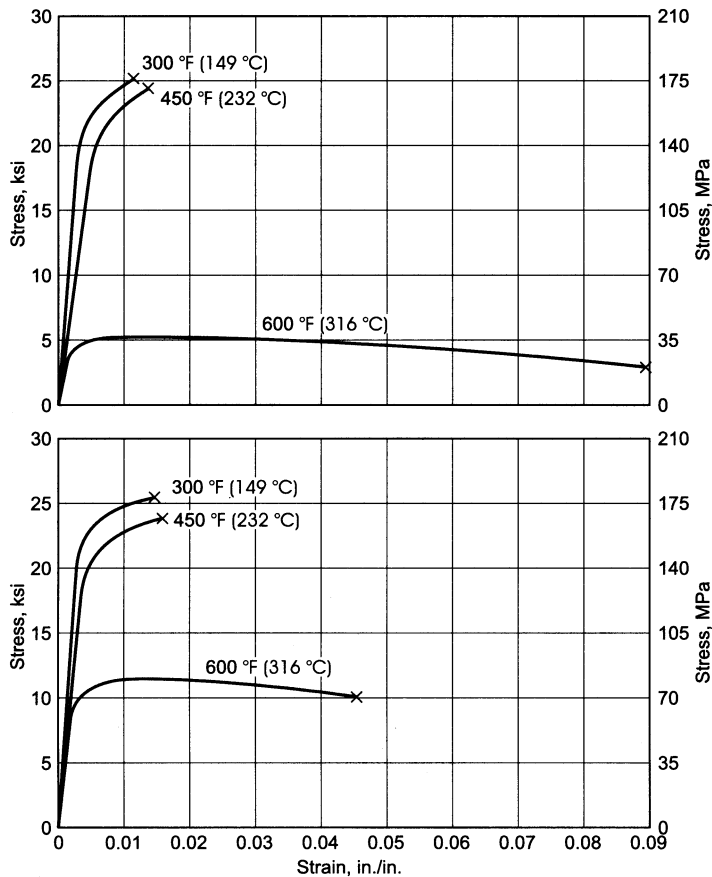


**Fig. D3.18 356.0-T6 aluminum casting, tensile stress-strain curves at several temperatures**

Effect of strain rate and temperature. Strain rate is  $0.01 \text{ s}^{-1}$ . Hold times at given temperatures: 1800 s (top); 10 s (bottom). Material was solution heat treated at  $540^\circ\text{C}$  ( $1000^\circ\text{F}$ ), water quenched, and aged at  $154^\circ\text{C}$  ( $310^\circ\text{F}$ ) for 3 h. UNS A3560

Source: H.E. Dedman, E.J. Wheelan, and E.J. Kattus, "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating," WADC TR-58-440, Southern Research Institute, Part 1, Nov 1958. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 2, CINDAS/Purdue University, 1994, p 71

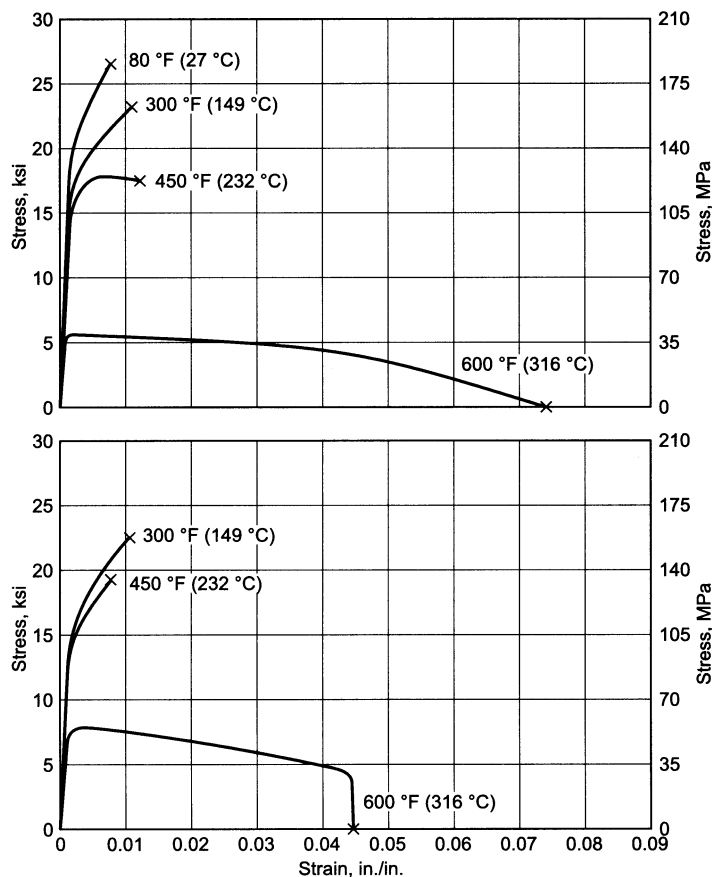


**Fig. D3.19 356.0-T6 aluminum casting, tensile stress-strain curves at several temperatures**

Effect of strain rate and temperature. Strain rate is  $0.00005 \text{ s}^{-1}$ . Hold times at given temperatures: 1800 s (top); 10 s (bottom). Material was solution heat treated at  $540^\circ\text{C}$  ( $1000^\circ\text{F}$ ), water quenched, and aged at  $154^\circ\text{C}$  ( $310^\circ\text{F}$ ) for 3 h. UNS A03560

Source: H.E. Dedman, E.J. Wheelan, and E.J. Kattus, "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating," WADC TR-58-440, Southern Research Institute, Part 1, Nov 1958. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 2, CINDAS/Purdue University, 1994, p 71

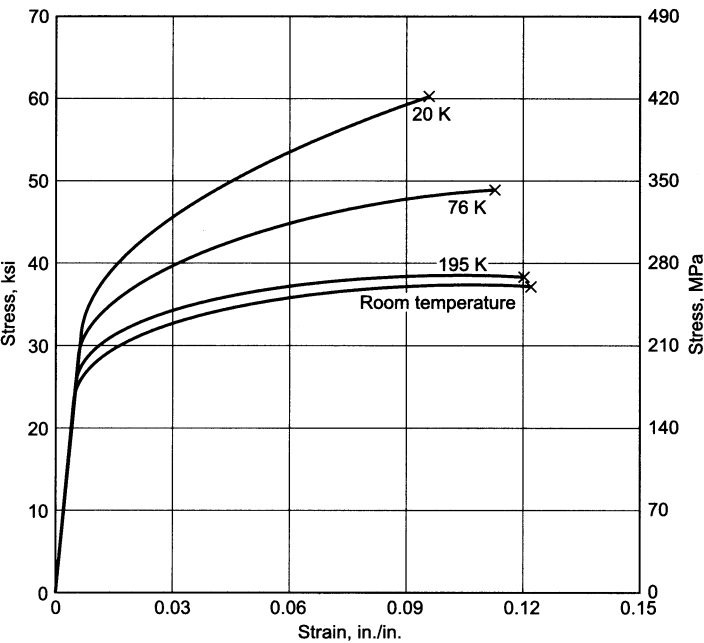


**Fig. D3.20 356.0-T6 aluminum casting, tensile stress-strain curves at low temperature**

Chill cast aluminum. Hardness, 41 HRB. UNS A03560

Source: K.A. Warren and R.P. Reed, *Tensile and Impact Properties of Selected Materials from 20 to 300 K*, Monograph 63, National Bureau of Standards, June 1963. As published in *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 70

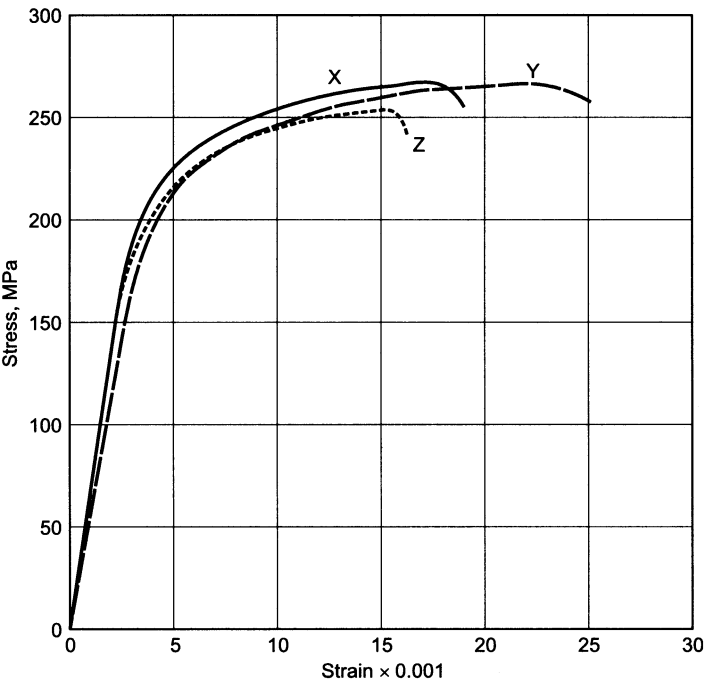


**Fig. D3.21 A356-T6 aluminum cast cylinder, monotonic tensile stress-strain curves**

Near-net-shape casting formed by pouring molten alloy, 704 °C (1300 °F) into investment molds at room temperature (X), 538 °C (1000 °F) (Y), and 982 °C (1800 °F) (Z). Three different cooling rates create different microstructures. Curves are results from one laboratory. Property values are averages from seven labs as part of a round-robin test program. Young's modulus, GPa (psi × 10<sup>6</sup>), X, 70 (10.1), Y, 70 (10.1), Z, 71 (10.3); yield strength 0.2% offset, MPa (ksi), X, 229 (33.3), Y, 224 (32.5), Z, 217 (31.5); ultimate strength MPa (ksi), X, 283 (41.1), Y, 266 (38.6), Z, 252 (36.6); strain hardening exponent (*n*), X, 0.083, Y, 0.087, Z, 0.091; strain-hardening coefficient *K*, MPa (ksi), X, 388 (56.4), Y, 397 (57.6), Z, 382 (55.4). UNS A13560

Source: *Fatigue and Fracture Toughness of A356-T6 Cast Aluminum Alloy*, R.I. Stephens, Ed., SP-760, Society of Automotive Engineers, 1988

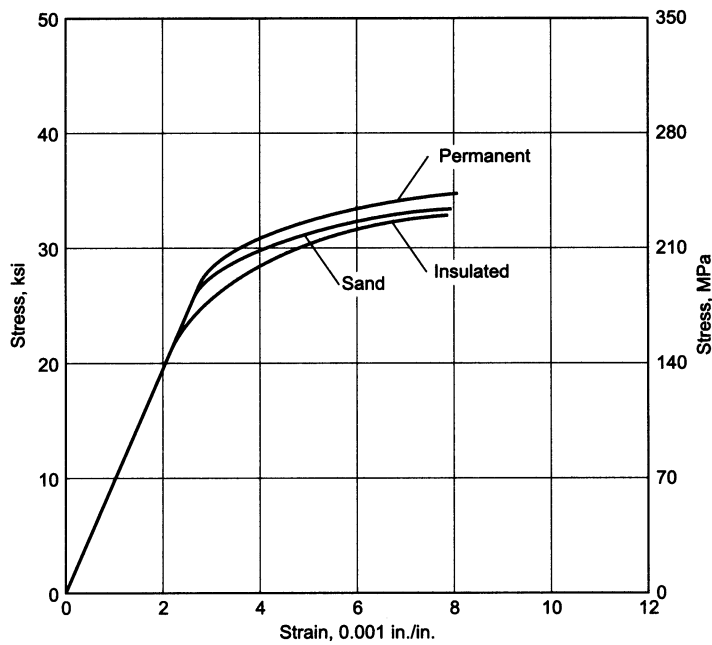


**Fig. D3.22 A356.0-T6 aluminum casting, tensile stress-strain curves, various casting processes**

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 3 h at 154 °C (310 °F), and air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 299 MPa (43.4 ksi); tensile yield strength, 215 MPa (31.2 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 253 MPa (36.7 ksi); tensile yield strength, 223 MPa (32.3 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 219 MPa (31.7 ksi); tensile yield strength, 205 MPa (29.8 ksi). UNS A13560

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 66

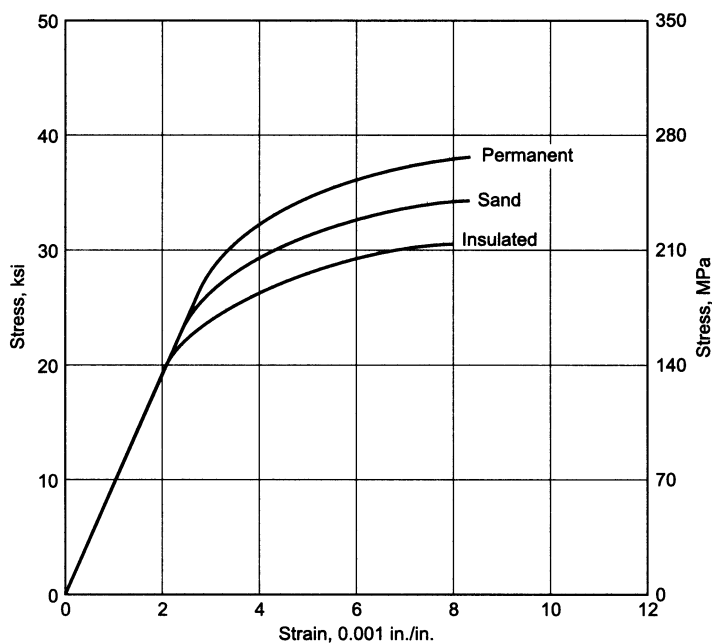


**Fig. D3.23 A356.0-T6 aluminum casting, compressive stress-strain curves, various casting processes**

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 3 h at 154 °C (310 °F), and air cooled. Average compressive yield strength: permanent mold castings, 219 MPa (31.7 ksi); sand castings, 245 MPa (35.6 ksi); insulated mold castings, 192 MPa (27.9 ksi). UNS A13560

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 66

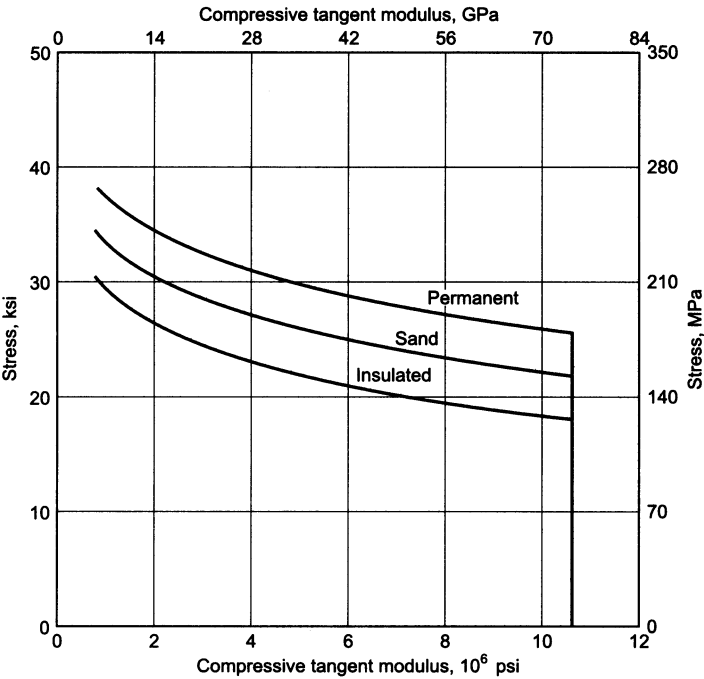


**Fig. D3.24 A356.0-T6 aluminum casting, compressive tangent modulus curves, various casting processes**

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 3 h at 154 °C (310 °F), and air cooled. UNS A13560

Source: “Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates,” Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 68

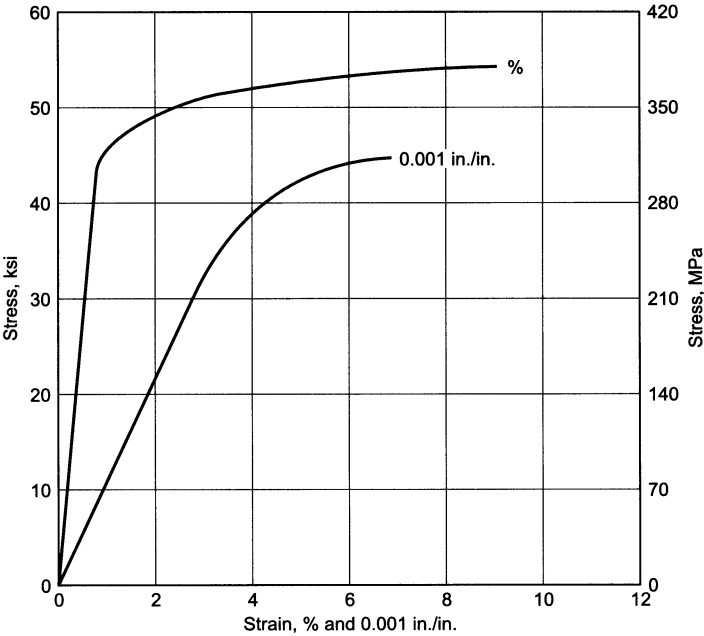


**Fig. D3.25 A357.0-T6 aluminum cast plate, tensile stress-strain curves**

Sand cast plate thickness: 6.35 mm (0.25 in.). The full range strain is given in percent (%) (top curve) and the expanded range strain is in 0.001 in./in. (bottom curve). Composition: Al-7.0Si-0.6Mg-0.1Te-Be. UNS A13570

Source: “Development: Premium Alloy Castings of Alloy A357.0-T6,” Alcoa, Pittsburgh, PA, 1971. As published in *Aerospace Structural Metals Handbook*, Vol 5, Code 3109, CINDAS/USAF CRDA Handbooks Operation, Purdue University, 1995, p 24

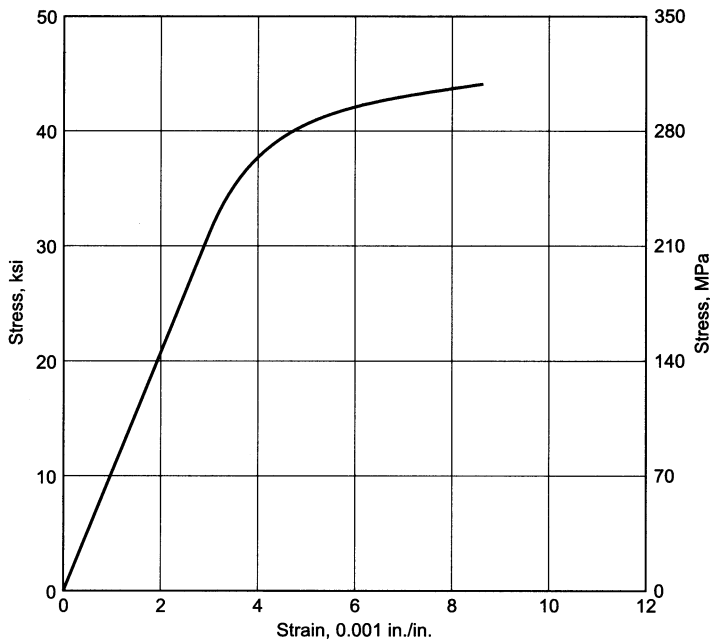


**Fig. D3.26 A357.0T6 aluminum casting, typical tensile stress-strain curve**

Class 2 alloy casting, designated area, at room temperature. Ramberg-Osgood parameter,  $n(\text{tension}) = 16$ . S basis design properties (originally presented in ksi) for strength class 2, designated area within casting: ultimate tensile strength, 345 MPa (50 ksi); tensile and compressive yield strength, 276 MPa (40 ksi). UNS A13570

Source: MIL-HDBK-5H, Dec 1998, p 3-485, 3-486

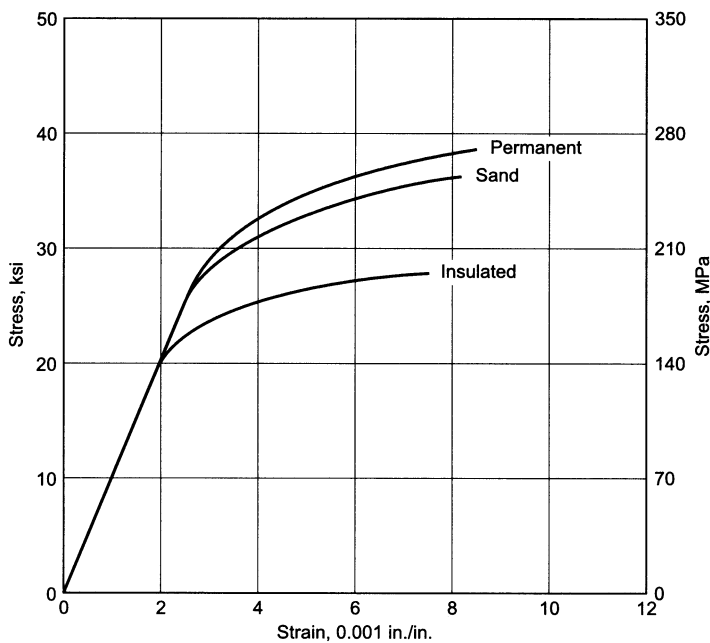


**Fig. D3.27 A357.0-T6 aluminum casting, tensile stress-strain curves, various casting processes**

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 5 h at 177 °C (350 °F), and air cooled. Average mechanical properties for permanent mold castings: ultimate tensile strength, 316 MPa (45.8 ksi); tensile yield strength, 243 MPa (35.2 ksi). Average mechanical properties for sand castings: ultimate tensile strength, 268 MPa (38.9 ksi); tensile yield strength, 229 MPa (33.2 ksi). Average mechanical properties for insulated mold castings: ultimate tensile strength, 179 MPa (26.0 ksi); tensile yield strength, 179 MPa (26.0 ksi). UNS A13570

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 66



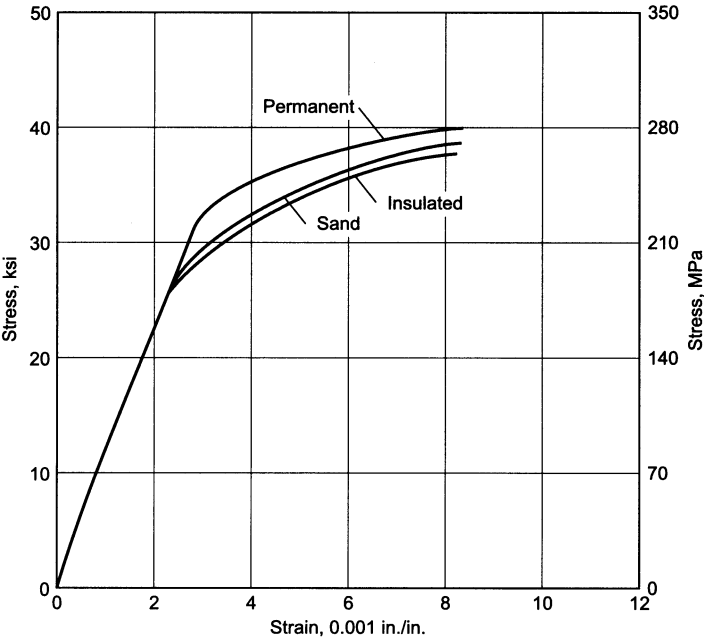


**Fig. D3.28 A357.0-T6 aluminum casting, compressive stress-strain curves, various casting processes**

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 5 h at 177 °C (350 °F), and air cooled. Average compressive yield strength: permanent mold castings, 256 MPa (37.2 ksi); sand castings, 240 MPa (34.8 ksi); insulated mold castings, 232 MPa (33.7 ksi). UNS A13570

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 66

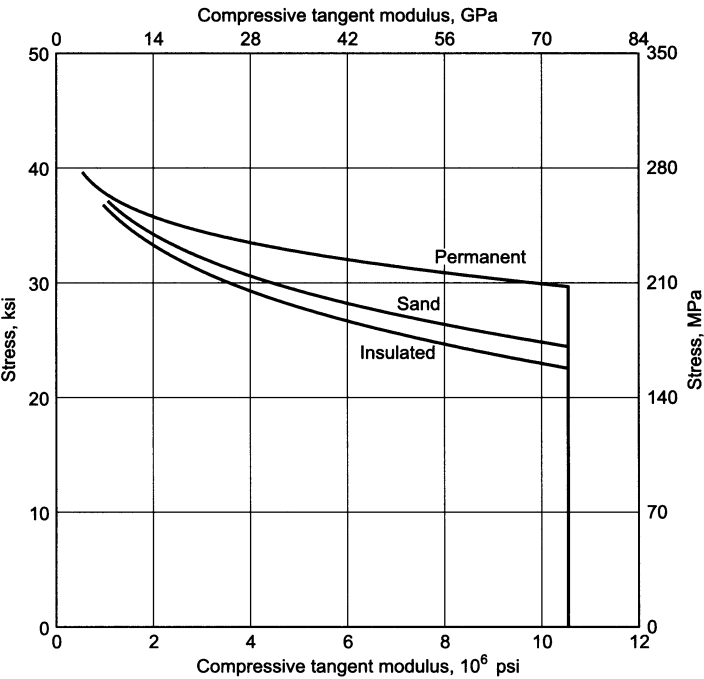


**Fig. D3.29 A357.0-T6 aluminum casting, compressive tangent modulus curves, various casting processes**

Effect of molding process. Heat treatment, 12 h at 538 °C (1000 °F), water quench, 12–24 h delay at room temperature, 5 h at 177 °C (350 °F), and air cooled. UNS A13570

Source: "Mechanical Properties of Premium Aluminum Casting Alloys with Various Cooling Rates," Olin Corp., Jan 1973. As published in Cast Aluminum Section, *Structural Alloys Handbook*, Vol 3, CINDAS/Purdue University, 1994, p 24, 68

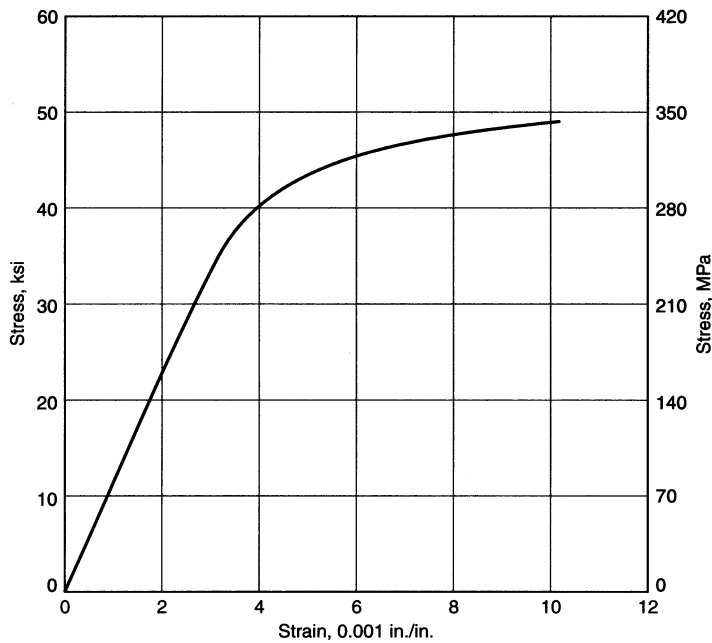


**Fig. D3.30 A357.0-T6 aluminum cast plate, compressive stress-strain curve**

Sand cast plate thickness: 6.35 mm (0.25 in.). Composition: Al-7.0Si-0.6Mg-0.1Te-Be. UNS A13570

Source: "Development: Premium Alloy Castings of Alloy A357.0-T6," Alcoa, Pittsburgh, PA, 1971. As published in *Aerospace Structural Metals Handbook*, Vol 5, Code 3109, CINDAS/USAF CRDA Handbooks Operation, Purdue University, 1995, p 29

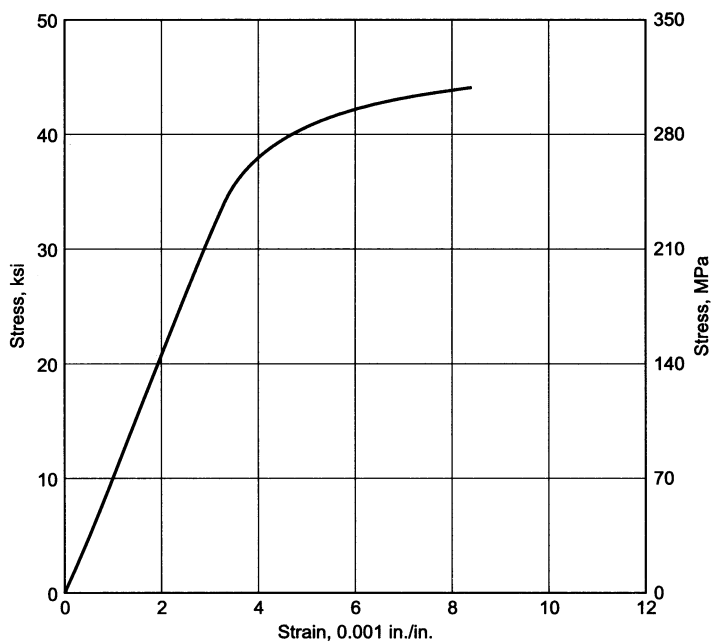


**Fig. D3.31 D357.0-T6 aluminum casting, typical tensile stress-strain curve**

Designated area, at room temperature. Ramberg-Osgood parameter,  $n(\text{tension}) = 16$ . B basis design properties (originally presented in ksi) for designated area within casting: ultimate tensile strength, 338 MPa (49 ksi); tensile and compressive yield strength, 285 MPa (41 ksi). UNS A43570

Source: *MIL-HDBK-5H*, Dec 1998, p 3-488, 3-489



## DATA SET 4

# Tensile Properties at High and Low Temperatures and at Room Temperature after High-Temperature Exposure

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This data set contains the results of uniaxial tensile tests of a wide range of aluminum casting alloys conducted at:

- High temperatures from 212 to 700 °F (100 to 370 °C) after various holding times at the testing temperature
- Subzero temperatures from –452 to –18 °F (–269 to –28 °C) after one-half hour at the testing temperature (holding time at subzero temperatures has no effect on properties)
- Room temperature after holding at high temperatures from 212 to 700 °F (100 to 370 °C)

These data were developed at the Alcoa Research Laboratories in New Kensington, PA, over the period of years from 1950 to the present time. The early generation and analysis of the data was led by Kenneth O. Bogardus and Robert C. Malcolm, Jr., with principal testing support from Robert C. Faulk and George Schofield. In more recent years, the activity has been led by Robert J. Bucci and Daniel Lege. Most of the data included here were originally published in Ref 1, although some additional data have been added for this publication.

The tensile tests were made in accordance with ASTM E 8 and E 21, with 0.5 in. (12.5 mm) diam tensile specimens per Appendix 3, Fig. A3.1. In most cases, the specimens were as-cast test bars. Yield strengths were measured at 0.2% offset using autographic extensometers; in the tests at high and low temperatures, the extensometers were used in conjunction with strain-transfer devices.

In the case of tests made at subzero temperatures, the low temperatures were achieved by immersion of the specimens in the following liquids for one-half hour prior to and during the tests:

- –18 °F (–28 °C), dry ice and alcohol
- –112 °F (–80 °C), liquefied petroleum gas
- –320 °F (–196 °C), liquefied nitrogen
- –452 °F (–269 °C), liquefied helium

In most cases, tests were made of several lots of material of each alloy and temper. The results for the several lots were then analyzed together graphically and statistically, and the averages normalized to the room-temperature typical values; in these cases, the values are identified as “typical values” in the table. In some cases, too few data, perhaps only for a single lot, were available, and so these are reported as “representative” values (raw data) rather than as typical values.

## REFERENCES

1. J.G. Kaufman, Ed., *Properties of Aluminum Alloys: Tensile, Creep and Fatigue Data at High and Low Temperatures*, ASM International, 1999
2. J.H. Belton, L.L. Godby, and B.L. Taft, *Materials for Use at Liquid Hydrogen Temperature*, STP 287, ASTM, 1960

Table D4.1 201.0-T7 Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     | At room temperature after heating |     |                  |     |                |     |                     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|-----------------------------------|-----|------------------|-----|----------------|-----|---------------------|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a)          |     | Tensile strength |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi               | GPa | ksi              | MPa | ksi            | MPa |                     |
| -452        | -269 | ...                    | 93                       | 640 | 81             | 560 | 7                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
| -423        | -253 | ...                    | 93                       | 640 | 79             | 545 | 8                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
| -320        | -196 | ...                    | 89                       | 615 | 67             | 460 | 8                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
| -112        | -80  | ...                    | 77                       | 530 | 70             | 485 | 6                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
| -18         | -28  | ...                    | 74                       | 510 | 87             | 600 | 6                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
| 75          | 25   | ...                    | 72                       | 495 | 65             | 450 | 6                   | 10.3                              | 71  | 72               | 495 | 65             | 450 | 6                   |
| 300         | 150  | 100                    | 64                       | 440 | 57             | 395 | 9                   | ...                               | ... | 72               | 495 | 65             | 450 | 6                   |
|             |      | 1,000                  | 60                       | 415 | 54             | 370 | 10                  | ...                               | ... | 70               | 485 | 61             | 420 | 6                   |
|             |      | 10,000                 | 58                       | 400 | 52             | 360 | 6                   | ...                               | ... | 68               | 470 | 58             | 400 | 4                   |
| 350         | 177  | 100                    | 54                       | 370 | 49             | 340 | 10                  | ...                               | ... | 68               | 470 | 61             | 420 | 4                   |
|             |      | 1,000                  | 51                       | 350 | 46             | 315 | 8                   | ...                               | ... | 63               | 435 | 57             | 395 | 4                   |
|             |      | 10,000                 | 43                       | 295 | 37             | 255 | 9                   | ...                               | ... | 58               | 400 | 45             | 310 | 6                   |
| 400         | 205  | 100                    | 48                       | 330 | 42             | 290 | 10                  | ...                               | ... | 66               | 455 | 58             | 400 | 5                   |
|             |      | 1,000                  | 39                       | 270 | 33             | 230 | 16                  | ...                               | ... | 55               | 380 | 44             | 305 | 4                   |
|             |      | 10,000                 | 24                       | 165 | 18             | 125 | 25                  | ...                               | ... | 41               | 285 | 22             | 150 | 12                  |
| 450         | 230  | 1,000                  | 22                       | 150 | 15             | 105 | 25                  | ...                               | ... | 41               | 285 | 22             | 150 | 12                  |
|             |      | 10,000                 | 19                       | 130 | 13             | 90  | 25                  | ...                               | ... | 37               | 255 | 18             | 125 | 13                  |
| 500         | 260  | 1,000                  | 16                       | 110 | 13             | 90  | 25                  | ...                               | ... | 38               | 260 | 20             | 140 | 12                  |
|             |      | 10,000                 | 14                       | 95  | 10             | 70  | 32                  | ...                               | ... | 34               | 235 | 17             | 115 | 11                  |
| 600         | 315  | 1,000                  | 9.0                      | 62  | 8.0            | 55  | 48                  | ...                               | ... | 34               | 235 | 14             | 95  | 12                  |
|             |      | 10,000                 | 8.0                      | 55  | 6.0            | 41  | 51                  | ...                               | ... | 29               | 200 | 11             | 75  | 13                  |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.2 224.0-T7 Sand and permanent mold castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                     | At room temperature after heating |     |                  |     |                |     |                     |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|---------------------|-----------------------------------|-----|------------------|-----|----------------|-----|---------------------|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a)          |     | Tensile strength |     | Yield strength |     | Elongation in 4D, % |
| F           | °C  |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi               | GPa | ksi              | MPa | ksi            | MPa |                     |
| 75          | 25  | ...                    | 61                       | 420 | 48             | 330 | 4                   | 10.5                              | 72  | 61               | 420 | 48             | 330 | 4                   |
|             |     | 0.1                    | 53                       | 365 | 42             | 290 | 7                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 0.5                    | 53                       | 365 | 41             | 285 | 7                   | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 100                    | 53                       | 365 | 41             | 285 | 5                   | ...                               | ... | 62               | 425 | 49             | 340 | 4                   |
|             |     | 1,000                  | 53                       | 365 | 38             | 260 | 6                   | ...                               | ... | 61               | 420 | 44             | 305 | 4                   |
| 300         | 150 | 10,000                 | 49                       | 340 | 37             | 255 | 5                   | ...                               | ... | 61               | 420 | 42             | 290 | 5                   |
|             |     | 0.1                    | 48                       | 330 | 41             | 285 | 10                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 0.5                    | 48                       | 330 | 41             | 285 | 10                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 100                    | 47                       | 325 | 37             | 255 | 7                   | ...                               | ... | 63               | 435 | 45             | 310 | 5                   |
|             |     | 1,000                  | 43                       | 295 | 32             | 220 | 11                  | ...                               | ... | 58               | 400 | 38             | 260 | 5                   |
| 350         | 177 | 10,000                 | 43                       | 295 | 31             | 215 | 10                  | ...                               | ... | 55               | 380 | 38             | 260 | 4                   |
|             |     | 0.1                    | 43                       | 295 | 37             | 255 | 14                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 0.5                    | 42                       | 290 | 36             | 250 | 14                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 100                    | 41                       | 285 | 30             | 205 | 10                  | ...                               | ... | 60               | 415 | 42             | 290 | 5                   |
|             |     | 1,000                  | 39                       | 270 | 28             | 195 | 11                  | ...                               | ... | 57               | 395 | 37             | 255 | 5                   |
| 400         | 205 | 10,000                 | 38                       | 260 | 28             | 195 | 10                  | ...                               | ... | 55               | 380 | 37             | 255 | 5                   |
|             |     | 0.1                    | 35                       | 240 | 30             | 205 | 16                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 0.5                    | 35                       | 240 | 29             | 200 | 16                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 100                    | 34                       | 235 | 23             | 160 | 13                  | ...                               | ... | 55               | 380 | 31             | 215 | 7                   |
|             |     | 1,000                  | 34                       | 235 | 23             | 160 | 12                  | ...                               | ... | 54               | 370 | 30             | 205 | 6                   |
| 450         | 230 | 10,000                 | 34                       | 235 | 23             | 160 | 10                  | ...                               | ... | 54               | 370 | 30             | 205 | 6                   |
|             |     | 0.1                    | 31                       | 215 | 25             | 170 | 18                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 0.5                    | 31                       | 215 | 24             | 165 | 18                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 100                    | 31                       | 215 | 20             | 140 | 13                  | ...                               | ... | 54               | 370 | 30             | 205 | 7                   |
|             |     | 1,000                  | 31                       | 215 | 20             | 140 | 10                  | ...                               | ... | 54               | 370 | 29             | 200 | 7                   |
| 500         | 260 | 10,000                 | 31                       | 215 | 20             | 140 | 9                   | ...                               | ... | 53               | 365 | 29             | 200 | 6                   |
|             |     | 0.1                    | 22                       | 150 | 18             | 125 | 20                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 0.5                    | 22                       | 150 | 18             | 125 | 20                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |
|             |     | 100                    | 23                       | 160 | 16             | 110 | 11                  | ...                               | ... | 51               | 350 | 28             | 195 | 6                   |
|             |     | 1,000                  | 23                       | 160 | 15             | 105 | 11                  | ...                               | ... | 50               | 345 | 27             | 185 | 6                   |
| 600         | 315 | 5,000                  | 21                       | 145 | 15             | 105 | 11                  | ...                               | ... | 47               | 325 | 26             | 180 | 5                   |
|             |     | 100                    | 23                       | 160 | 16             | 110 | 11                  | ...                               | ... | 51               | 350 | 28             | 195 | 6                   |
|             |     | 1,000                  | 23                       | 160 | 15             | 105 | 11                  | ...                               | ... | 50               | 345 | 27             | 185 | 6                   |
|             |     | 5,000                  | 21                       | 145 | 15             | 105 | 11                  | ...                               | ... | 47               | 325 | 26             | 180 | 5                   |
|             |     | 1,000                  | 6.5                      | 45  | 6.0            | 41  | 46                  | ...                               | ... | ...              | ... | ...            | ... | ...                 |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.3 240.0-F Sand castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                     |                          |     | At room temperature after heating |     |                |     |                     |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|---------------------|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                     |
| 75          | 25  | ...                    | 34                       | 235 | 29             | 200 | 1                   | 11.2                     | 77  | 34                                | 235 | 29             | 200 | 1                   |
| 212         | 100 | 0.5                    | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 10                     | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 100                    | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 1,000                  | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 10,000                 | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
| 300         | 150 | 0.5                    | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 10                     | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 100                    | 34                       | 235 | 29             | 200 | 1                   | ...                      | ... | 34                                | 235 | 30             | 207 | 1                   |
|             |     | 1,000                  | 34                       | 235 | 30             | 205 | 1                   | ...                      | ... | 34                                | 235 | 31             | 215 | 1                   |
|             |     | 10,000                 | 34                       | 235 | 30             | 205 | 1                   | ...                      | ... | 34                                | 235 | 31             | 215 | 1                   |
| 400         | 205 | 0.5                    | 33                       | 230 | 27             | 185 | 1                   | ...                      | ... | 34                                | 235 | 29             | 200 | 1                   |
|             |     | 10                     | 34                       | 235 | 30             | 205 | 1                   | ...                      | ... | 35                                | 240 | 31             | 215 | 1                   |
|             |     | 100                    | 35                       | 240 | 29             | 200 | 1                   | ...                      | ... | 36                                | 250 | 31             | 215 | 1                   |
|             |     | 1,000                  | 34                       | 235 | 27             | 185 | 1                   | ...                      | ... | 36                                | 250 | 29             | 200 | 1                   |
|             |     | 10,000                 | 33                       | 230 | 25             | 170 | 1                   | ...                      | ... | 35                                | 240 | 27             | 185 | 1                   |
| 500         | 260 | 0.5                    | 31                       | 215 | 24             | 165 | 1                   | ...                      | ... | 34                                | 235 | 30             | 205 | 1                   |
|             |     | 10                     | 30                       | 205 | 20             | 140 | 1.5                 | ...                      | ... | 34                                | 235 | 28             | 195 | 1                   |
|             |     | 100                    | 28                       | 195 | 19             | 130 | 2.5                 | ...                      | ... | 34                                | 235 | 26             | 180 | 1                   |
|             |     | 1,000                  | 27                       | 185 | 18             | 125 | 3                   | ...                      | ... | 35                                | 240 | 24             | 165 | 1                   |
|             |     | 10,000                 | 26                       | 180 | 16             | 110 | 4                   | ...                      | ... | 35                                | 240 | 23             | 160 | 1                   |
| 600         | 315 | 0.5                    | 21                       | 145 | 16             | 110 | 25                  | ...                      | ... | 31                                | 215 | 26             | 180 | 1                   |
|             |     | 10                     | 21                       | 145 | 16             | 110 | 25                  | ...                      | ... | 30                                | 205 | 25             | 170 | 1                   |
|             |     | 100                    | 20                       | 140 | 15             | 105 | 25                  | ...                      | ... | 29                                | 200 | 23             | 160 | 1                   |
|             |     | 1,000                  | 19                       | 130 | 13             | 90  | 26                  | ...                      | ... | 28                                | 195 | 22             | 150 | 1                   |
|             |     | 10,000                 | 17                       | 115 | 12             | 85  | 40                  | ...                      | ... | 28                                | 195 | 20             | 140 | 1                   |
| 700         | 370 | 0.5                    | 13                       | 90  | 7.5            | 52  | 48                  | ...                      | ... | 30                                | 205 | 22             | 150 | 1                   |
|             |     | 10                     | 12                       | 85  | 7.0            | 48  | 50                  | ...                      | ... | 29                                | 200 | 21             | 145 | 1                   |
|             |     | 100                    | 11                       | 75  | 6.5            | 45  | 62                  | ...                      | ... | 27                                | 185 | 20             | 140 | 1                   |
|             |     | 1,000                  | 10                       | 70  | 6.0            | 41  | 66                  | ...                      | ... | 26                                | 180 | 18             | 125 | 1                   |
|             |     | 10,000                 | 9.0                      | 62  | 5.5            | 38  | 70                  | ...                      | ... | 25                                | 170 | 17             | 115 | 1                   |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.

Table D4.4 242.0-T571 Permanent mold castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |     |                |     |                        |                          |     | At room temperature after heating |     |                   |     |                        |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|-----|-----------------------------------|-----|-------------------|-----|------------------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |     | Tensile strength(b)               |     | Yield strength(b) |     | Elongation<br>in 4D, % |
| °F          | °C   | Time at<br>temperature, h | ksi                      | MPa | ksi            | MPa |                        | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi               | MPa |                        |
| −320        | −196 | ...                       | 44                       | 305 | 41             | 285 | 1                      | ...                      | ... | ...                               | ... | ...               | ... |                        |
| −112        | −80  | ...                       | 41                       | 285 | 36             | 250 | 1                      | ...                      | ... | ...                               | ... | ...               | ... |                        |
| −18         | −28  | ...                       | 40                       | 275 | 34             | 235 | 1                      | ...                      | ... | ...                               | ... | ...               | ... |                        |
| 75          | 25   | ...                       | 40                       | 275 | 34             | 235 | 1                      | 10.2                     | 70  | 40                                | 275 | 34                | 235 |                        |
| 212         | 100  | 0.5                       | 40                       | 275 | 34             | 235 | 1                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 10                        | 40                       | 275 | 34             | 235 | 1                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 100                       | 40                       | 275 | 34             | 235 | 1                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 1,000                     | 40                       | 275 | 37             | 255 | 1                      | ...                      | ... | 40                                | 275 | 37                | 255 |                        |
|             |      | 10,000                    | 42                       | 290 | 38             | 260 | 1                      | ...                      | ... | 45                                | 310 | 40                | 275 |                        |
| 300         | 150  | 0.5                       | 40                       | 275 | 33             | 230 | 2                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 10                        | 40                       | 275 | 34             | 235 | 1                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 100                       | 41                       | 285 | 36             | 250 | 1                      | ...                      | ... | 46                                | 315 | 36                | 250 |                        |
|             |      | 1,000                     | 40                       | 275 | 37             | 255 | 1                      | ...                      | ... | 44                                | 305 | 41                | 285 |                        |
|             |      | 10,000                    | 38                       | 260 | 30             | 205 | 1                      | ...                      | ... | 42                                | 290 | 38                | 260 |                        |
| 350         | 177  | 0.5                       | 39                       | 270 | 31             | 215 | 3                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 10                        | 40                       | 275 | 34             | 235 | 2                      | ...                      | ... | 41                                | 285 | 35                | 240 |                        |
|             |      | 100                       | 40                       | 275 | 36             | 250 | 1                      | ...                      | ... | 46                                | 315 | 41                | 285 |                        |
|             |      | 1,000                     | 36                       | 250 | 30             | 205 | 2                      | ...                      | ... | 41                                | 285 | 39                | 270 |                        |
|             |      | 10,000                    | 33                       | 230 | 24             | 165 | 4                      | ...                      | ... | 39                                | 270 | 30                | 205 |                        |
| 400         | 205  | 0.5                       | 38                       | 260 | 29             | 200 | 4                      | ...                      | ... | 40                                | 275 | 34                | 235 |                        |
|             |      | 10                        | 40                       | 275 | 35             | 240 | 2                      | ...                      | ... | 46                                | 315 | 40                | 275 |                        |
|             |      | 100                       | 35                       | 240 | 28             | 195 | 2                      | ...                      | ... | 42                                | 290 | 40                | 275 |                        |
|             |      | 1,000                     | 30                       | 205 | 23             | 160 | 6                      | ...                      | ... | 38                                | 260 | 29                | 200 |                        |
|             |      | 10,000                    | 27                       | 185 | 18             | 125 | 9                      | ...                      | ... | 35                                | 240 | 22                | 150 |                        |
| 450         | 230  | 0.5                       | 35                       | 240 | 26             | 180 | 5                      | ...                      | ... | 45                                | 310 | 41                | 285 |                        |
|             |      | 10                        | 33                       | 230 | 27             | 185 | 4                      | ...                      | ... | 45                                | 310 | 40                | 275 |                        |
|             |      | 100                       | 28                       | 195 | 21             | 145 | 5                      | ...                      | ... | 38                                | 260 | 30                | 205 |                        |
|             |      | 1,000                     | 24                       | 165 | 16             | 110 | 10                     | ...                      | ... | 34                                | 235 | 21                | 145 |                        |
|             |      | 10,000                    | 20                       | 140 | 12             | 85  | 15                     | ...                      | ... | 30                                | 205 | 16                | 110 |                        |
| 500         | 260  | 0.5                       | 30                       | 205 | 23             | 160 | 8                      | ...                      | ... | 43                                | 295 | 38                | 260 |                        |
|             |      | 10                        | 26                       | 180 | 19             | 130 | 6                      | ...                      | ... | 40                                | 275 | 28                | 195 |                        |
|             |      | 100                       | 22                       | 150 | 15             | 105 | 10                     | ...                      | ... | 34                                | 235 | 22                | 150 |                        |
|             |      | 1,000                     | 18                       | 125 | 11             | 75  | 15                     | ...                      | ... | 30                                | 205 | 15                | 105 |                        |
|             |      | 10,000                    | 15                       | 105 | 8.0            | 55  | 20                     | ...                      | ... | 26                                | 180 | 12                | 85  |                        |
| 600         | 315  | 0.5                       | 16                       | 110 | 12             | 85  | 25                     | ...                      | ... | 34                                | 235 | 22                | 150 |                        |
|             |      | 10                        | 13                       | 90  | 9.0            | 62  | 30                     | ...                      | ... | 33                                | 230 | 14                | 95  |                        |
|             |      | 100                       | 12                       | 85  | 7.5            | 52  | 35                     | ...                      | ... | 30                                | 205 | 12                | 85  |                        |
|             |      | 1,000                     | 10                       | 70  | 6.5            | 45  | 35                     | ...                      | ... | 28                                | 195 | 11                | 75  |                        |
|             |      | 10,000                    | 10                       | 70  | 6.0            | 41  | 35                     | ...                      | ... | 26                                | 180 | 10                | 70  |                        |
| 700         | 370  | 0.5                       | 8.5                      | 59  | 6.0            | 41  | 65                     | ...                      | ... | ...                               | ... | ...               | ... |                        |
|             |      | 10                        | 7.5                      | 52  | 5.5            | 38  | 65                     | ...                      | ... | ...                               | ... | ...               | ... |                        |
|             |      | 100                       | 7.0                      | 48  | 4.8            | 33  | 70                     | ...                      | ... | ...                               | ... | ...               | ... |                        |
|             |      | 1,000                     | 6.5                      | 45  | 4.3            | 30  | 75                     | ...                      | ... | ...                               | ... | ...               | ... |                        |
|             |      | 10,000                    | 6.0                      | 41  | 3.8            | 26  | 85                     | ...                      | ... | ...                               | ... | ...               | ... |                        |

(a) The modulus of elasticity in compression is about 2% greater than in tension. (b) Cooled in still air at room temperature; tested within 2 h after removal from furnace. These properties may increase with time after removal from furnace.

Source data are in English units; metric values are converted and rounded.



Table D4.5 242.0-T77 Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| -320        | -196 | ...                    | 37                       | 255 | 28             | 195 | 2                   | ...                      | ... |
| -112        | -80  | ...                    | 32                       | 220 | 24             | 165 | 2                   | ...                      | ... |
| -18         | -28  | ...                    | 31                       | 215 | 23             | 160 | 2                   | ...                      | ... |
| 75          | 25   | ...                    | 30                       | 205 | 23             | 160 | 2                   | 10.3                     | 71  |
| 212         | 100  | 0.5                    | 30                       | 205 | 23             | 160 | 2                   | ...                      | ... |
|             |      | 10                     | 30                       | 205 | 23             | 160 | 2                   | ...                      | ... |
|             |      | 100                    | 30                       | 205 | 23             | 160 | 2                   | ...                      | ... |
|             |      | 1,000                  | 30                       | 205 | 23             | 160 | 2                   | ...                      | ... |
|             |      | 10,000                 | 30                       | 205 | 23             | 160 | 2                   | ...                      | ... |
| 300         | 150  | 0.5                    | 29                       | 200 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 10                     | 29                       | 200 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 100                    | 29                       | 200 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 1,000                  | 28                       | 195 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 10,000                 | 27                       | 185 | 21             | 145 | 2                   | ...                      | ... |
| 400         | 205  | 0.5                    | 26                       | 180 | 19             | 130 | 2                   | ...                      | ... |
|             |      | 10                     | 24                       | 165 | 18             | 125 | 2                   | ...                      | ... |
|             |      | 100                    | 23                       | 160 | 17             | 115 | 2                   | ...                      | ... |
|             |      | 1,000                  | 22                       | 150 | 16             | 110 | 2                   | ...                      | ... |
|             |      | 10,000                 | 20                       | 140 | 15             | 105 | 3                   | ...                      | ... |
| 500         | 260  | 0.5                    | 21                       | 145 | 16             | 110 | 2                   | ...                      | ... |
|             |      | 10                     | 19                       | 130 | 15             | 105 | 2                   | ...                      | ... |
|             |      | 100                    | 17                       | 115 | 13             | 90  | 3                   | ...                      | ... |
|             |      | 1,000                  | 15                       | 105 | 10             | 70  | 4                   | ...                      | ... |
|             |      | 10,000                 | 13                       | 90  | 8.0            | 55  | 6                   | ...                      | ... |
| 600         | 315  | 0.5                    | 15                       | 105 | 11             | 75  | 4                   | ...                      | ... |
|             |      | 10                     | 13                       | 90  | 9.5            | 66  | 6                   | ...                      | ... |
|             |      | 100                    | 11                       | 75  | 7.5            | 52  | 8                   | ...                      | ... |
|             |      | 1,000                  | 9.5                      | 66  | 5.5            | 38  | 12                  | ...                      | ... |
|             |      | 10,000                 | 8.0                      | 55  | 4.0            | 28  | 20                  | ...                      | ... |
| 700         | 370  | 0.5                    | 9.0                      | 62  | 6.0            | 41  | 8                   | ...                      | ... |
|             |      | 10                     | 7.5                      | 52  | 5.0            | 34  | 20                  | ...                      | ... |
|             |      | 100                    | 6.0                      | 41  | 4.0            | 28  | 30                  | ...                      | ... |
|             |      | 1,000                  | 5.0                      | 34  | 3.5            | 24  | 35                  | ...                      | ... |
|             |      | 10,000                 | 5.0                      | 34  | 3.0            | 21  | 40                  | ...                      | ... |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.

Table D4.6 249.0-T7 Sand and permanent mold castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |     |                |     |                        |                          |                     | At room temperature after heating |     |                |     |                        |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|---------------------|-----------------------------------|-----|----------------|-----|------------------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |                     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
| °F          | °C   | Time at<br>temperature, h | ksi                      | MPa | ksi            | MPa |                        |                          | 10 <sup>6</sup> psi | GPa                               | ksi | MPa            | ksi |                        |
| −452        | −269 | ...                       | 94                       | 650 | 76             | 525 | 10                     | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| −423        | −253 | ...                       | 91                       | 627 | 75             | 515 | 9                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| −320        | −196 | ...                       | 81                       | 560 | 69             | 475 | 7                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| −112        | −80  | ...                       | 70                       | 485 | 62             | 425 | 6                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| −18         | −28  | ...                       | 69                       | 475 | 60             | 415 | 6                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| 75          | 25   | ...                       | 68                       | 470 | 59             | 405 | 6                      | 10.3                     | 71                  | 68                                | 470 | 59             | 405 | 6                      |
| 300         | 150  | 0.5                       | 55                       | 380 | 52             | 360 | 10                     | ...                      | ...                 | 67                                | 460 | 59             | 405 | 6                      |
|             |      | 10                        | 57                       | 395 | 52             | 360 | 10                     | ...                      | ...                 | 68                                | 470 | 60             | 415 | 5                      |
|             |      | 100                       | 55                       | 380 | 50             | 345 | 11                     | ...                      | ...                 | 67                                | 460 | 59             | 405 | 5                      |
|             |      | 1,000                     | 47                       | 325 | 41             | 285 | 14                     | ...                      | ...                 | 63                                | 435 | 51             | 350 | 6                      |
|             |      | 10,000                    | 42                       | 290 | 35             | 240 | 14                     | ...                      | ...                 | 57                                | 395 | 42             | 290 | 6                      |
| 350         | 177  | 0.5                       | 51                       | 350 | 48             | 330 | 10                     | ...                      | ...                 | 68                                | 470 | 60             | 415 | 7                      |
|             |      | 10                        | 50                       | 345 | 46             | 315 | 11                     | ...                      | ...                 | 66                                | 455 | 57             | 395 | 5                      |
|             |      | 100                       | 45                       | 310 | 41             | 285 | 13                     | ...                      | ...                 | 62                                | 425 | 50             | 345 | 6                      |
|             |      | 1,000                     | 37                       | 255 | 32             | 220 | 14                     | ...                      | ...                 | 57                                | 395 | 42             | 290 | 6                      |
|             |      | 10,000                    | 34                       | 235 | 28             | 195 | 17                     | ...                      | ...                 | 50                                | 345 | 35             | 240 | 6                      |
| 400         | 205  | 0.5                       | 46                       | 315 | 41             | 285 | 10                     | ...                      | ...                 | 66                                | 455 | 57             | 395 | 6                      |
|             |      | 10                        | 40                       | 275 | 36             | 250 | 12                     | ...                      | ...                 | 62                                | 425 | 50             | 345 | 6                      |
|             |      | 100                       | 36                       | 250 | 32             | 220 | 15                     | ...                      | ...                 | 56                                | 385 | 42             | 290 | 7                      |
|             |      | 1,000                     | 29                       | 200 | 25             | 170 | 16                     | ...                      | ...                 | 50                                | 345 | 35             | 240 | 7                      |
|             |      | 10,000                    | 27                       | 185 | 23             | 160 | 20                     | ...                      | ...                 | 45                                | 310 | 30             | 205 | 9                      |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.7 295.0-T6 Sand castings: typical tensile properties

| At temperature indicated |     |                        |                  |     |                |     |                     |                          |     |
|--------------------------|-----|------------------------|------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature              |     | Time at temperature, h | Tensile strength |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F                       | °C  |                        | ksi              | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| 75                       | 25  | ...                    | 36               | 250 | 24             | 165 | 5                   | 10                       | 69  |
| 212                      | 100 | 10,000                 | 34               | 235 | 23             | 160 | 5                   | ...                      | ... |
| 300                      | 150 | 10,000                 | 28               | 195 | 20             | 140 | 5                   | ...                      | ... |
| 400                      | 205 | 10,000                 | 15               | 105 | 9.0            | 62  | 15                  | ...                      | ... |
| 500                      | 260 | 10,000                 | 9.0              | 62  | 6.0            | 41  | 25                  | ...                      | ... |
| 600                      | 315 | 10,000                 | 4.0              | 28  | 3.0            | 21  | 75                  | ...                      | ... |
| 700                      | 370 | 10,000                 | 2.5              | 17  | 1.5            | 10  | 100                 | ...                      | ... |

(a) Average of tensile and compressive moduli  
Source data are in English units; metric values are converted and rounded.

Table D4.8 319.0-F Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                                   |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|-----------------------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in<br>2 in. (50 mm), % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                                   | 10 <sup>6</sup> psi      | GPa |
| -320        | -196 | ...                    | 32                       | 220 | 25             | 170 | 2                                 | ...                      | ... |
| -112        | -80  | ...                    | 28                       | 195 | 20             | 140 | 2                                 | ...                      | ... |
| -18         | -28  | ...                    | 27                       | 185 | 18             | 125 | 2                                 | ...                      | ... |
| 75          | 25   | ...                    | 27                       | 185 | 18             | 125 | 2                                 | 10.6                     | 73  |
| 212         | 100  | 0.5                    | 26                       | 180 | 17             | 115 | 1.5                               | ...                      | ... |
|             |      | 10                     | 26                       | 180 | 17             | 115 | 1.5                               | ...                      | ... |
|             |      | 100                    | 27                       | 185 | 18             | 125 | 1.5                               | ...                      | ... |
|             |      | 1,000                  | 32                       | 220 | 30             | 205 | 1.5                               | ...                      | ... |
|             |      | 10,000                 | 34                       | 235 | 34             | 235 | 1.5                               | ...                      | ... |
| 300         | 150  | 0.5                    | 23                       | 160 | 14             | 95  | 1                                 | ...                      | ... |
|             |      | 10                     | 26                       | 180 | 19             | 130 | 1                                 | ...                      | ... |
|             |      | 100                    | 30                       | 205 | 30             | 205 | 1                                 | ...                      | ... |
|             |      | 1,000                  | 30                       | 205 | 29             | 200 | 1                                 | ...                      | ... |
|             |      | 10,000                 | 28                       | 195 | 25             | 170 | 1                                 | ...                      | ... |
| 350         | 177  | 0.5                    | 23                       | 160 | 16             | 110 | 1                                 | ...                      | ... |
|             |      | 10                     | 27                       | 185 | 26             | 180 | 1                                 | ...                      | ... |
|             |      | 100                    | 28                       | 195 | 27             | 185 | 1                                 | ...                      | ... |
|             |      | 1,000                  | 27                       | 185 | 24             | 165 | 1                                 | ...                      | ... |
|             |      | 10,000                 | 24                       | 165 | 20             | 140 | 1                                 | ...                      | ... |
| 400         | 205  | 0.5                    | 24                       | 165 | 22             | 150 | 1                                 | ...                      | ... |
|             |      | 10                     | 25                       | 170 | 23             | 160 | 1                                 | ...                      | ... |
|             |      | 100                    | 24                       | 165 | 21             | 145 | 1                                 | ...                      | ... |
|             |      | 1,000                  | 23                       | 160 | 18             | 125 | 2                                 | ...                      | ... |
|             |      | 10,000                 | 20                       | 140 | 16             | 110 | 2                                 | ...                      | ... |
| 450         | 230  | 0.5                    | 22                       | 150 | 20             | 140 | 1                                 | ...                      | ... |
|             |      | 10                     | 22                       | 150 | 19             | 130 | 1.5                               | ...                      | ... |
|             |      | 100                    | 20                       | 140 | 16             | 110 | 1.5                               | ...                      | ... |
|             |      | 1,000                  | 18                       | 125 | 14             | 95  | 2.5                               | ...                      | ... |
|             |      | 10,000                 | 17                       | 115 | 13             | 90  | 3.5                               | ...                      | ... |
| 500         | 260  | 0.5                    | 19                       | 130 | 17             | 115 | 1.5                               | ...                      | ... |
|             |      | 10                     | 18                       | 125 | 15             | 105 | 2                                 | ...                      | ... |
|             |      | 100                    | 15                       | 105 | 12             | 85  | 2.5                               | ...                      | ... |
|             |      | 1,000                  | 15                       | 105 | 11             | 75  | 3.5                               | ...                      | ... |
|             |      | 10,000                 | 14                       | 95  | 10             | 70  | 4.5                               | ...                      | ... |
| 600         | 315  | 0.5                    | 13                       | 90  | 11             | 75  | 3                                 | ...                      | ... |
|             |      | 10                     | 11                       | 75  | 8.5            | 59  | 5                                 | ...                      | ... |
|             |      | 100                    | 9.5                      | 66  | 7.5            | 52  | 5.5                               | ...                      | ... |
|             |      | 1,000                  | 9.5                      | 66  | 7.0            | 48  | 5.5                               | ...                      | ... |
|             |      | 10,000                 | 9.5                      | 66  | 6.5            | 45  | 5.5                               | ...                      | ... |
| 700         | 370  | 0.5                    | 7.0                      | 48  | 6.0            | 41  | 8                                 | ...                      | ... |
|             |      | 10                     | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |
|             |      | 100                    | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |
|             |      | 1,000                  | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |
|             |      | 10,000                 | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |

(a) The modulus of elasticity in compression is about 2% greater than in tension.

Source data are in English units; metric values are converted and rounded.

Table D4.9 319.0-T5 Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                                   |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|-----------------------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in<br>2 in. (50 mm), % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                                   | 10 <sup>6</sup> psi      | GPa |
| -320        | -196 | ...                    | 35                       | 240 | 32             | 220 | 1                                 | ...                      | ... |
| -112        | -80  | ...                    | 32                       | 220 | 27             | 185 | 1.5                               | ...                      | ... |
| -18         | -28  | ...                    | 31                       | 215 | 27             | 185 | 1.5                               | ...                      | ... |
| 75          | 25   | ...                    | 30                       | 205 | 26             | 180 | 1.5                               | 10.6                     | 73  |
| 212         | 100  | 0.5                    | 28                       | 195 | 25             | 170 | 1.5                               | ...                      | ... |
|             |      | 10                     | 28                       | 195 | 25             | 170 | 1.5                               | ...                      | ... |
|             |      | 100                    | 28                       | 195 | 25             | 170 | 1.5                               | ...                      | ... |
|             |      | 1,000                  | 29                       | 200 | 26             | 180 | 1.5                               | ...                      | ... |
|             |      | 10,000                 | 31                       | 215 | 29             | 200 | 1.5                               | ...                      | ... |
| 300         | 150  | 0.5                    | 26                       | 180 | 23             | 160 | 1                                 | ...                      | ... |
|             |      | 10                     | 29                       | 200 | 26             | 180 | 1                                 | ...                      | ... |
|             |      | 100                    | 29                       | 200 | 26             | 180 | 1                                 | ...                      | ... |
|             |      | 1,000                  | 28                       | 195 | 25             | 170 | 1                                 | ...                      | ... |
|             |      | 10,000                 | 27                       | 185 | 24             | 165 | 1                                 | ...                      | ... |
| 350         | 177  | 0.5                    | 25                       | 170 | 22             | 150 | 1                                 | ...                      | ... |
|             |      | 10                     | 28                       | 195 | 24             | 165 | 1                                 | ...                      | ... |
|             |      | 100                    | 27                       | 185 | 23             | 160 | 1                                 | ...                      | ... |
|             |      | 1,000                  | 26                       | 180 | 22             | 150 | 1                                 | ...                      | ... |
|             |      | 10,000                 | 23                       | 160 | 19             | 130 | 1                                 | ...                      | ... |
| 400         | 205  | 0.5                    | 24                       | 165 | 22             | 150 | 1                                 | ...                      | ... |
|             |      | 10                     | 25                       | 170 | 22             | 150 | 1                                 | ...                      | ... |
|             |      | 100                    | 24                       | 165 | 21             | 145 | 1                                 | ...                      | ... |
|             |      | 1,000                  | 23                       | 160 | 18             | 125 | 2                                 | ...                      | ... |
|             |      | 10,000                 | 20                       | 140 | 16             | 110 | 2                                 | ...                      | ... |
| 450         | 230  | 0.5                    | 22                       | 150 | 20             | 140 | 1                                 | ...                      | ... |
|             |      | 10                     | 22                       | 150 | 19             | 130 | 1.5                               | ...                      | ... |
|             |      | 100                    | 20                       | 140 | 16             | 110 | 1.5                               | ...                      | ... |
|             |      | 1,000                  | 18                       | 125 | 14             | 95  | 2.5                               | ...                      | ... |
|             |      | 10,000                 | 17                       | 115 | 13             | 90  | 3.5                               | ...                      | ... |
| 500         | 260  | 0.5                    | 19                       | 130 | 17             | 115 | 1.5                               | ...                      | ... |
|             |      | 10                     | 18                       | 125 | 15             | 105 | 2                                 | ...                      | ... |
|             |      | 100                    | 15                       | 105 | 12             | 85  | 2.5                               | ...                      | ... |
|             |      | 1,000                  | 15                       | 105 | 11             | 75  | 3.5                               | ...                      | ... |
|             |      | 10,000                 | 14                       | 95  | 10             | 70  | 4.5                               | ...                      | ... |
| 600         | 315  | 0.5                    | 13                       | 90  | 11             | 75  | 3                                 | ...                      | ... |
|             |      | 10                     | 11                       | 75  | 8.5            | 59  | 5                                 | ...                      | ... |
|             |      | 100                    | 9.5                      | 66  | 7.5            | 52  | 5.5                               | ...                      | ... |
|             |      | 1,000                  | 9.5                      | 66  | 7.0            | 48  | 5.5                               | ...                      | ... |
|             |      | 10,000                 | 9.5                      | 66  | 6.5            | 45  | 5.5                               | ...                      | ... |
| 700         | 370  | 0.5                    | 7.0                      | 48  | 6.0            | 41  | 8                                 | ...                      | ... |
|             |      | 10                     | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |
|             |      | 100                    | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |
|             |      | 1,000                  | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |
|             |      | 10,000                 | 7.0                      | 48  | 5.5            | 38  | 11                                | ...                      | ... |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.10 332.0-T5 Permanent mold castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| 75          | 24  | ...                    | 36                       | 250 | 28             | 195 | 1                   | 11.1                     | 77  |
| 400         | 205 | 100                    | 24                       | 165 | 17             | 115 | 3                   | ...                      | ... |
|             |     | 1,000                  | 21                       | 145 | 14             | 95  | 4                   | ...                      | ... |
|             |     | 10,000                 | 20                       | 140 | 13             | 90  | 5                   | ...                      | ... |
| 450         | 230 | 100                    | 20                       | 140 | 14             | 95  | 4                   | ...                      | ... |
|             |     | 1,000                  | 18                       | 125 | 11             | 75  | 5                   | ...                      | ... |
|             |     | 10,000                 | 17                       | 115 | 10             | 70  | 5                   | ...                      | ... |
| 500         | 260 | 100                    | 16                       | 110 | 11             | 75  | 6                   | ...                      | ... |
|             |     | 1,000                  | 14                       | 95  | 8.5            | 59  | 7                   | ...                      | ... |
|             |     | 10,000                 | 13                       | 90  | 7.5            | 52  | 8                   | ...                      | ... |
| 600         | 315 | 0.5                    | 13                       | 90  | 9.5            | 66  | 10                  | ...                      | ... |
|             |     | 10                     | 12                       | 85  | 7.5            | 52  | 12                  | ...                      | ... |
|             |     | 100                    | 10                       | 70  | 6.0            | 41  | 14                  | ...                      | ... |
|             |     | 1,000                  | 9.0                      | 62  | 5.0            | 34  | 17                  | ...                      | ... |
|             |     | 10,000                 | 7.5                      | 52  | 5.0            | 34  | 25                  | ...                      | ... |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.11 330.0-T5 Permanent mold castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     | At room temperature after heating |     |                |     |                     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|-----------------------------------|-----|----------------|-----|---------------------|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Tensile strength                  |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | ksi                               | MPa | ksi            | MPa |                     |
| -320        | -196 | ...                    | 40                       | 275 | 28             | 195 | 1                   | ...                               | ... | ...            | ... | ...                 |
| -112        | -80  | ...                    | 37                       | 255 | 26             | 180 | 1                   | ...                               | ... | ...            | ... | ...                 |
| -18         | -28  | ...                    | 35                       | 240 | 25             | 170 | 1                   | ...                               | ... | ...            | ... | ...                 |
| 75          | 25   | ...                    | 34                       | 235 | 25             | 170 | 1                   | 34                                | 235 | 25             | 170 | 1                   |
| 212         | 100  | 0.5                    | 34                       | 235 | 25             | 170 | 1                   | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 10                     | 34                       | 235 | 25             | 170 | 1                   | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 100                    | 34                       | 235 | 25             | 170 | 1                   | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 1,000                  | 34                       | 235 | 25             | 170 | 1.5                 | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 10,000                 | 34                       | 235 | 25             | 170 | 2                   | 34                                | 235 | 25             | 170 | 1                   |
| 300         | 150  | 0.5                    | 34                       | 235 | 25             | 170 | 1                   | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 10                     | 34                       | 235 | 25             | 170 | 1.5                 | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 100                    | 33                       | 230 | 25             | 170 | 2                   | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 1,000                  | 32                       | 220 | 25             | 170 | 2.5                 | 34                                | 235 | 25             | 170 | 1                   |
|             |      | 10,000                 | 31                       | 215 | 22             | 150 | 3                   | 34                                | 235 | 25             | 170 | 1.5                 |
| 350         | 177  | 0.5                    | 33                       | 230 | 25             | 170 | 1.5                 | 34                                | 235 | 25             | 170 | 1.5                 |
|             |      | 10                     | 32                       | 220 | 25             | 170 | 2                   | 34                                | 235 | 25             | 170 | 1.5                 |
|             |      | 100                    | 31                       | 215 | 25             | 170 | 2.5                 | 34                                | 235 | 25             | 170 | 1.5                 |
|             |      | 1,000                  | 30                       | 205 | 23             | 160 | 3                   | 34                                | 235 | 24             | 165 | 1.5                 |
|             |      | 10,000                 | 28                       | 195 | 19             | 130 | 3.5                 | 34                                | 235 | 23             | 160 | 2                   |
| 400         | 205  | 0.5                    | 32                       | 220 | 24             | 165 | 2                   | 34                                | 235 | 25             | 170 | 1.5                 |
|             |      | 10                     | 30                       | 205 | 24             | 165 | 2.5                 | 34                                | 235 | 25             | 170 | 1.5                 |
|             |      | 100                    | 28                       | 195 | 22             | 150 | 3                   | 34                                | 235 | 24             | 165 | 2                   |
|             |      | 1,000                  | 26                       | 180 | 19             | 130 | 4                   | 34                                | 235 | 22             | 150 | 2                   |
|             |      | 10,000                 | 24                       | 165 | 16             | 110 | 5                   | 33                                | 230 | 20             | 140 | 2.5                 |
| 500         | 260  | 0.5                    | 25                       | 170 | 19             | 130 | 4                   | 34                                | 235 | 24             | 165 | 2                   |
|             |      | 10                     | 23                       | 160 | 16             | 110 | 6                   | 34                                | 235 | 22             | 150 | 2                   |
|             |      | 100                    | 20                       | 140 | 12             | 85  | 8                   | 33                                | 230 | 18             | 125 | 2                   |
|             |      | 1,000                  | 18                       | 125 | 11             | 75  | 10                  | 32                                | 220 | 16             | 110 | 3                   |
|             |      | 10,000                 | 17                       | 115 | 10             | 70  | 11                  | 30                                | 205 | 15             | 105 | 4                   |
| 600         | 315  | 0.5                    | 16                       | 110 | 11             | 75  | 13                  | 33                                | 230 | 22             | 150 | 2                   |
|             |      | 10                     | 14                       | 95  | 8.5            | 59  | 17                  | 32                                | 220 | 18             | 125 | 3                   |
|             |      | 100                    | 13                       | 90  | 7.5            | 52  | 20                  | 31                                | 215 | 16             | 110 | 3                   |
|             |      | 1,000                  | 12                       | 85  | 7.0            | 48  | 25                  | 30                                | 205 | 15             | 105 | 4                   |
|             |      | 10,000                 | 10                       | 70  | 7.0            | 48  | 30                  | 29                                | 200 | 14             | 95  | 5                   |
| 700         | 370  | 0.5                    | 9.0                      | 62  | 6.0            | 41  | 30                  | 31                                | 215 | 15             | 105 | 3                   |
|             |      | 10                     | 8.0                      | 55  | 5.5            | 38  | 35                  | 30                                | 205 | 15             | 105 | 4                   |
|             |      | 100                    | 7.5                      | 52  | 5.0            | 34  | 35                  | 30                                | 205 | 14             | 95  | 5                   |
|             |      | 1,000                  | 6.5                      | 45  | 4.8            | 33  | 40                  | 30                                | 205 | 13             | 90  | 6                   |
|             |      | 10,000                 | 6.0                      | 41  | 4.8            | 33  | 45                  | 29                                | 200 | 13             | 90  | 7                   |

Source data are in English units; metric values are converted and rounded.

Table D4.12 330.0-T7 Permanent mold castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |     |                |     |                        | At room temperature after heating |     |                |     |               |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|-----------------------------------|-----|----------------|-----|---------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Tensile strength                  |     | Yield strength |     | Elongation, % |
|             |      |                           | ksi                      | MPa | ksi            | MPa |                        | ksi                               | MPa | ksi            | MPa |               |
| °F          | °C   | Time at<br>temperature, h |                          |     |                |     |                        |                                   |     |                |     |               |
| -320        | -196 | ...                       | 46                       | 315 | 32             | 220 | 2                      | ...                               | ... | ...            | ... | ...           |
| -112        | -80  | ...                       | 41                       | 285 | 29             | 200 | 2                      | ...                               | ... | ...            | ... | ...           |
| -18         | -28  | ...                       | 38                       | 260 | 28             | 195 | 2                      | ...                               | ... | ...            | ... | ...           |
| 75          | 25   | ...                       | 37                       | 255 | 28             | 195 | 2                      | 37                                | 255 | 28             | 195 | 2             |
| 212         | 100  | 0.5                       | 37                       | 255 | 28             | 195 | 4                      | 37                                | 255 | 28             | 195 | 2             |
|             |      | 10                        | 37                       | 255 | 28             | 195 | 4                      | 37                                | 255 | 28             | 195 | 2             |
|             |      | 100                       | 37                       | 255 | 28             | 195 | 4                      | 37                                | 255 | 28             | 195 | 2             |
|             |      | 1,000                     | 36                       | 250 | 28             | 195 | 4                      | 37                                | 255 | 28             | 195 | 2             |
|             |      | 10,000                    | 36                       | 250 | 27             | 185 | 4                      | 37                                | 255 | 28             | 195 | 2             |
| 300         | 150  | 0.5                       | 34                       | 235 | 25             | 170 | 6                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 10                        | 34                       | 235 | 25             | 170 | 6                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 100                       | 34                       | 235 | 25             | 170 | 6                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 1,000                     | 33                       | 230 | 25             | 170 | 6                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 10,000                    | 31                       | 215 | 24             | 165 | 6                      | 37                                | 255 | 26             | 180 | 3             |
| 350         | 177  | 0.5                       | 32                       | 220 | 24             | 165 | 6                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 10                        | 32                       | 220 | 24             | 165 | 6                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 100                       | 31                       | 215 | 23             | 160 | 7                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 1,000                     | 30                       | 205 | 22             | 150 | 8                      | 37                                | 255 | 27             | 185 | 4             |
|             |      | 10,000                    | 26                       | 180 | 20             | 140 | 9                      | 35                                | 240 | 22             | 150 | 4             |
| 400         | 205  | 0.5                       | 29                       | 200 | 22             | 150 | 7                      | 37                                | 255 | 28             | 195 | 3             |
|             |      | 10                        | 29                       | 200 | 22             | 150 | 8                      | 37                                | 255 | 28             | 195 | 4             |
|             |      | 100                       | 27                       | 185 | 21             | 145 | 10                     | 37                                | 255 | 27             | 185 | 4             |
|             |      | 1,000                     | 25                       | 170 | 18             | 125 | 12                     | 35                                | 240 | 22             | 150 | 5             |
|             |      | 10,000                    | 20                       | 140 | 14             | 95  | 14                     | 32                                | 220 | 18             | 125 | 5             |
| 500         | 260  | 0.5                       | 21                       | 145 | 17             | 115 | 10                     | 37                                | 255 | 26             | 180 | 4             |
|             |      | 10                        | 19                       | 130 | 14             | 95  | 15                     | 36                                | 250 | 21             | 145 | 5             |
|             |      | 100                       | 14                       | 95  | 10             | 70  | 20                     | 33                                | 230 | 16             | 110 | 6             |
|             |      | 1,000                     | 13                       | 90  | 8.5            | 59  | 30                     | 30                                | 205 | 13             | 90  | 7             |
|             |      | 10,000                    | 12                       | 85  | 7.5            | 52  | 35                     | 27                                | 185 | 11             | 75  | 7             |
| 600         | 315  | 0.5                       | 13                       | 90  | 9.5            | 66  | 40                     | 36                                | 250 | 19             | 130 | 5             |
|             |      | 10                        | 9.5                      | 66  | 7.0            | 48  | 45                     | 33                                | 230 | 15             | 105 | 6             |
|             |      | 100                       | 9.0                      | 62  | 6.0            | 41  | 50                     | 30                                | 205 | 13             | 90  | 7             |
|             |      | 1,000                     | 8.0                      | 55  | 5.5            | 38  | 50                     | 28                                | 195 | 11             | 75  | 7             |
|             |      | 10,000                    | 8.0                      | 55  | 5.0            | 34  | 55                     | 26                                | 180 | 10             | 70  | 8             |
| 700         | 370  | 0.5                       | 6.5                      | 45  | 5.0            | 34  | 55                     | 34                                | 235 | 15             | 105 | 7             |
|             |      | 10                        | 6.5                      | 45  | 4.8            | 33  | 55                     | 32                                | 220 | 13             | 90  | 7             |
|             |      | 100                       | 6.0                      | 41  | 4.4            | 30  | 60                     | 30                                | 205 | 11             | 75  | 7             |
|             |      | 1,000                     | 6.0                      | 41  | 4.1            | 28  | 60                     | 28                                | 195 | 10             | 70  | 8             |
|             |      | 10,000                    | 5.5                      | 38  | 3.8            | 26  | 60                     | 26                                | 180 | 10             | 70  | 8             |

Source data are in English units; metric values are converted and rounded.

Table D4.13 336.0-T551 Permanent mold castings: typical tensile properties

| Temperature |      |        | At temperature indicated  |     |                |     |                        | At room temperature after heating |     |                |     |                        |     |
|-------------|------|--------|---------------------------|-----|----------------|-----|------------------------|-----------------------------------|-----|----------------|-----|------------------------|-----|
|             |      |        | Tensile strength          |     | Yield strength |     | Elongation<br>in 4D, % | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |     |
|             |      |        | Time at<br>temperature, h | ksi | MPa            | ksi |                        | MPa                               | ksi | MPa            | ksi |                        | MPa |
| °F          | °C   |        |                           |     |                |     |                        |                                   |     |                |     |                        |     |
| −320        | −196 | ...    | 44                        | 305 | 39             | 270 | 1                      | ...                               | ... | ...            | ... | ...                    | ... |
| −112        | −80  | ...    | 38                        | 260 | 30             | 205 | 0.5                    | ...                               | ... | ...            | ... | ...                    | ... |
| −18         | −28  | ...    | 37                        | 255 | 28             | 195 | 0.5                    | ...                               | ... | ...            | ... | ...                    | ... |
| 75          | 25   | ...    | 36                        | 250 | 28             | 195 | 0.5                    | ...                               | ... | ...            | ... | ...                    | ... |
| 212         | 100  | 0.5    | 36                        | 250 | 28             | 195 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 10     | 36                        | 250 | 28             | 195 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 100    | 36                        | 250 | 28             | 195 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 1,000  | 36                        | 250 | 28             | 195 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 10,000 | 35                        | 240 | 27             | 185 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 0.5    | 34                        | 235 | 26             | 180 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 10     | 34                        | 235 | 26             | 180 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 100    | 34                        | 235 | 25             | 170 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 1,000  | 33                        | 230 | 24             | 165 | 0.5                    | 36                                | 250 | 27             | 185 | 0.5                    | 0.5 |
|             |      | 10,000 | 32                        | 220 | 23             | 160 | 0.5                    | 36                                | 250 | 24             | 165 | 0.5                    | 0.5 |
| 300         | 150  | 0.5    | 32                        | 220 | 24             | 165 | 0.5                    | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 10     | 32                        | 220 | 23             | 160 | 0.5                    | 36                                | 250 | 27             | 185 | 0.5                    | 0.5 |
|             |      | 100    | 31                        | 215 | 22             | 150 | 0.5                    | 36                                | 250 | 26             | 180 | 0.5                    | 0.5 |
|             |      | 1,000  | 30                        | 205 | 21             | 145 | 0.5                    | 36                                | 250 | 23             | 160 | 0.5                    | 0.5 |
|             |      | 10,000 | 28                        | 195 | 19             | 130 | 1                      | 35                                | 240 | 20             | 140 | 0.5                    | 0.5 |
|             |      | 0.5    | 30                        | 205 | 20             | 140 | 1                      | 36                                | 250 | 28             | 195 | 0.5                    | 0.5 |
|             |      | 10     | 29                        | 200 | 19             | 130 | 1                      | 36                                | 250 | 26             | 180 | 0.5                    | 0.5 |
|             |      | 100    | 29                        | 200 | 18             | 125 | 1                      | 36                                | 250 | 24             | 165 | 0.5                    | 0.5 |
|             |      | 1,000  | 27                        | 185 | 17             | 115 | 1                      | 36                                | 250 | 21             | 145 | 0.5                    | 0.5 |
|             |      | 10,000 | 25                        | 170 | 15             | 105 | 2                      | 33                                | 230 | 18             | 125 | 0.8                    | 0.8 |
| 350         | 177  | 0.5    | 27                        | 185 | 17             | 115 | 1                      | 36                                | 250 | 27             | 185 | 0.5                    | 0.5 |
|             |      | 10     | 26                        | 180 | 16             | 110 | 1                      | 36                                | 250 | 25             | 170 | 0.5                    | 0.5 |
|             |      | 100    | 25                        | 170 | 15             | 105 | 1.5                    | 35                                | 240 | 23             | 160 | 0.5                    | 0.5 |
|             |      | 1,000  | 24                        | 165 | 14             | 95  | 2                      | 35                                | 240 | 20             | 140 | 0.5                    | 0.5 |
|             |      | 10,000 | 22                        | 150 | 12             | 85  | 4                      | 31                                | 215 | 18             | 125 | 1.3                    | 1.3 |
|             |      | 0.5    | 23                        | 160 | 14             | 95  | 2                      | 36                                | 250 | 26             | 180 | 0.5                    | 0.5 |
|             |      | 10     | 22                        | 150 | 13             | 90  | 2                      | 36                                | 250 | 24             | 165 | 0.5                    | 0.5 |
|             |      | 100    | 21                        | 145 | 12             | 85  | 3                      | 34                                | 235 | 22             | 150 | 0.5                    | 0.5 |
|             |      | 1,000  | 20                        | 140 | 11             | 75  | 3.5                    | 33                                | 230 | 20             | 140 | 0.7                    | 0.7 |
|             |      | 10,000 | 18                        | 125 | 10             | 70  | 5                      | 31                                | 215 | 18             | 125 | 2                      | 2   |
| 400         | 205  | 0.5    | 14                        | 95  | 8.0            | 55  | 10                     | 36                                | 250 | 24             | 165 | 0.7                    | 0.7 |
|             |      | 10     | 13                        | 90  | 7.5            | 52  | 10                     | 35                                | 240 | 22             | 150 | 0.7                    | 0.7 |
|             |      | 100    | 12                        | 85  | 7.0            | 48  | 11                     | 33                                | 230 | 20             | 140 | 0.9                    | 0.9 |
|             |      | 1,000  | 12                        | 85  | 6.5            | 45  | 12                     | 31                                | 215 | 18             | 124 | 2                      | 2   |
|             |      | 10,000 | 11                        | 75  | 6.0            | 41  | 15                     | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 0.5    | 8.5                       | 59  | 4.8            | 33  | 27                     | 36                                | 250 | 22             | 150 | 1.5                    | 1.5 |
|             |      | 10     | 8.0                       | 55  | 4.5            | 31  | 33                     | 35                                | 240 | 20             | 140 | 1.5                    | 1.5 |
|             |      | 100    | 7.5                       | 52  | 4.3            | 30  | 38                     | 31                                | 215 | 18             | 125 | 2                      | 2   |
|             |      | 1,000  | 7.0                       | 48  | 4.2            | 29  | 41                     | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | 7.0                       | 48  | 4.0            | 28  | 43                     | ...                               | ... | ...            | ... | ...                    | ... |
| 450         | 230  | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
| 500         | 260  | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
| 600         | 315  | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
| 700         | 370  | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 0.5    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10     | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 100    | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 1,000  | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |
|             |      | 10,000 | ...                       | ... | ...            | ... | ...                    | ...                               | ... | ...            | ... | ...                    | ... |

Source data are in English units; metric values are converted and rounded.

Table D4.14 A344.0-T4 Permanent mold castings (results of tests on permanent mold test bars): typical tensile properties

| Temperature |    | At temperature indicated |     |                |     |                     |
|-------------|----|--------------------------|-----|----------------|-----|---------------------|
|             |    | Tensile strength         |     | Yield strength |     | Elongation in 4D, % |
|             |    | ksi                      | MPa | ksi            | MPa |                     |
| 75          | 25 | 22                       | 150 | 8.0            | 55  | 30                  |

Source data are in English units; metric values are converted and rounded.



Table D4.15 354.0-T6, -T61 Permanent mold castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |     |                |     |                        |                          |     | At room temperature after heating |     |                |     |                        |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|------------------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
|             |      |                           | ksi                      | MPa | ksi            | MPa |                        | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                        |
| °F          | °C   | Time at<br>temperature, h |                          |     |                |     |                        |                          |     |                                   |     |                |     |                        |
| -320        | -196 | ...                       | 68                       | 470 | 49             | 340 | 5                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| -112        | -80  | ...                       | 58                       | 400 | 42             | 290 | 5                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| -18         | -28  | ...                       | 58                       | 400 | 42             | 290 | 5                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 75          | 25   | ...                       | 55                       | 380 | 41             | 285 | 6                      | 10.6                     | 73  | 55                                | 380 | 41             | 285 | 6                      |
| 212         | 100  | 0.5                       | 50                       | 345 | 41             | 285 | 6                      | ...                      | ... | 55                                | 380 | 41             | 285 | 6                      |
|             |      | 10                        | 51                       | 350 | 41             | 285 | 6                      | ...                      | ... | 56                                | 385 | 42             | 290 | 6                      |
|             |      | 100                       | 52                       | 360 | 42             | 290 | 6                      | ...                      | ... | 58                                | 400 | 43             | 295 | 6                      |
|             |      | 1,000                     | 54                       | 370 | 45             | 310 | 6                      | ...                      | ... | 61                                | 420 | 45             | 310 | 6                      |
|             |      | 10,000                    | 60                       | 415 | 49             | 340 | 6                      | ...                      | ... | 63                                | 435 | 51             | 350 | 5                      |
| 300         | 150  | 0.5                       | 47                       | 325 | 40             | 275 | 6                      | ...                      | ... | 55                                | 380 | 42             | 290 | 6                      |
|             |      | 10                        | 50                       | 345 | 43             | 295 | 6                      | ...                      | ... | 57                                | 395 | 44             | 305 | 5                      |
|             |      | 100                       | 51                       | 350 | 46             | 315 | 6                      | ...                      | ... | 62                                | 425 | 50             | 345 | 5                      |
|             |      | 1,000                     | 49                       | 340 | 44             | 305 | 6                      | ...                      | ... | 59                                | 405 | 52             | 360 | 4                      |
|             |      | 10,000                    | 42                       | 290 | 35             | 240 | 6                      | ...                      | ... | 49                                | 340 | 40             | 275 | 6                      |
| 350         | 177  | 0.5                       | 45                       | 310 | 39             | 270 | 6                      | ...                      | ... | 55                                | 380 | 43             | 295 | 6                      |
|             |      | 10                        | 47                       | 325 | 42             | 290 | 6                      | ...                      | ... | 59                                | 405 | 49             | 340 | 4                      |
|             |      | 100                       | 43                       | 295 | 38             | 260 | 8                      | ...                      | ... | 59                                | 405 | 51             | 350 | 5                      |
|             |      | 1,000                     | 33                       | 230 | 28             | 195 | 13                     | ...                      | ... | 47                                | 325 | 37             | 255 | 8                      |
|             |      | 10,000                    | 19                       | 130 | 14             | 95  | 24                     | ...                      | ... | 30                                | 205 | 17             | 115 | 16                     |
| 400         | 205  | 0.5                       | 42                       | 290 | 39             | 270 | 6                      | ...                      | ... | 59                                | 405 | 49             | 340 | 5                      |
|             |      | 10                        | 39                       | 270 | 36             | 250 | 9                      | ...                      | ... | 58                                | 400 | 49             | 340 | 5                      |
|             |      | 100                       | 30                       | 205 | 26             | 180 | 17                     | ...                      | ... | 48                                | 330 | 37             | 255 | 7                      |
|             |      | 1,000                     | 19                       | 130 | 15             | 105 | 30                     | ...                      | ... | 32                                | 220 | 18             | 125 | 14                     |
|             |      | 10,000                    | 15                       | 105 | 11             | 75  | 45                     | ...                      | ... | 27                                | 185 | 13             | 90  | 20                     |
| 450         | 230  | 0.5                       | 37                       | 255 | 35             | 240 | 9                      | ...                      | ... | 58                                | 400 | 50             | 345 | 5                      |
|             |      | 10                        | 28                       | 195 | 25             | 170 | 15                     | ...                      | ... | 46                                | 315 | 36             | 250 | 8                      |
|             |      | 100                       | 18                       | 125 | 14             | 95  | 25                     | ...                      | ... | 35                                | 240 | 20             | 140 | 11                     |
|             |      | 1,000                     | 14                       | 95  | 11             | 75  | 40                     | ...                      | ... | 28                                | 195 | 14             | 95  | 17                     |
|             |      | 10,000                    | 12                       | 85  | 8.5            | 59  | 55                     | ...                      | ... | 25                                | 170 | 11             | 75  | 22                     |
| 500         | 260  | 0.5                       | 28                       | 195 | 25             | 170 | 16                     | ...                      | ... | 52                                | 360 | 42             | 290 | 6                      |
|             |      | 10                        | 17                       | 115 | 15             | 105 | 22                     | ...                      | ... | 36                                | 250 | 22             | 150 | 11                     |
|             |      | 100                       | 12                       | 85  | 9.5            | 66  | 35                     | ...                      | ... | 30                                | 205 | 15             | 105 | 15                     |
|             |      | 1,000                     | 9.5                      | 66  | 7.5            | 52  | 50                     | ...                      | ... | 27                                | 185 | 12             | 85  | 19                     |
|             |      | 10,000                    | 8.5                      | 59  | 6.0            | 41  | 65                     | ...                      | ... | 24                                | 165 | 10             | 70  | 22                     |
| 600         | 315  | 0.5                       | 13                       | 90  | 12             | 85  | 29                     | ...                      | ... | 38                                | 260 | 21             | 145 | 13                     |
|             |      | 10                        | 8.5                      | 59  | 7.0            | 48  | 60                     | ...                      | ... | 30                                | 205 | 13             | 90  | 17                     |
|             |      | 100                       | 6.0                      | 41  | 5.0            | 34  | 85                     | ...                      | ... | 27                                | 185 | 11             | 75  | 19                     |
|             |      | 1,000                     | ...                      | ... | ...            | ... | ...                    | ...                      | ... | 25                                | 170 | 9.5            | 66  | 21                     |
|             |      | 10,000                    | ...                      | ... | ...            | ... | ...                    | ...                      | ... | 23                                | 160 | 8.5            | 59  | 23                     |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.16 355.0-T51 Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| -320        | -196 | ...                    | 33                       | 230 | 27             | 185 | 1.5                 | ...                      | ... |
| -112        | -80  | ...                    | 29                       | 200 | 24             | 165 | 1.5                 | ...                      | ... |
| -18         | -28  | ...                    | 28                       | 195 | 23             | 160 | 1.5                 | ...                      | ... |
| 75          | 25   | ...                    | 28                       | 195 | 23             | 160 | 1.5                 | 10.2                     | 70  |
| 212         | 100  | 0.5                    | 28                       | 195 | 22             | 150 | 1.5                 | ...                      | ... |
|             |      | 10                     | 28                       | 195 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 100                    | 28                       | 195 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 1,000                  | 28                       | 195 | 22             | 150 | 2                   | ...                      | ... |
|             |      | 10,000                 | 28                       | 195 | 22             | 150 | 2                   | ...                      | ... |
| 300         | 150  | 0.5                    | 26                       | 180 | 21             | 145 | 2                   | ...                      | ... |
|             |      | 10                     | 26                       | 180 | 21             | 145 | 2                   | ...                      | ... |
|             |      | 100                    | 26                       | 180 | 20             | 140 | 2                   | ...                      | ... |
|             |      | 1,000                  | 25                       | 170 | 20             | 140 | 2                   | ...                      | ... |
|             |      | 10,000                 | 24                       | 165 | 19             | 130 | 3                   | ...                      | ... |
| 400         | 205  | 0.5                    | 22                       | 150 | 18             | 125 | 3                   | ...                      | ... |
|             |      | 10                     | 22                       | 150 | 17             | 115 | 3                   | ...                      | ... |
|             |      | 100                    | 20                       | 140 | 16             | 110 | 3                   | ...                      | ... |
|             |      | 1,000                  | 17                       | 115 | 14             | 95  | 5                   | ...                      | ... |
|             |      | 10,000                 | 14                       | 95  | 10             | 70  | 8                   | ...                      | ... |
| 500         | 260  | 0.5                    | 15                       | 105 | 14             | 95  | 5                   | ...                      | ... |
|             |      | 10                     | 14                       | 95  | 12             | 85  | 7                   | ...                      | ... |
|             |      | 100                    | 12                       | 85  | 10             | 70  | 10                  | ...                      | ... |
|             |      | 1,000                  | 10                       | 70  | 7.5            | 52  | 13                  | ...                      | ... |
|             |      | 10,000                 | 9.5                      | 66  | 5.0            | 34  | 16                  | ...                      | ... |
| 600         | 315  | 0.5                    | 9.5                      | 66  | 8.5            | 59  | 13                  | ...                      | ... |
|             |      | 10                     | 8.0                      | 55  | 7.0            | 48  | 19                  | ...                      | ... |
|             |      | 100                    | 7.0                      | 48  | 5.0            | 34  | 24                  | ...                      | ... |
|             |      | 1,000                  | 6.0                      | 41  | 4.0            | 28  | 30                  | ...                      | ... |
|             |      | 10,000                 | 6.0                      | 41  | 3.0            | 21  | 36                  | ...                      | ... |
| 700         | 370  | 0.5                    | 5.5                      | 38  | 4.5            | 31  | 25                  | ...                      | ... |
|             |      | 10                     | 5.0                      | 34  | 3.5            | 24  | 30                  | ...                      | ... |
|             |      | 100                    | 4.5                      | 31  | 3.0            | 21  | 40                  | ...                      | ... |
|             |      | 1,000                  | 3.5                      | 24  | 2.0            | 14  | 45                  | ...                      | ... |
|             |      | 10,000                 | 3.5                      | 24  | 2.0            | 14  | 50                  | ...                      | ... |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.

Table D4.17 355.0-T6 Sand castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                     |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|---------------------|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                     |
| 75          | 25  | ...                    | 35                       | 240 | 25             | 170 | 3                   |
| 212         | 100 | 0.5                    | 35                       | 240 | 25             | 170 | 3                   |
|             |     | 10                     | 35                       | 240 | 25             | 170 | 3                   |
|             |     | 100                    | 36                       | 250 | 26             | 180 | 3                   |
|             |     | 1,000                  | 37                       | 255 | 30             | 205 | 3                   |
|             |     | 10,000                 | 40                       | 275 | 35             | 240 | 3                   |
| 300         | 150 | 0.5                    | 34                       | 235 | 25             | 170 | 3                   |
|             |     | 10                     | 37                       | 255 | 30             | 205 | 3                   |
|             |     | 100                    | 39                       | 270 | 34             | 235 | 3                   |
|             |     | 1,000                  | 39                       | 270 | 36             | 250 | 3                   |
|             |     | 10,000                 | 33                       | 230 | 29             | 200 | 3                   |
| 350         | 177 | 0.5                    | 34                       | 235 | 25             | 170 | 3                   |
|             |     | 10                     | 38                       | 260 | 33             | 230 | 3                   |
|             |     | 100                    | 37                       | 255 | 34             | 235 | 3                   |
|             |     | 1,000                  | 30                       | 205 | 28             | 195 | 3                   |
|             |     | 10,000                 | 23                       | 160 | 18             | 125 | 5                   |
| 400         | 205 | 0.5                    | 33                       | 230 | 25             | 170 | 3                   |
|             |     | 10                     | 35                       | 240 | 30             | 205 | 3                   |
|             |     | 100                    | 30                       | 205 | 26             | 180 | 3                   |
|             |     | 1,000                  | 20                       | 140 | 17             | 115 | 5                   |
|             |     | 10,000                 | 15                       | 105 | 11             | 75  | 6                   |
| 500         | 260 | 0.5                    | 22                       | 150 | 19             | 130 | 5                   |
|             |     | 10                     | 17                       | 115 | 15             | 105 | 6                   |
|             |     | 100                    | 14                       | 95  | 11             | 75  | 8                   |
|             |     | 1,000                  | 11                       | 75  | 9.0            | 62  | 13                  |
|             |     | 10,000                 | 9.5                      | 66  | 6.0            | 41  | 16                  |
| 600         | 315 | 0.5                    | 10                       | 70  | 9.0            | 62  | 10                  |
|             |     | 10                     | 8.5                      | 59  | 7.0            | 48  | 15                  |
|             |     | 100                    | 7.5                      | 52  | 6.0            | 41  | 22                  |
|             |     | 1,000                  | 6.5                      | 45  | 4.5            | 31  | 30                  |
|             |     | 10,000                 | 6.0                      | 41  | 3.0            | 21  | 36                  |
| 700         | 370 | 0.5                    | 5.5                      | 38  | 4.5            | 31  | 25                  |
|             |     | 10                     | 5.0                      | 34  | 3.5            | 24  | 30                  |
|             |     | 100                    | 4.5                      | 31  | 3.0            | 21  | 40                  |
|             |     | 1,000                  | 4.0                      | 28  | 2.5            | 17  | 45                  |
|             |     | 10,000                 | 3.5                      | 24  | 2.0            | 14  | 50                  |

Source data are in English units; metric values are converted and rounded.

Table D4.18 355.0-T6 Sand castings: cryogenic tensile properties (not typical)

| Temperature |      | Tensile yield strength |     | Tensile ultimate strength |     | Elongation,<br>% | Reduction in<br>area, % |
|-------------|------|------------------------|-----|---------------------------|-----|------------------|-------------------------|
| °F          | °C   | ksi                    | MPa | ksi                       | MPa |                  |                         |
| -423        | -253 | 57.2                   | 394 | 63.6                      | 439 | 2.5              | 2.5                     |
| -423        | -253 | 56.3                   | 388 | 63.5                      | 438 | 1.0              | 1.0                     |
| -320        | -196 | 48.0                   | 331 | 61.2                      | 422 | 2.0              | 4.0                     |
| -320        | -196 | 45.0                   | 310 | 57.3                      | 395 | 2.0              | 4.0                     |
| -104        | -76  | 41.2                   | 284 | 52.0                      | 359 | 4.0              | 7.0                     |
| -104        | -76  | 28.6                   | 197 | 37.4                      | 258 | 5.0              | 6.0                     |
| 78          | 26   | 24.0                   | 165 | 32.8                      | 226 | 4.0              | 4.0                     |
| 78          | 26   | 28.6                   | 197 | 32.6                      | 225 | 4.0              | 3.0                     |

Source data are in English units; metric values are converted and rounded.

Source: Ref 2

Table D4.19 355.0-T62 Permanent mold castings: typical tensile properties

| Temperature |    | Modulus of elasticity(a) |     |
|-------------|----|--------------------------|-----|
| °F          | °C | 10 <sup>6</sup> psi      | GPa |
| 75          | 25 | 10.2                     | 70  |

(a) Average of tensile and compressive moduli  
Source data are in English units; metric values are converted and rounded.

Table D4.20 355.0-T71 Permanent mold castings: typical tensile properties

| Temperature |    | Modulus of elasticity(a) |     |
|-------------|----|--------------------------|-----|
| °F          | °C | 10 <sup>6</sup> psi      | GPa |
| 75          | 25 | 10.2                     | 70  |

(a) Average of tensile and compressive moduli  
Source data are in English units; metric values are converted and rounded.

Table D4.21 355.0-T71 Sand castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| 75          | 25  | ...                    | 35                       | 240 | 29             | 200 | 1.5                 | 10.2                     | 70  |
| 212         | 100 | 0.5                    | 34                       | 235 | 28             | 195 | 1.5                 | ...                      | ... |
|             |     | 10                     | 34                       | 235 | 28             | 195 | 2                   | ...                      | ... |
|             |     | 100                    | 34                       | 235 | 28             | 195 | 2                   | ...                      | ... |
|             |     | 1,000                  | 34                       | 235 | 28             | 195 | 2                   | ...                      | ... |
| 300         | 150 | 10,000                 | 34                       | 235 | 28             | 195 | 2                   | ...                      | ... |
|             |     | 0.5                    | 30                       | 205 | 26             | 180 | 2                   | ...                      | ... |
|             |     | 10                     | 30                       | 205 | 26             | 180 | 2                   | ...                      | ... |
|             |     | 100                    | 30                       | 205 | 26             | 180 | 2                   | ...                      | ... |
|             |     | 1,000                  | 30                       | 205 | 26             | 180 | 2                   | ...                      | ... |
|             |     | 10,000                 | 30                       | 205 | 26             | 180 | 3                   | ...                      | ... |
| 400         | 205 | 0.5                    | 26                       | 180 | 23             | 160 | 3                   | ...                      | ... |
|             |     | 10                     | 26                       | 180 | 23             | 160 | 3                   | ...                      | ... |
|             |     | 100                    | 25                       | 170 | 21             | 145 | 3                   | ...                      | ... |
|             |     | 1,000                  | 20.                      | 140 | 16             | 110 | 5                   | ...                      | ... |
|             |     | 10,000                 | 17                       | 115 | 13             | 90  | 8                   | ...                      | ... |
| 500         | 260 | 0.5                    | 20                       | 140 | 18             | 125 | 5                   | ...                      | ... |
|             |     | 10                     | 17                       | 115 | 15             | 105 | 6                   | ...                      | ... |
|             |     | 100                    | 14                       | 95  | 11             | 75  | 8                   | ...                      | ... |
|             |     | 1,000                  | 11                       | 75  | 8.0            | 55  | 13                  | ...                      | ... |
|             |     | 10,000                 | 9.5                      | 66  | 5.0            | 34  | 16                  | ...                      | ... |
| 600         | 315 | 0.5                    | 12                       | 85  | 10             | 70  | 10                  | ...                      | ... |
|             |     | 10                     | 9.5                      | 66  | 8.0            | 55  | 15                  | ...                      | ... |
|             |     | 100                    | 7.0                      | 48  | 5.5            | 38  | 22                  | ...                      | ... |
|             |     | 1,000                  | 6.0                      | 41  | 4.0            | 28  | 30                  | ...                      | ... |
|             |     | 10,000                 | 6.0                      | 41  | 3.0            | 21  | 36                  | ...                      | ... |
| 700         | 370 | 0.5                    | 5.5                      | 38  | 4.5            | 31  | 25                  | ...                      | ... |
|             |     | 10                     | 5.0                      | 34  | 3.5            | 24  | 30                  | ...                      | ... |
|             |     | 100                    | 4.5                      | 31  | 3.0            | 21  | 40                  | ...                      | ... |
|             |     | 1,000                  | 3.5                      | 24  | 2.0            | 14  | 45                  | ...                      | ... |
|             |     | 10,000                 | 3.5                      | 24  | 2.0            | 14  | 50                  | ...                      | ... |

(a) Average of tensile and compressive moduli  
Source data are in English units; metric values are converted and rounded.

Table D4.22 A355.0-T51 Sand castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                        |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|------------------------|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in in 4D, % |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                        |
| 75          | 25  | ...                    | 28                       | 195 | 24             | 165 | 1.5                    |
| 212         | 100 | 0.5                    | 28                       | 195 | 23             | 160 | 1.5                    |
|             |     | 10                     | 28                       | 195 | 23             | 160 | 1.5                    |
|             |     | 100                    | 28                       | 195 | 23             | 160 | 1.5                    |
|             |     | 1,000                  | 27                       | 185 | 23             | 160 | 1.5                    |
|             |     | 10,000                 | 27                       | 185 | 23             | 160 | 1.5                    |
| 300         | 150 | 0.5                    | 26                       | 180 | 21             | 145 | 1.5                    |
|             |     | 10                     | 25                       | 170 | 21             | 145 | 1.5                    |
|             |     | 100                    | 25                       | 170 | 20             | 140 | 1.5                    |
|             |     | 1,000                  | 24                       | 165 | 20             | 140 | 1.5                    |
|             |     | 10,000                 | 24                       | 165 | 20             | 140 | 2                      |
| 400         | 205 | 0.5                    | 22                       | 150 | 18             | 125 | 2                      |
|             |     | 10                     | 21                       | 145 | 16             | 110 | 2                      |
|             |     | 100                    | 19                       | 130 | 15             | 105 | 3                      |
|             |     | 1,000                  | 18                       | 125 | 13             | 90  | 3                      |
|             |     | 10,000                 | 17                       | 115 | 12             | 85  | 4                      |
| 500         | 260 | 0.5                    | 17                       | 115 | 14             | 95  | 4                      |
|             |     | 10                     | 15                       | 105 | 11             | 75  | 5                      |
|             |     | 100                    | 13                       | 90  | 9.5            | 66  | 6                      |
|             |     | 1,000                  | 12                       | 85  | 8.0            | 55  | 8                      |
|             |     | 10,000                 | 11                       | 75  | 7.0            | 48  | 10                     |
| 600         | 315 | 0.5                    | 12                       | 85  | 8.5            | 59  | 9                      |
|             |     | 10                     | 10                       | 70  | 7.0            | 48  | 9                      |
|             |     | 100                    | 9.0                      | 62  | 6.0            | 41  | 9                      |
|             |     | 1,000                  | 8.5                      | 59  | 5.5            | 38  | 9                      |
|             |     | 10,000                 | 7.5                      | 52  | 5.0            | 34  | 10                     |
| 700         | 370 | 0.5                    | 7.0                      | 48  | 5.0            | 34  | 10                     |
|             |     | 10                     | 7.0                      | 48  | 4.5            | 31  | 10                     |
|             |     | 100                    | 6.5                      | 45  | 4.5            | 31  | 10                     |
|             |     | 1,000                  | 6.0                      | 41  | 4.0            | 28  | 12                     |
|             |     | 10,000                 | 6.0                      | 41  | 4.0            | 28  | 15                     |

Source data are in English units; metric values are converted and rounded.

Table D4.23 C355.0-T6 Sand and permanent mold castings: typical tensile properties

| Temperature |       |                           | At temperature indicated |     |                |     |                        |                          |     | At room temperature after heating |     |                |     |                        |
|-------------|-------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|------------------------|
|             |       |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
|             |       |                           | ksi                      | MPa | ksi            | MPa |                        | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                        |
| °F          | °C    | Time at<br>temperature, h |                          |     |                |     |                        |                          |     |                                   |     |                |     |                        |
| − 320       | − 196 | ...                       | 56                       | 385 | 37             | 255 | 7                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| − 112       | − 80  | ...                       | 50                       | 345 | 34             | 235 | 7                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| − 18        | − 28  | ...                       | 48                       | 330 | 34             | 235 | 7                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 75          | 25    | ...                       | 46                       | 315 | 34             | 235 | 6                      | 10.1                     | 70  | 46                                | 315 | 34             | 235 | 6                      |
| 212         | 100   | 0.5                       | 44                       | 305 | 32             | 220 | 6                      | ...                      | ... | 46                                | 315 | 34             | 235 | 6                      |
|             |       | 10                        | 44                       | 305 | 33             | 230 | 6                      | ...                      | ... | 46                                | 315 | 34             | 235 | 6                      |
|             |       | 100                       | 44                       | 305 | 35             | 240 | 6                      | ...                      | ... | 48                                | 330 | 35             | 240 | 6                      |
|             |       | 1,000                     | 45                       | 310 | 36             | 250 | 6                      | ...                      | ... | 50                                | 345 | 38             | 260 | 6                      |
|             |       | 10,000                    | 46                       | 315 | 40             | 275 | 7                      | ...                      | ... | 50                                | 345 | 42             | 290 | 5                      |
|             |       | 0.5                       | 42                       | 290 | 32             | 220 | 10                     | ...                      | ... | 46                                | 315 | 35             | 240 | 6                      |
|             |       | 10                        | 42                       | 290 | 34             | 235 | 10                     | ...                      | ... | 49                                | 340 | 39             | 270 | 5                      |
|             |       | 100                       | 43                       | 295 | 38             | 260 | 10                     | ...                      | ... | 50                                | 345 | 42             | 290 | 4                      |
|             |       | 1,000                     | 42                       | 290 | 37             | 255 | 11                     | ...                      | ... | 48                                | 330 | 45             | 310 | 3                      |
|             |       | 10,000                    | 37                       | 255 | 32             | 220 | 12                     | ...                      | ... | 45                                | 310 | 37             | 255 | 6                      |
| 350         | 177   | 0.5                       | 40                       | 275 | 33             | 230 | 11                     | ...                      | ... | 48                                | 330 | 38             | 260 | 5                      |
|             |       | 10                        | 40                       | 275 | 35             | 240 | 13                     | ...                      | ... | 49                                | 340 | 43             | 295 | 4                      |
|             |       | 100                       | 39                       | 270 | 34             | 235 | 15                     | ...                      | ... | 47                                | 325 | 43             | 295 | 3                      |
|             |       | 1,000                     | 31                       | 215 | 24             | 165 | 20                     | ...                      | ... | 41                                | 285 | 33             | 230 | 7                      |
|             |       | 10,000                    | 22                       | 150 | 15             | 105 | 25                     | ...                      | ... | 33                                | 230 | 19             | 130 | 12                     |
| 400         | 205   | 0.5                       | 37                       | 255 | 34             | 235 | 13                     | ...                      | ... | 49                                | 340 | 41             | 285 | 4                      |
|             |       | 10                        | 35                       | 240 | 32             | 220 | 15                     | ...                      | ... | 46                                | 315 | 41             | 285 | 4                      |
|             |       | 100                       | 27                       | 185 | 24             | 165 | 20                     | ...                      | ... | 42                                | 290 | 33             | 230 | 8                      |
|             |       | 1,000                     | 16                       | 110 | 13             | 90  | 30                     | ...                      | ... | 30                                | 205 | 18             | 125 | 12                     |
|             |       | 10,000                    | 13                       | 90  | 9.0            | 62  | 40                     | ...                      | ... | 24                                | 165 | 11             | 75  | 18                     |
| 450         | 230   | 0.5                       | 31                       | 215 | 30             | 205 | 14                     | ...                      | ... | 48                                | 330 | 40             | 275 | 4                      |
|             |       | 10                        | 25                       | 170 | 23             | 160 | 17                     | ...                      | ... | 41                                | 285 | 32             | 220 | 7                      |
|             |       | 100                       | 17                       | 115 | 15             | 105 | 25                     | ...                      | ... | 32                                | 220 | 21             | 145 | 13                     |
|             |       | 1,000                     | 11                       | 75  | 8.5            | 59  | 40                     | ...                      | ... | 25                                | 170 | 12             | 85  | 16                     |
|             |       | 10,000                    | 9.0                      | 62  | 6.5            | 45  | 50                     | ...                      | ... | 23                                | 160 | 9.0            | 62  | 19                     |
| 500         | 260   | 0.5                       | 25                       | 170 | 24             | 165 | 15                     | ...                      | ... | 44                                | 305 | 35             | 240 | 6                      |
|             |       | 10                        | 17                       | 115 | 15             | 105 | 20                     | ...                      | ... | 35                                | 241 | 23             | 160 | 10                     |
|             |       | 100                       | 11                       | 75  | 10             | 70  | 30                     | ...                      | ... | 27                                | 185 | 14             | 95  | 15                     |
|             |       | 1,000                     | 8.5                      | 59  | 6.5            | 45  | 50                     | ...                      | ... | 24                                | 165 | 10             | 70  | 18                     |
|             |       | 10,000                    | 7.0                      | 48  | 5.0            | 34  | 60                     | ...                      | ... | 22                                | 150 | 8.0            | 55  | 20                     |
| 600         | 315   | 0.5                       | 13                       | 90  | 12             | 83  | 20                     | ...                      | ... | 35                                | 240 | 20             | 140 | 10                     |
|             |       | 10                        | 8.5                      | 59  | 6.5            | 45  | 35                     | ...                      | ... | 29                                | 200 | 13             | 90  | 12                     |
|             |       | 100                       | 6.0                      | 41  | 5.0            | 34  | 50                     | ...                      | ... | 25                                | 170 | 9.0            | 62  | 15                     |
|             |       | 1,000                     | 5.0                      | 34  | 3.5            | 24  | 65                     | ...                      | ... | 23                                | 160 | 7.5            | 52  | 20                     |
|             |       | 10,000                    | 4.5                      | 31  | 3.0            | 21  | 70                     | ...                      | ... | 21                                | 145 | 6.5            | 45  | 30                     |
| 700         | 370   | 0.5                       | 5.5                      | 38  | 4.5            | 31  | 45                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |       | 10                        | 4.0                      | 28  | 3.5            | 24  | 70                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |       | 100                       | 3.5                      | 24  | 3.0            | 21  | 90                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |       | 1,000                     | 3.5                      | 24  | 2.5            | 17  | 95                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |       | 10,000                    | 3.5                      | 24  | 2.5            | 17  | 95                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.24 356.0-T51 Sand castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |     |                |     |                        |                          |     | At room temperature after heating |     |                |     |                        |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|------------------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
|             |      |                           | ksi                      | MPa | ksi            | MPa |                        | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                        |
| °F          | °C   | Time at<br>temperature, h |                          |     |                |     |                        |                          |     |                                   |     |                |     |                        |
| -320        | -196 | ...                       | 31                       | 215 | 22             | 150 | 2                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| -112        | -80  | ...                       | 26                       | 180 | 20             | 140 | 2                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| -18         | -28  | ...                       | 26                       | 180 | 20             | 140 | 2                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 75          | 25   | ...                       | 25                       | 170 | 20             | 140 | 2                      | 10.5                     | 72  | 25                                | 170 | 20             | 140 | 2                      |
| 212         | 100  | 0.5                       | 24                       | 165 | 20             | 140 | 2                      | 10.3                     | 71  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 10                        | 24                       | 165 | 20             | 140 | 2                      | 10.3                     | 71  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 100                       | 24                       | 165 | 20             | 140 | 2                      | 10.3                     | 71  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 1,000                     | 24                       | 165 | 20             | 140 | 2                      | 10.3                     | 71  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 10,000                    | 24                       | 165 | 20             | 140 | 2                      | 10.3                     | 71  | 25                                | 170 | 20             | 140 | 2                      |
| 300         | 150  | 0.5                       | 22                       | 150 | 18             | 125 | 2                      | 10.0                     | 69  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 10                        | 22                       | 150 | 18             | 125 | 2                      | 10.0                     | 69  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 100                       | 22                       | 150 | 18             | 125 | 2                      | 10.0                     | 69  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 1,000                     | 22                       | 150 | 18             | 125 | 3                      | 10.0                     | 69  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 10,000                    | 21                       | 145 | 18             | 125 | 4                      | 10.0                     | 69  | 25                                | 170 | 18             | 125 | 3                      |
| 400         | 205  | 0.5                       | 20                       | 140 | 16             | 110 | 3                      | 9.4                      | 65  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 10                        | 19                       | 130 | 16             | 110 | 4                      | 9.4                      | 65  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 100                       | 18                       | 125 | 14             | 95  | 5                      | 9.4                      | 65  | 25                                | 170 | 18             | 125 | 3                      |
|             |      | 1,000                     | 14                       | 95  | 11             | 75  | 6                      | 9.4                      | 65  | 22                                | 150 | 14             | 95  | 4                      |
|             |      | 10,000                    | 12                       | 85  | 8.5            | 59  | 8                      | 9.4                      | 65  | 22                                | 150 | 11             | 75  | 4                      |
| 500         | 260  | 0.5                       | 15                       | 105 | 13             | 90  | 6                      | 8.4                      | 58  | 25                                | 170 | 20             | 140 | 2                      |
|             |      | 10                        | 11                       | 75  | 9.0            | 62  | 8                      | 8.4                      | 58  | 23                                | 160 | 14             | 95  | 3                      |
|             |      | 100                       | 9.0                      | 62  | 7.0            | 48  | 10                     | 8.4                      | 58  | 20                                | 140 | 9.5            | 66  | 4                      |
|             |      | 1,000                     | 8.0                      | 55  | 6.0            | 41  | 12                     | 8.4                      | 58  | 18                                | 125 | 9.0            | 62  | 5                      |
|             |      | 10,000                    | 7.5                      | 52  | 5.0            | 34  | 15                     | 8.4                      | 58  | 17                                | 115 | 8.5            | 59  | 6                      |
| 600         | 315  | 0.5                       | 7.5                      | 52  | 6.5            | 45  | 12                     | 6.8                      | 47  | 25                                | 170 | 18             | 125 | 2                      |
|             |      | 10                        | 6.5                      | 45  | 5.0            | 34  | 15                     | 6.8                      | 47  | 20                                | 140 | 10             | 70  | 4                      |
|             |      | 100                       | 5.5                      | 38  | 4.0            | 28  | 18                     | 6.8                      | 47  | 19                                | 130 | 8.5            | 59  | 6                      |
|             |      | 1,000                     | 5.0                      | 34  | 3.5            | 24  | 24                     | 6.8                      | 47  | 18                                | 125 | 8.0            | 55  | 8                      |
|             |      | 10,000                    | 4.0                      | 28  | 3.0            | 21  | 30                     | 6.8                      | 47  | 17                                | 115 | 7.5            | 52  | 9                      |
| 700         | 370  | 0.5                       | 5.0                      | 34  | 4.0            | 28  | 25                     | 4.2                      | 29  | 20                                | 140 | 10             | 70  | 4                      |
|             |      | 10                        | 4.0                      | 28  | 3.0            | 21  | 30                     | 4.2                      | 29  | 19                                | 130 | 9.0            | 62  | 6                      |
|             |      | 100                       | 3.0                      | 21  | 2.5            | 17  | 35                     | 4.2                      | 29  | 18                                | 125 | 8.0            | 55  | 8                      |
|             |      | 1,000                     | 2.5                      | 17  | 2.0            | 14  | 42                     | 4.2                      | 29  | 17                                | 115 | 7.0            | 48  | 9                      |
|             |      | 10,000                    | 2.5                      | 17  | 2.0            | 14  | 50                     | 4.2                      | 29  | 16                                | 110 | 7.0            | 48  | 10                     |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.



Table D4.25 356.0-T6 Permanent mold castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| -423        | -253 | ...                    | 61                       | 420 | 36             | 250 | 3                   | ...                      | ... |
| -320        | -196 | ...                    | 47                       | 325 | 32             | 220 | 3                   | ...                      | ... |
| -112        | -80  | ...                    | 43                       | 295 | 30             | 205 | 4                   | ...                      | ... |
| -18         | -28  | ...                    | 41                       | 285 | 28             | 195 | 4                   | ...                      | ... |
| 75          | 25   | ...                    | 38                       | 260 | 27             | 185 | 5                   | 10.4                     | 72  |
| 212         | 100  | 0.5                    | 34                       | 235 | 27             | 185 | 6                   | 10.2                     | 70  |
|             |      | 10                     | 36                       | 250 | 27             | 185 | 6                   | 10.2                     | 70  |
|             |      | 100                    | 36                       | 250 | 27             | 185 | 6                   | 10.2                     | 70  |
|             |      | 1,000                  | 33                       | 230 | 26             | 180 | 6                   | 10.2                     | 70  |
|             |      | 10,000                 | 30                       | 205 | 25             | 170 | 6                   | 10.2                     | 70  |
| 300         | 150  | 0.5                    | 29                       | 200 | 25             | 170 | 7                   | 9.9                      | 68  |
|             |      | 10                     | 32                       | 220 | 26             | 180 | 7                   | 9.9                      | 68  |
|             |      | 100                    | 29                       | 200 | 25             | 170 | 8                   | 9.9                      | 68  |
|             |      | 1,000                  | 23                       | 160 | 21             | 145 | 9                   | 9.9                      | 68  |
|             |      | 10,000                 | 21                       | 145 | 17             | 115 | 10                  | 9.9                      | 68  |
| 350         | 177  | 0.5                    | 26                       | 180 | 23             | 160 | 8                   | 9.7                      | 67  |
|             |      | 10                     | 27                       | 185 | 24             | 165 | 10                  | 9.7                      | 67  |
|             |      | 100                    | 23                       | 160 | 20             | 140 | 13                  | 9.7                      | 67  |
|             |      | 1,000                  | 18                       | 125 | 15             | 105 | 15                  | 9.7                      | 67  |
|             |      | 10,000                 | 16                       | 110 | 12             | 85  | 17                  | 9.7                      | 67  |
| 400         | 205  | 0.5                    | 23                       | 160 | 20             | 140 | 9                   | 9.4                      | 65  |
|             |      | 10                     | 21                       | 145 | 19             | 130 | 15                  | 9.4                      | 65  |
|             |      | 100                    | 16                       | 110 | 13             | 90  | 20                  | 9.4                      | 65  |
|             |      | 1,000                  | 13                       | 90  | 9.5            | 66  | 25                  | 9.4                      | 65  |
|             |      | 10,000                 | 12                       | 85  | 8.5            | 59  | 30                  | 9.4                      | 65  |
| 450         | 230  | 0.5                    | 19                       | 130 | 17             | 115 | 11                  | 8.9                      | 61  |
|             |      | 10                     | 16                       | 110 | 13             | 90  | 21                  | 8.9                      | 61  |
|             |      | 100                    | 12                       | 85  | 9.0            | 62  | 29                  | 8.9                      | 61  |
|             |      | 1,000                  | 10                       | 70  | 7.5            | 52  | 35                  | 8.9                      | 61  |
|             |      | 10,000                 | 9.5                      | 66  | 6.5            | 45  | 45                  | 8.9                      | 61  |
| 500         | 260  | 0.5                    | 15                       | 105 | 13             | 90  | 17                  | 8.3                      | 57  |
|             |      | 10                     | 11                       | 75  | 9.0            | 62  | 28                  | 8.3                      | 57  |
|             |      | 100                    | 9.0                      | 62  | 7.0            | 48  | 38                  | 8.3                      | 57  |
|             |      | 1,000                  | 8.0                      | 55  | 6.0            | 41  | 46                  | 8.3                      | 57  |
|             |      | 10,000                 | 7.5                      | 52  | 5.0            | 34  | 55                  | 8.3                      | 57  |
| 600         | 315  | 0.5                    | 7.5                      | 52  | 6.5            | 45  | 40                  | 6.8                      | 47  |
|             |      | 10                     | 6.5                      | 45  | 5.0            | 34  | 45                  | 6.8                      | 47  |
|             |      | 100                    | 5.5                      | 38  | 4.0            | 28  | 50                  | 6.8                      | 47  |
|             |      | 1,000                  | 5.0                      | 34  | 3.5            | 24  | 60                  | 6.8                      | 47  |
|             |      | 10,000                 | 4.0                      | 28  | 3.0            | 21  | 70                  | 6.8                      | 47  |
| 700         | 370  | 0.5                    | 5.0                      | 34  | 4.0            | 28  | 60                  | 4.2                      | 29  |
|             |      | 10                     | 4.0                      | 28  | 3.0            | 21  | 64                  | 4.2                      | 29  |
|             |      | 100                    | 3.0                      | 21  | 2.5            | 17  | 68                  | 4.2                      | 29  |
|             |      | 1,000                  | 2.5                      | 17  | 2.0            | 14  | 72                  | 4.2                      | 29  |
|             |      | 10,000                 | 2.5                      | 17  | 2.0            | 14  | 80                  | 4.2                      | 29  |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.26 356.0-T6 Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                           |     | At room temperature after heating |     |                |     |                     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|---------------------------|-----|-----------------------------------|-----|----------------|-----|---------------------|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity (a) |     | Tensile strength                  |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi       | GPa | ksi                               | MPa | ksi            | MPa |                     |
| -320        | -196 | ...                    | 40                       | 275 | 28             | 195 | 3.5                 | ...                       | ... | ...                               | ... | ...            | ... | ...                 |
| -112        | -80  | ...                    | 35                       | 240 | 25             | 170 | 3.5                 | ...                       | ... | ...                               | ... | ...            | ... | ...                 |
| -18         | -28  | ...                    | 33                       | 230 | 24             | 165 | 3.5                 | ...                       | ... | ...                               | ... | ...            | ... | ...                 |
| 75          | 25   | ...                    | 33                       | 230 | 24             | 165 | 3.5                 | 10.4                      | 72  | 33                                | 230 | 24             | 165 | 3.5                 |
| 212         | 100  | 0.5                    | 32                       | 220 | 24             | 165 | 4                   | 10.2                      | 70  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10                     | 33                       | 230 | 25             | 170 | 4                   | 10.2                      | 70  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 100                    | 33                       | 230 | 26             | 180 | 4                   | 10.2                      | 70  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 1,000                  | 33                       | 230 | 27             | 185 | 4                   | 10.2                      | 70  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10,000                 | 33                       | 230 | 25             | 170 | 4                   | 10.2                      | 70  | (b)                               | (b) | (b)            | (b) | ...                 |
| 300         | 150  | 0.5                    | 30                       | 205 | 24             | 165 | 4                   | 9.9                       | 68  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10                     | 32                       | 220 | 27             | 185 | 4                   | 9.9                       | 68  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 100                    | 32                       | 220 | 27             | 185 | 4                   | 9.9                       | 68  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 1,000                  | 29                       | 200 | 25             | 170 | 5                   | 9.9                       | 68  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10,000                 | 23                       | 160 | 20             | 140 | 6                   | 9.9                       | 68  | 30                                | 205 | 23             | 160 | 4                   |
| 350         | 177  | 0.5                    | 28                       | 195 | 24             | 165 | 4                   | 9.7                       | 67  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10                     | 29                       | 200 | 26             | 180 | 5                   | 9.7                       | 67  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 100                    | 26                       | 180 | 23             | 160 | 6                   | 9.7                       | 67  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 1,000                  | 21                       | 145 | 18             | 125 | 8                   | 9.7                       | 67  | 28                                | 195 | 21             | 145 | 5                   |
|             |      | 10,000                 | 17                       | 115 | 13             | 90  | 11                  | 9.7                       | 67  | 24                                | 165 | 16             | 110 | 8                   |
| 400         | 205  | 0.5                    | 26                       | 180 | 22             | 150 | 5                   | 9.4                       | 65  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10                     | 23                       | 160 | 20             | 140 | 6                   | 9.4                       | 65  | 32                                | 220 | 26             | 180 | 2                   |
|             |      | 100                    | 18                       | 125 | 15             | 105 | 8                   | 9.4                       | 65  | 28                                | 195 | 21             | 145 | 4                   |
|             |      | 1,000                  | 14                       | 95  | 11             | 75  | 13                  | 9.4                       | 65  | 22                                | 150 | 14             | 95  | 8                   |
|             |      | 10,000                 | 12                       | 85  | 8.5            | 59  | 18                  | 9.4                       | 65  | 20                                | 140 | 11             | 75  | 12                  |
| 450         | 230  | 0.5                    | 21                       | 145 | 19             | 130 | 6                   | 8.9                       | 61  | (b)                               | (b) | (b)            | (b) | ...                 |
|             |      | 10                     | 16                       | 110 | 14             | 95  | 8                   | 8.9                       | 61  | 28                                | 195 | 20             | 140 | 3                   |
|             |      | 100                    | 12                       | 85  | 9.0            | 62  | 12                  | 8.9                       | 61  | 22                                | 150 | 14             | 95  | 7                   |
|             |      | 1,000                  | 10                       | 70  | 7.5            | 52  | 19                  | 8.9                       | 61  | 19                                | 130 | 10             | 70  | 11                  |
|             |      | 10,000                 | 9.5                      | 66  | 6.5            | 45  | 26                  | 8.9                       | 61  | 18                                | 125 | 9.0            | 62  | 14                  |
| 500         | 260  | 0.5                    | 15                       | 105 | 13             | 90  | 8                   | 8.3                       | 57  | 32                                | 220 | 27             | 186 | 3                   |
|             |      | 10                     | 11                       | 75  | 9.0            | 62  | 12                  | 8.3                       | 57  | 23                                | 160 | 14             | 95  | 6                   |
|             |      | 100                    | 9.0                      | 62  | 7.0            | 48  | 18                  | 8.3                       | 57  | 20                                | 140 | 9.5            | 66  | 10                  |
|             |      | 1,000                  | 8.0                      | 55  | 6.0            | 41  | 25                  | 8.3                       | 57  | 18                                | 125 | 9.0            | 62  | 13                  |
|             |      | 10,000                 | 7.5                      | 52  | 5.0            | 34  | 35                  | 8.3                       | 57  | 17                                | 115 | 8.5            | 59  | 15                  |
| 600         | 315  | 0.5                    | 7.5                      | 52  | 6.5            | 45  | 20                  | 6.8                       | 47  | 29                                | 200 | 22             | 150 | 5                   |
|             |      | 10                     | 6.5                      | 45  | 5.0            | 34  | 24                  | 6.8                       | 47  | 20                                | 140 | 10             | 70  | 8                   |
|             |      | 100                    | 5.5                      | 38  | 4.0            | 28  | 33                  | 6.8                       | 47  | 19                                | 130 | 8.5            | 59  | 12                  |
|             |      | 1,000                  | 5.0                      | 34  | 3.5            | 24  | 45                  | 6.8                       | 47  | 18                                | 125 | 8.0            | 55  | 15                  |
|             |      | 10,000                 | 4.0                      | 28  | 3.0            | 21  | 60                  | 6.8                       | 47  | 17                                | 115 | 7.5            | 52  | 16                  |
| 700         | 370  | 0.5                    | 5.0                      | 34  | 4.0            | 28  | 35                  | 4.2                       | 29  | 20                                | 140 | 10             | 70  | 10                  |
|             |      | 10                     | 4.0                      | 28  | 3.0            | 21  | 46                  | 4.2                       | 29  | 19                                | 130 | 9.0            | 62  | 13                  |
|             |      | 100                    | 3.0                      | 21  | 2.5            | 17  | 58                  | 4.2                       | 29  | 18                                | 125 | 8.0            | 55  | 15                  |
|             |      | 1,000                  | 2.5                      | 17  | 2.0            | 14  | 68                  | 4.2                       | 29  | 17                                | 115 | 7.0            | 48  | 16                  |
|             |      | 10,000                 | 2.5                      | 17  | 2.0            | 14  | 80                  | 4.2                       | 29  | 16                                | 110 | 7.0            | 48  | 17                  |

(a) The modulus of elasticity in compression is about 2% greater than in tension. (b) Strengths are as high as, or higher than, the original room-temperature strengths. Source data are in English units; metric values are converted and rounded.

Table D4.27 356.0-T7 Permanent mold castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |     |                |     |                        |                          |                     | At room temperature after heating |     |                |     |                        |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|---------------------|-----------------------------------|-----|----------------|-----|------------------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |                     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
| °F          | °C   | Time at<br>temperature, h | ksi                      | MPa | ksi            | MPa |                        |                          | 10 <sup>6</sup> psi | GPa                               | ksi | MPa            | ksi |                        |
| −320        | −196 | ...                       | 40                       | 275 | 30             | 205 | 6                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| −112        | −80  | ...                       | 35                       | 240 | 26             | 180 | 6                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| −18         | −28  | ...                       | 34                       | 235 | 25             | 170 | 6                      | ...                      | ...                 | ...                               | ... | ...            | ... | ...                    |
| 75          | 25   | ...                       | 32                       | 220 | 24             | 165 | 6                      | 10.5                     | 72                  | 32                                | 220 | 24             | 165 | 6                      |
| 212         | 100  | 0.5                       | 27                       | 185 | 23             | 160 | 8                      | 10.3                     | 71                  | 32                                | 220 | 24             | 165 | 6                      |
|             |      | 10                        | 27                       | 185 | 23             | 160 | 8                      | 10.3                     | 71                  | 32                                | 220 | 24             | 165 | 6                      |
|             |      | 100                       | 27                       | 185 | 23             | 160 | 8                      | 10.3                     | 71                  | 32                                | 220 | 24             | 165 | 6                      |
|             |      | 1,000                     | 27                       | 185 | 23             | 160 | 9                      | 10.3                     | 71                  | 32                                | 220 | 24             | 165 | 7                      |
|             |      | 10,000                    | 27                       | 185 | 23             | 160 | 10                     | 10.3                     | 71                  | 32                                | 220 | 24             | 165 | 8                      |
| 300         | 150  | 0.5                       | 24                       | 165 | 22             | 150 | 10                     | 10.0                     | 69                  | 31                                | 215 | 24             | 165 | 7                      |
|             |      | 10                        | 24                       | 165 | 22             | 150 | 12                     | 10.0                     | 69                  | 31                                | 215 | 24             | 165 | 8                      |
|             |      | 100                       | 24                       | 165 | 22             | 150 | 14                     | 10.0                     | 69                  | 31                                | 215 | 24             | 165 | 9                      |
|             |      | 1,000                     | 23                       | 160 | 21             | 145 | 17                     | 10.0                     | 69                  | 31                                | 215 | 24             | 165 | 10                     |
|             |      | 10,000                    | 21                       | 145 | 17             | 115 | 20                     | 10.0                     | 69                  | 27                                | 185 | 18             | 125 | 12                     |
| 350         | 177  | 0.5                       | 22                       | 150 | 20             | 140 | 11                     | ...                      | ...                 | 31                                | 215 | 24             | 165 | 8                      |
|             |      | 10                        | 22                       | 150 | 20             | 140 | 17                     | ...                      | ...                 | 31                                | 215 | 24             | 165 | 11                     |
|             |      | 100                       | 21                       | 145 | 19             | 130 | 22                     | ...                      | ...                 | 31                                | 215 | 23             | 160 | 13                     |
|             |      | 1,000                     | 18                       | 125 | 15             | 105 | 26                     | ...                      | ...                 | 27                                | 185 | 18             | 125 | 16                     |
|             |      | 10,000                    | 16                       | 110 | 12             | 85  | 31                     | ...                      | ...                 | 22                                | 150 | 13             | 90  | 20                     |
| 400         | 205  | 0.5                       | 21                       | 145 | 19             | 130 | 12                     | 9.4                      | 65                  | 30                                | 205 | 23             | 160 | 10                     |
|             |      | 10                        | 19                       | 130 | 17             | 115 | 21                     | 9.4                      | 65                  | 30                                | 205 | 22             | 150 | 14                     |
|             |      | 100                       | 15                       | 105 | 13             | 90  | 28                     | 9.4                      | 65                  | 26                                | 180 | 18             | 125 | 19                     |
|             |      | 1,000                     | 13                       | 90  | 9.5            | 66  | 34                     | 9.4                      | 65                  | 22                                | 150 | 12             | 85  | 25                     |
|             |      | 10,000                    | 12                       | 85  | 8.5            | 59  | 40                     | 9.4                      | 65                  | 20                                | 140 | 11             | 75  | 30                     |
| 500         | 260  | 0.5                       | 15                       | 105 | 13             | 90  | 20                     | 8.4                      | 58                  | 29                                | 200 | 20             | 140 | 15                     |
|             |      | 10                        | 11                       | 75  | 9.0            | 62  | 28                     | 8.4                      | 58                  | 22                                | 150 | 12             | 85  | 20                     |
|             |      | 100                       | 9.0                      | 62  | 7.0            | 48  | 38                     | 8.4                      | 58                  | 20                                | 140 | 9.5            | 66  | 25                     |
|             |      | 1,000                     | 8.0                      | 55  | 6.0            | 41  | 46                     | 8.4                      | 58                  | 18                                | 125 | 9.0            | 62  | 30                     |
|             |      | 10,000                    | 7.5                      | 52  | 5.0            | 34  | 55                     | 8.4                      | 58                  | 17                                | 115 | 8.5            | 59  | 34                     |
| 600         | 315  | 0.5                       | 7.5                      | 52  | 6.5            | 45  | 40                     | 6.8                      | 47                  | 22                                | 150 | 12             | 85  | 20                     |
|             |      | 10                        | 6.5                      | 45  | 5.0            | 34  | 45                     | 6.8                      | 47                  | 20                                | 140 | 10             | 70  | 25                     |
|             |      | 100                       | 5.5                      | 38  | 4.0            | 28  | 50                     | 6.8                      | 47                  | 19                                | 130 | 8.5            | 59  | 30                     |
|             |      | 1,000                     | 5.0                      | 34  | 3.5            | 24  | 60                     | 6.8                      | 47                  | 18                                | 125 | 8.0            | 55  | 33                     |
|             |      | 10,000                    | 4.0                      | 28  | 3.0            | 21  | 70                     | 6.8                      | 47                  | 17                                | 115 | 7.5            | 52  | 35                     |
| 700         | 370  | 0.5                       | 5.0                      | 34  | 4.0            | 28  | 60                     | 4.2                      | 29                  | 20                                | 140 | 10             | 70  | 25                     |
|             |      | 10                        | 4.0                      | 28  | 3.0            | 21  | 64                     | 4.2                      | 29                  | 19                                | 130 | 9.0            | 62  | 28                     |
|             |      | 100                       | 3.0                      | 21  | 2.5            | 17  | 68                     | 4.2                      | 29                  | 18                                | 125 | 8.0            | 55  | 32                     |
|             |      | 1,000                     | 2.5                      | 17  | 2.0            | 14  | 72                     | 4.2                      | 29                  | 17                                | 115 | 7.0            | 48  | 34                     |
|             |      | 10,000                    | 2.5                      | 17  | 2.0            | 14  | 80                     | 4.2                      | 29                  | 16                                | 110 | 7.0            | 48  | 35                     |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.

Table D4.28 356.0-T7 Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                          |     | At room temperature after heating |     |                |     |                     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|---------------------|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                     |
| −320        | −196 | ...                    | 41                       | 285 | 35             | 240 | 2                   | ...                      | ... | ...                               | ... | ...            | ... | ...                 |
| −112        | −80  | ...                    | 36                       | 250 | 32             | 220 | 2                   | ...                      | ... | ...                               | ... | ...            | ... | ...                 |
| −18         | −28  | ...                    | 34                       | 235 | 31             | 215 | 2                   | ...                      | ... | ...                               | ... | ...            | ... | ...                 |
| 75          | 25   | ...                    | 34                       | 235 | 30             | 205 | 2                   | 10.5                     | 72  | 34                                | 235 | 30             | 205 | 2                   |
| 212         | 100  | 0.5                    | 30                       | 205 | 28             | 195 | 2                   | 10.3                     | 71  | 34                                | 235 | 30             | 205 | 2                   |
|             |      | 10                     | 30                       | 205 | 28             | 195 | 2                   | 10.3                     | 71  | 34                                | 235 | 30             | 205 | 2                   |
|             |      | 100                    | 30                       | 205 | 28             | 195 | 2                   | 10.3                     | 71  | 34                                | 235 | 30             | 205 | 2                   |
|             |      | 1,000                  | 30                       | 205 | 28             | 195 | 2                   | 10.3                     | 71  | 34                                | 235 | 30             | 205 | 2                   |
|             |      | 10,000                 | 30                       | 205 | 28             | 195 | 2                   | 10.3                     | 71  | 34                                | 235 | 30             | 205 | 2                   |
| 300         | 150  | 0.5                    | 26                       | 180 | 25             | 170 | 2                   | 10.0                     | 69  | 33                                | 230 | 30             | 205 | 2                   |
|             |      | 10                     | 26                       | 180 | 25             | 170 | 2                   | 10.0                     | 69  | 33                                | 230 | 30             | 205 | 2                   |
|             |      | 100                    | 26                       | 180 | 25             | 170 | 2                   | 10.0                     | 69  | 33                                | 230 | 30             | 205 | 2                   |
|             |      | 1,000                  | 26                       | 180 | 24             | 165 | 3                   | 10.0                     | 69  | 33                                | 230 | 28             | 195 | 3                   |
|             |      | 10,000                 | 23                       | 160 | 20             | 140 | 6                   | 10.0                     | 69  | 30                                | 205 | 23             | 160 | 4                   |
| 350         | 177  | 0.5                    | 24                       | 165 | 23             | 160 | 2                   | ...                      | ... | 33                                | 230 | 30             | 205 | 2                   |
|             |      | 10                     | 24                       | 165 | 23             | 160 | 3                   | ...                      | ... | 33                                | 230 | 30             | 205 | 2                   |
|             |      | 100                    | 23                       | 160 | 20             | 140 | 4                   | ...                      | ... | 33                                | 230 | 28             | 195 | 2                   |
|             |      | 1,000                  | 20                       | 140 | 17             | 115 | 8                   | ...                      | ... | 28                                | 195 | 21             | 145 | 5                   |
|             |      | 10,000                 | 17                       | 115 | 13             | 90  | 11                  | ...                      | ... | 24                                | 165 | 16             | 110 | 8                   |
| 400         | 205  | 0.5                    | 22                       | 150 | 20             | 140 | 3                   | 9.4                      | 65  | 33                                | 230 | 29             | 200 | 2                   |
|             |      | 10                     | 21                       | 145 | 20             | 140 | 5                   | 9.4                      | 65  | 32                                | 220 | 26             | 180 | 2                   |
|             |      | 100                    | 18                       | 125 | 15             | 105 | 8                   | 9.4                      | 65  | 28                                | 195 | 21             | 145 | 4                   |
|             |      | 1,000                  | 14                       | 95  | 11             | 75  | 13                  | 9.4                      | 65  | 22                                | 150 | 14             | 95  | 8                   |
|             |      | 10,000                 | 12                       | 85  | 8.5            | 59  | 18                  | 9.4                      | 65  | 20                                | 140 | 11             | 75  | 12                  |
| 500         | 260  | 0.5                    | 15                       | 105 | 13             | 90  | 8                   | 8.4                      | 58  | 32                                | 220 | 27             | 185 | 3                   |
|             |      | 10                     | 11                       | 75  | 9.0            | 62  | 12                  | 8.4                      | 58  | 23                                | 160 | 14             | 95  | 6                   |
|             |      | 100                    | 9.0                      | 62  | 7.0            | 48  | 18                  | 8.4                      | 58  | 20                                | 140 | 9.5            | 66  | 10                  |
|             |      | 1,000                  | 8.0                      | 55  | 6.0            | 41  | 25                  | 8.4                      | 58  | 18                                | 125 | 9.0            | 62  | 13                  |
|             |      | 10,000                 | 7.5                      | 52  | 5.0            | 34  | 35                  | 8.4                      | 58  | 17                                | 115 | 8.5            | 59  | 15                  |
| 600         | 315  | 0.5                    | 7.5                      | 52  | 6.5            | 45  | 20                  | 6.8                      | 47  | 29                                | 200 | 22             | 150 | 5                   |
|             |      | 10                     | 6.5                      | 45  | 5.0            | 34  | 24                  | 6.8                      | 47  | 20                                | 140 | 10             | 70  | 8                   |
|             |      | 100                    | 5.5                      | 38  | 4.0            | 28  | 33                  | 6.8                      | 47  | 19                                | 130 | 8.5            | 59  | 12                  |
|             |      | 1,000                  | 5.0                      | 34  | 3.5            | 24  | 45                  | 6.8                      | 47  | 18                                | 125 | 8.0            | 55  | 15                  |
|             |      | 10,000                 | 4.0                      | 28  | 3.0            | 21  | 60                  | 6.8                      | 47  | 17                                | 115 | 7.5            | 52  | 16                  |
| 700         | 370  | 0.5                    | 5.0                      | 34  | 4.0            | 28  | 35                  | 4.2                      | 29  | 20                                | 140 | 10             | 70  | 10                  |
|             |      | 10                     | 4.0                      | 28  | 3.0            | 21  | 46                  | 4.2                      | 29  | 19                                | 130 | 9.0            | 62  | 13                  |
|             |      | 100                    | 3.0                      | 21  | 2.5            | 17  | 58                  | 4.2                      | 29  | 18                                | 125 | 8.0            | 55  | 15                  |
|             |      | 1,000                  | 2.5                      | 17  | 2.0            | 14  | 68                  | 4.2                      | 29  | 17                                | 115 | 7.0            | 48  | 16                  |
|             |      | 10,000                 | 2.5                      | 17  | 2.0            | 14  | 80                  | 4.2                      | 29  | 16                                | 110 | 7.0            | 48  | 17                  |

(a) Average of tensile and compressive moduli  
 Source data are in English units; metric values are converted and rounded.

Table D4.29 A356.0-T6, -T61 Permanent mold castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| -452        | -269 | ...                    | 63                       | 435 | 48             | 330 | 8                   | ...                      | ... |
| -423        | -253 | ...                    | 61                       | 420 | 45             | 310 | 8                   | ...                      | ... |
| -320        | -196 | ...                    | 54                       | 370 | 36             | 250 | 10                  | ...                      | ... |
| -112        | -80  | ...                    | 46                       | 315 | 32             | 220 | 10                  | ...                      | ... |
| -18         | -28  | ...                    | 43                       | 295 | 31             | 215 | 10                  | ...                      | ... |
| 75          | 25   | ...                    | 41                       | 285 | 30             | 205 | 10                  | 10.4                     | 72  |
| 212         | 100  | 0.5                    | 37                       | 255 | 28             | 195 | 16                  | 10.2                     | 70  |
|             |      | 10                     | 37                       | 255 | 28             | 195 | 16                  | 10.2                     | 70  |
|             |      | 100                    | 37                       | 255 | 29             | 200 | 14                  | 10.2                     | 70  |
|             |      | 1,000                  | 38                       | 260 | 31             | 215 | 13                  | 10.2                     | 70  |
|             |      | 10,000                 | 38                       | 260 | 33             | 230 | 12                  | 10.2                     | 70  |
| 300         | 150  | 0.5                    | 34                       | 235 | 27             | 185 | 19                  | 9.9                      | 68  |
|             |      | 10                     | 35                       | 240 | 28             | 195 | 17                  | 9.9                      | 68  |
|             |      | 100                    | 36                       | 250 | 31             | 215 | 15                  | 9.9                      | 68  |
|             |      | 1,000                  | 32                       | 220 | 28             | 195 | 17                  | 9.9                      | 68  |
|             |      | 10,000                 | 21                       | 145 | 17             | 115 | 20                  | 9.9                      | 68  |
| 350         | 177  | 0.5                    | 32                       | 220 | 27             | 185 | 17                  | 9.7                      | 67  |
|             |      | 10                     | 32                       | 220 | 28             | 195 | 16                  | 9.7                      | 67  |
|             |      | 100                    | 26                       | 180 | 24             | 165 | 21                  | 9.7                      | 67  |
|             |      | 1,000                  | 18                       | 125 | 15             | 105 | 26                  | 9.7                      | 67  |
|             |      | 10,000                 | 16                       | 110 | 12             | 85  | 30                  | 9.7                      | 67  |
| 400         | 205  | 0.5                    | 28                       | 195 | 26             | 180 | 15                  | 9.4                      | 65  |
|             |      | 10                     | 25                       | 170 | 24             | 165 | 18                  | 9.4                      | 65  |
|             |      | 100                    | 16                       | 110 | 13             | 90  | 27                  | 9.4                      | 65  |
|             |      | 1,000                  | 13                       | 90  | 9.5            | 66  | 34                  | 9.4                      | 65  |
|             |      | 10,000                 | 12                       | 85  | 8.5            | 59  | 40                  | 9.4                      | 65  |
| 450         | 230  | 0.5                    | 23                       | 160 | 22             | 150 | 17                  | 8.9                      | 61  |
|             |      | 10                     | 17                       | 115 | 16             | 110 | 22                  | 8.9                      | 61  |
|             |      | 100                    | 12                       | 85  | 9.0            | 62  | 30                  | 8.9                      | 61  |
|             |      | 1,000                  | 10                       | 70  | 7.5            | 52  | 40                  | 8.9                      | 61  |
|             |      | 10,000                 | 9.5                      | 66  | 6.5            | 45  | 50                  | 8.9                      | 61  |
| 500         | 260  | 0.5                    | 16                       | 110 | 15             | 105 | 21                  | 8.3                      | 57  |
|             |      | 10                     | 11                       | 75  | 9.0            | 62  | 28                  | 8.3                      | 57  |
|             |      | 100                    | 9.0                      | 62  | 7.0            | 48  | 38                  | 8.3                      | 57  |
|             |      | 1,000                  | 8.0                      | 55  | 6.0            | 41  | 46                  | 8.3                      | 57  |
|             |      | 10,000                 | 7.5                      | 52  | 5.0            | 34  | 55                  | 8.3                      | 57  |
| 600         | 315  | 0.5                    | 7.5                      | 52  | 6.5            | 45  | 40                  | 6.8                      | 47  |
|             |      | 10                     | 6.5                      | 45  | 5.0            | 34  | 45                  | 6.8                      | 47  |
|             |      | 100                    | 5.5                      | 38  | 4.0            | 28  | 50                  | 6.8                      | 47  |
|             |      | 1,000                  | 5.0                      | 34  | 3.5            | 24  | 60                  | 6.8                      | 47  |
|             |      | 10,000                 | 4.0                      | 28  | 3.0            | 21  | 70                  | 6.8                      | 47  |
| 700         | 370  | 0.5                    | 5.0                      | 34  | 4.0            | 28  | 60                  | 4.2                      | 29  |
|             |      | 10                     | 4.0                      | 28  | 3.0            | 21  | 64                  | 4.2                      | 29  |
|             |      | 100                    | 3.0                      | 21  | 2.5            | 17  | 68                  | 4.2                      | 29  |
|             |      | 1,000                  | 2.5                      | 17  | 2.0            | 14  | 72                  | 4.2                      | 29  |
|             |      | 10,000                 | 2.5                      | 17  | 2.0            | 14  | 80                  | 4.2                      | 29  |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.30 A357.0-T6, -T61, -T62 Permanent mold castings: typical tensile properties

| Temperature |      | Time at temperature, h | At temperature indicated |     |                |     |                     |                          | At room temperature after heating |                  |     |                |     |                     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----------------------------------|------------------|-----|----------------|-----|---------------------|
|             |      |                        | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |                                   | Tensile strength |     | Yield strength |     | Elongation in 4D, % |
|             |      |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa                               | ksi              | MPa | ksi            | MPa |                     |
| °F          | °C   |                        |                          |     |                |     |                     |                          |                                   |                  |     |                |     |                     |
| -320        | -196 | ...                    | 62                       | 425 | 48             | 330 | 6                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| -112        | -80  | ...                    | 55                       | 380 | 45             | 310 | 6                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| -18         | -28  | ...                    | 54                       | 370 | 44             | 305 | 6                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 75          | 25   | ...                    | 52                       | 360 | 42             | 290 | 8                   | 10.4                     | 72                                | ...              | ... | ...            | ... | ...                 |
| 212         | 100  | 0.5                    | 46                       | 315 | 39             | 270 | 10                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10                     | 46                       | 315 | 39             | 270 | 10                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 100                    | 46                       | 315 | 39             | 270 | 10                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 1,000                  | 46                       | 315 | 40             | 275 | 8                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10,000                 | 48                       | 330 | 45             | 310 | 6                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 300         | 150  | 0.5                    | 39                       | 270 | 35             | 240 | 10                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10                     | 41                       | 285 | 37             | 255 | 9                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 100                    | 42                       | 290 | 40             | 275 | 7                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 1,000                  | 38                       | 260 | 36             | 250 | 7                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10,000                 | 23                       | 160 | 21             | 145 | 20                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 350         | 177  | 0.5                    | 37                       | 255 | 34             | 235 | 7                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10                     | 40                       | 275 | 38             | 260 | 6                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 100                    | 35                       | 240 | 33             | 230 | 7                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 1,000                  | 22                       | 150 | 20             | 140 | 19                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10,000                 | 13                       | 90  | 11             | 75  | 35                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 400         | 205  | 0.5                    | 36                       | 250 | 35             | 240 | 6                   | ...                      | ...                               | 52               | 360 | 45             | 310 | 6                   |
|             |      | 10                     | 30                       | 205 | 28             | 195 | 7                   | ...                      | ...                               | 44               | 305 | 38             | 260 | 7                   |
|             |      | 100                    | 23                       | 160 | 21             | 145 | 23                  | ...                      | ...                               | 35               | 230 | 27             | 185 | 9                   |
|             |      | 1,000                  | 12                       | 85  | 10             | 70  | 40                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10,000                 | 10                       | 70  | 7.5            | 50  | 50                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 450         | 230  | 0.5                    | 31                       | 215 | 30             | 205 | 9                   | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10                     | 19                       | 130 | 18             | 125 | 13                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 100                    | 14                       | 95  | 13             | 90  | 45                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 500         | 260  | 0.5                    | 23                       | 160 | 22             | 150 | 16                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 10                     | 12                       | 85  | 11             | 75  | 23                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
|             |      | 100                    | 8.0                      | 55  | 7.0            | 50  | 55                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |
| 600         | 315  | 0.5                    | 10                       | 70  | 9.5            | 65  | 35                  | ...                      | ...                               | ...              | ... | ...            | ... | ...                 |

(a) Average of tensile and compressive moduli.  
Source data are in English units; metric values are converted and rounded.

Table D4.31 A359.0-T6, -T61 Permanent mold castings: typical tensile properties

| Temperature |      | Time at<br>temperature, h | At temperature indicated |     |                |     |                        |                          |     | At room temperature after heating |     |                |     |                        |
|-------------|------|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|------------------------|
|             |      |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
|             |      |                           | ksi                      | MPa | ksi            | MPa |                        | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                        |
| −320        | −196 | ...                       | 60                       | 415 | 43             | 295 | 4                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| −112        | −80  | ...                       | 53                       | 365 | 41             | 285 | 5                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| −18         | −28  | ...                       | 49                       | 340 | 38             | 260 | 6                      | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 75          | 25   | ...                       | 47                       | 325 | 37             | 255 | 7                      | 10.5                     | 72  | 47                                | 325 | 37             | 255 | 7                      |
| 212         | 100  | 0.5                       | 41                       | 285 | 34             | 235 | 9                      | ...                      | ... | 47                                | 325 | 37             | 255 | 7                      |
|             |      | 10                        | 42                       | 290 | 35             | 240 | 9                      | ...                      | ... | 47                                | 325 | 37             | 255 | 7                      |
|             |      | 100                       | 43                       | 295 | 35             | 240 | 9                      | ...                      | ... | 49                                | 340 | 38             | 260 | 7                      |
|             |      | 1,000                     | 44                       | 305 | 36             | 250 | 9                      | ...                      | ... | 52                                | 360 | 40             | 275 | 7                      |
|             |      | 10,000                    | 46                       | 315 | 40             | 275 | 9                      | ...                      | ... | 55                                | 380 | 48             | 330 | 7                      |
| 300         | 149  | 0.5                       | 38                       | 260 | 33             | 230 | 10                     | ...                      | ... | 47                                | 325 | 37             | 255 | 7                      |
|             |      | 10                        | 40                       | 275 | 35             | 240 | 10                     | ...                      | ... | 51                                | 350 | 41             | 285 | 7                      |
|             |      | 100                       | 42                       | 290 | 38             | 260 | 10                     | ...                      | ... | 55                                | 380 | 48             | 330 | 7                      |
|             |      | 1,000                     | 36                       | 250 | 34             | 235 | 11                     | ...                      | ... | 49                                | 340 | 42             | 290 | 7                      |
|             |      | 10,000                    | 18                       | 125 | 14             | 95  | 30                     | ...                      | ... | 26                                | 180 | 17             | 115 | 16                     |
| 350         | 177  | 0.5                       | 37                       | 255 | 33             | 230 | 11                     | ...                      | ... | 47                                | 325 | 38             | 260 | 7                      |
|             |      | 10                        | 38                       | 260 | 36             | 250 | 11                     | ...                      | ... | 55                                | 380 | 48             | 330 | 7                      |
|             |      | 100                       | 32                       | 220 | 30             | 205 | 15                     | ...                      | ... | 44                                | 305 | 38             | 260 | 7                      |
|             |      | 1,000                     | 17                       | 115 | 14             | 95  | 35                     | ...                      | ... | 26                                | 180 | 17             | 115 | 18                     |
|             |      | 10,000                    | 13                       | 90  | 10             | 70  | 40                     | ...                      | ... | 22                                | 150 | 12             | 85  | 25                     |
| 400         | 205  | 0.5                       | 35                       | 240 | 33             | 230 | 12                     | ...                      | ... | 50                                | 345 | 46             | 315 | 7                      |
|             |      | 10                        | 26                       | 180 | 24             | 165 | 16                     | ...                      | ... | 43                                | 295 | 36             | 250 | 9                      |
|             |      | 100                       | 16                       | 110 | 14             | 95  | 30                     | ...                      | ... | 27                                | 185 | 18             | 125 | 18                     |
|             |      | 1,000                     | 12                       | 85  | 9.5            | 66  | 40                     | ...                      | ... | 22                                | 150 | 12             | 85  | 27                     |
|             |      | 10,000                    | 11                       | 75  | 8.5            | 59  | 45                     | ...                      | ... | 20                                | 140 | 11             | 75  | 27                     |
| 450         | 230  | 0.5                       | 28                       | 195 | 26             | 180 | 16                     | ...                      | ... | 51                                | 350 | 44             | 305 | 10                     |
|             |      | 10                        | 14                       | 95  | 12             | 85  | 29                     | ...                      | ... | 30                                | 205 | 20             | 140 | 15                     |
|             |      | 100                       | 11                       | 75  | 9.0            | 62  | 40                     | ...                      | ... | 22                                | 150 | 12             | 85  | 28                     |
|             |      | 1,000                     | 9.5                      | 66  | 7.5            | 52  | 45                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |      | 10,000                    | 8.5                      | 59  | 6.5            | 45  | 50                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 500         | 260  | 0.5                       | 18                       | 125 | 17             | 115 | 25                     | ...                      | ... | 37                                | 255 | 28             | 195 | 13                     |
|             |      | 10                        | 9.5                      | 66  | 8.5            | 59  | 40                     | ...                      | ... | 24                                | 165 | 13             | 90  | 25                     |
|             |      | 100                       | 8.5                      | 59  | 7.0            | 48  | 50                     | ...                      | ... | 21                                | 145 | 10             | 70  | 30                     |
|             |      | 1,000                     | 7.5                      | 52  | 6.0            | 41  | 55                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |      | 10,000                    | 7.0                      | 48  | 5.0            | 34  | 60                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 600         | 315  | 0.5                       | 7.5                      | 52  | 6.5            | 45  | 50                     | ...                      | ... | 22                                | 150 | 12             | 85  | 20                     |
|             |      | 10                        | 6.0                      | 41  | 5.5            | 38  | 60                     | ...                      | ... | 21                                | 145 | 11             | 75  | 28                     |
|             |      | 100                       | 5.5                      | 38  | 4.4            | 30  | 65                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 700         | 370  | 0.5                       | 4.4                      | 30  | 4.0            | 28  | 55                     | ...                      | ... | 21                                | 145 | 10             | 70  | 28                     |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.



Table D4.32 359.0-T62 Permanent mold castings: typical tensile properties

| Temperature |      |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
|             |      |                        | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
|             |      |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| °F          | °C   | Time at temperature, h |                          |     |                |     |                     |                          |     |
| -320        | -196 | ...                    | 63                       | 435 | 47             | 325 | 4                   | ...                      | ... |
| -112        | -80  | ...                    | 55                       | 380 | 47             | 325 | 5                   | ...                      | ... |
| -18         | -28  | ...                    | 52                       | 360 | 45             | 310 | 6                   | ...                      | ... |
| 75          | 25   | ...                    | 50                       | 345 | 42             | 290 | 5                   | 10.5                     | 72  |
| 300         | 150  | 100                    | 42                       | 290 | 38             | 260 | 10                  | ...                      | ... |
|             |      | 1,000                  | 36                       | 250 | 34             | 235 | 11                  | ...                      | ... |
|             |      | 10,000                 | 18                       | 125 | 14             | 95  | 30                  | ...                      | ... |
| 500         | 260  | 0.5                    | 18                       | 125 | 17             | 115 | 25                  | ...                      | ... |
|             |      | 10                     | 9.5                      | 66  | 8.5            | 59  | 40                  | ...                      | ... |
|             |      | 100                    | 8.5                      | 59  | 7.0            | 48  | 50                  | ...                      | ... |
|             |      | 1,000                  | 7.5                      | 52  | 6.0            | 41  | 55                  | ...                      | ... |
|             |      | 10,000                 | 7.0                      | 48  | 5.0            | 34  | 60                  | ...                      | ... |
| 600         | 315  | 0.5                    | 7.5                      | 52  | 6.5            | 45  | 50                  | ...                      | ... |
|             |      | 10                     | 6.0                      | 41  | 5.5            | 38  | 60                  | ...                      | ... |
|             |      | 100                    | 5.5                      | 38  | 4.4            | 30  | 65                  | ...                      | ... |
| 700         | 370  | 0.5                    | 4.4                      | 30  | 4.0            | 28  | 55                  | ...                      | ... |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.33 360.0-F Die castings: typical tensile properties

| Temperature |     |                        | At temperature indicated |     |                |     |                                |                          | At room temperature after heating |                  |     |                |     |                                |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|--------------------------------|--------------------------|-----------------------------------|------------------|-----|----------------|-----|--------------------------------|
|             |     |                        | Tensile strength         |     | Yield strength |     | Elongation in 2 in. (50 mm), % | Modulus of elasticity(a) |                                   | Tensile strength |     | Yield strength |     | Elongation in 2 in. (50 mm), % |
|             |     |                        | ksi                      | MPa | ksi            | MPa |                                | 10 <sup>6</sup> psi      | GPa                               | ksi              | MPa | ksi            | MPa |                                |
| °F          | °C  | Time at temperature, h |                          |     |                |     |                                |                          |                                   |                  |     |                |     |                                |
| -112        | -80 | ...                    | 50                       | 345 | 24             | 165 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| -18         | -28 | ...                    | 48                       | 330 | 25             | 170 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 75          | 25  | ...                    | 47                       | 325 | 25             | 170 | 3                              | 10.3                     | 71                                | 47               | 325 | 25             | 170 | 3                              |
| 212         | 100 | 0.5                    | 44                       | 305 | 25             | 170 | 4                              | ...                      | ...                               | 49               | 340 | 26             | 180 | 3                              |
|             |     | 10                     | 44                       | 305 | 25             | 170 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 44                       | 305 | 26             | 180 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 48                       | 330 | 32             | 220 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 49                       | 340 | 33             | 230 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 300         | 150 | 0.5                    | 41                       | 285 | 25             | 170 | 4                              | ...                      | ...                               | 50               | 345 | 27             | 185 | 3                              |
|             |     | 10                     | 43                       | 295 | 29             | 200 | 3                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 44                       | 305 | 29             | 200 | 2                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 36                       | 250 | 28             | 195 | 4                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 35                       | 240 | 27             | 185 | 4                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 350         | 177 | 0.5                    | 38                       | 260 | 24             | 165 | 4                              | ...                      | ...                               | 50               | 345 | 30             | 205 | 2                              |
|             |     | 10                     | 39                       | 270 | 28             | 195 | 4                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 34                       | 235 | 24             | 165 | 4                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 29                       | 200 | 21             | 145 | 6                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 27                       | 185 | 19             | 130 | 6                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 400         | 205 | 0.5                    | 34                       | 235 | 24             | 165 | 4                              | ...                      | ...                               | 50               | 345 | 34             | 235 | 1                              |
|             |     | 10                     | 31                       | 215 | 24             | 165 | 5                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 28                       | 195 | 21             | 145 | 6                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 24                       | 165 | 16             | 110 | 9                              | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 22                       | 150 | 14             | 95  | 10                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 500         | 260 | 0.5                    | 23                       | 160 | 18             | 125 | 9                              | ...                      | ...                               | 47               | 325 | 30             | 205 | 2                              |
|             |     | 10                     | 21                       | 145 | 16             | 110 | 10                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 18                       | 125 | 13             | 90  | 13                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 14                       | 95  | 9.0            | 62  | 17                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 11                       | 75  | 7.0            | 48  | 22                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 600         | 315 | 0.5                    | 13                       | 90  | 9.0            | 62  | 14                             | ...                      | ...                               | 42               | 290 | 25             | 170 | 3                              |
|             |     | 10                     | 12                       | 85  | 8.0            | 55  | 17                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 9.0                      | 62  | 6.0            | 41  | 30                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 7.0                      | 48  | 4.4            | 30  | 45                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 7.0                      | 48  | 4.4            | 30  | 45                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
| 700         | 370 | 0.5                    | 6.0                      | 41  | 3.8            | 26  | 32                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10                     | 4.5                      | 31  | 2.9            | 20  | 34                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 100                    | 4.4                      | 30  | 2.8            | 19  | 40                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 4.4                      | 30  | 2.8            | 19  | 40                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 4.4                      | 30  | 2.8            | 19  | 40                             | ...                      | ...                               | ...              | ... | ...            | ... | ...                            |

(a) Average of tensile and compressive moduli  
Source data are in English units; metric values are converted and rounded.

Table D4.34 360.0-F Die castings: typical tensile properties

|             |     |                        | At temperature indicated |     |                |     |                                | At room temperature after heating |     |                |     |                                |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|--------------------------------|-----------------------------------|-----|----------------|-----|--------------------------------|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 2 in. (50 mm), % | Tensile strength                  |     | Yield strength |     | Elongation in 2 in. (50 mm), % |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                                | ksi                               | MPa | ksi            | MPa |                                |
| -112        | -80 | ...                    | 50                       | 345 | 24             | 165 | 3                              | ...                               | ... | ...            | ... | ...                            |
| -18         | -28 | ...                    | 48                       | 330 | 24             | 165 | 3                              | ...                               | ... | ...            | ... | ...                            |
| 75          | 25  | ...                    | 46                       | 315 | 24             | 165 | 5                              | 46                                | 315 | 24             | 165 | 5                              |
| 212         | 100 | 0.5                    | 39                       | 270 | 24             | 165 | 5                              | 48                                | 330 | 25             | 170 | 6                              |
|             |     | 10                     | 39                       | 270 | 24             | 165 | 5                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 41                       | 285 | 26             | 180 | 5                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 45                       | 310 | 32             | 220 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 45                       | 310 | 33             | 230 | 2                              | ...                               | ... | ...            | ... | ...                            |
| 300         | 150 | 0.5                    | 36                       | 250 | 24             | 165 | 9                              | 48                                | 330 | 27             | 185 | 5                              |
|             |     | 10                     | 39                       | 270 | 29             | 200 | 3                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 39                       | 270 | 29             | 200 | 2                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 36                       | 250 | 28             | 195 | 6                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 35                       | 240 | 27             | 185 | 7                              | ...                               | ... | ...            | ... | ...                            |
| 350         | 177 | 0.5                    | 34                       | 235 | 24             | 165 | 7                              | 49                                | 340 | 30             | 205 | 4                              |
|             |     | 10                     | 37                       | 255 | 28             | 195 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 33                       | 230 | 24             | 165 | 5                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 29                       | 200 | 21             | 145 | 9                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 27                       | 185 | 19             | 130 | 10                             | ...                               | ... | ...            | ... | ...                            |
| 400         | 205 | 0.5                    | 32                       | 220 | 24             | 165 | 6                              | 50                                | 345 | 34             | 235 | 4                              |
|             |     | 10                     | 30                       | 205 | 24             | 165 | 6                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 28                       | 195 | 21             | 145 | 9                              | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 24                       | 165 | 16             | 110 | 13                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 22                       | 150 | 14             | 95  | 14                             | ...                               | ... | ...            | ... | ...                            |
| 500         | 260 | 0.5                    | 23                       | 160 | 18             | 125 | 13                             | 46                                | 315 | 30             | 205 | 4                              |
|             |     | 10                     | 21                       | 145 | 16             | 110 | 16                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 18                       | 125 | 13             | 90  | 21                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 14                       | 95  | 9.0            | 62  | 25                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 11                       | 75  | 7.0            | 48  | 31                             | ...                               | ... | ...            | ... | ...                            |
| 600         | 315 | 0.5                    | 13                       | 90  | 9.0            | 62  | 32                             | 41                                | 285 | 25             | 170 | 6                              |
|             |     | 10                     | 12                       | 85  | 8.0            | 55  | 36                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 9.0                      | 62  | 6.0            | 41  | 45                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 7.0                      | 48  | 4.4            | 30  | 45                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 7.0                      | 48  | 4.4            | 30  | 45                             | ...                               | ... | ...            | ... | ...                            |
| 700         | 370 | 0.5                    | 6.0                      | 41  | 3.8            | 26  | 40                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 10                     | 4.5                      | 31  | 2.9            | 20  | 40                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 100                    | 4.4                      | 30  | 2.8            | 19  | 40                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 1,000                  | 4.4                      | 30  | 2.8            | 19  | 40                             | ...                               | ... | ...            | ... | ...                            |
|             |     | 10,000                 | 4.4                      | 30  | 2.8            | 19  | 40                             | ...                               | ... | ...            | ... | ...                            |

Source data are in English units; metric values are converted and rounded.

Table D4.35 380.0-F Die castings: typical tensile properties

| Temperature |      | Time at temperature, h | At temperature indicated |     |                |     |                                | At room temperature after heating |     |                |     |                                |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|--------------------------------|-----------------------------------|-----|----------------|-----|--------------------------------|
|             |      |                        | Tensile strength         |     | Yield strength |     | Elongation in 2 in. (50 mm), % | Tensile strength                  |     | Yield strength |     | Elongation in 2 in. (50 mm), % |
|             |      |                        | ksi                      | MPa | ksi            | MPa |                                | ksi                               | MPa | ksi            | MPa |                                |
| -320        | -196 | ...                    | 59                       | 405 | 30             | 205 | 2.5                            | ...                               | ... | ...            | ... | ...                            |
| -112        | -80  | ...                    | 49                       | 340 | 22             | 150 | 2.5                            | ...                               | ... | ...            | ... | ...                            |
| -18         | -28  | ...                    | 49                       | 340 | 23             | 160 | 3                              | ...                               | ... | ...            | ... | ...                            |
| 75          | 25   | ...                    | 48                       | 330 | 24             | 165 | 3                              | 48                                | 330 | 24             | 165 | 3                              |
| 212         | 100  | 0.5                    | 46                       | 315 | 24             | 165 | 3                              | 46                                | 315 | 24             | 165 | 2                              |
|             |      | 10                     | 46                       | 315 | 24             | 165 | 3                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 46                       | 315 | 24             | 165 | 3                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 48                       | 330 | 27             | 185 | 3                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 47                       | 325 | 29             | 200 | 3                              | ...                               | ... | ...            | ... | ...                            |
| 300         | 150  | 0.5                    | 40                       | 275 | 23             | 160 | 4                              | 45                                | 310 | 22             | 150 | 2                              |
|             |      | 10                     | 42                       | 290 | 24             | 165 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 38                       | 260 | 25             | 170 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 36                       | 250 | 24             | 165 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 34                       | 235 | 23             | 160 | 4                              | ...                               | ... | ...            | ... | ...                            |
| 350         | 177  | 0.5                    | 36                       | 250 | 22             | 150 | 4                              | 46                                | 315 | 23             | 160 | 1.5                            |
|             |      | 10                     | 37                       | 255 | 23             | 160 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 33                       | 230 | 22             | 150 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 32                       | 220 | 21             | 145 | 4                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 31                       | 215 | 19             | 130 | 5                              | ...                               | ... | ...            | ... | ...                            |
| 400         | 205  | 0.5                    | 32                       | 220 | 21             | 145 | 5                              | 47                                | 325 | 24             | 165 | 1.5                            |
|             |      | 10                     | 29                       | 200 | 20             | 140 | 5                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 28                       | 195 | 19             | 130 | 6                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 27                       | 185 | 17             | 115 | 6                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 26                       | 180 | 16             | 110 | 8                              | ...                               | ... | ...            | ... | ...                            |
| 500         | 260  | 0.5                    | 22                       | 150 | 15             | 105 | 11                             | 44                                | 305 | 21             | 145 | 3                              |
|             |      | 10                     | 21                       | 145 | 14             | 95  | 11                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 21                       | 145 | 13             | 90  | 12                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 17                       | 115 | 10             | 70  | 18                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 12                       | 83  | 8.5            | 59  | 20                             | ...                               | ... | ...            | ... | ...                            |
| 600         | 315  | 0.5                    | 13                       | 90  | 9.0            | 62  | 20                             | 43                                | 295 | 21             | 145 | 2.5                            |
|             |      | 10                     | 12                       | 85  | 8.0            | 55  | 24                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 9.5                      | 66  | 6.5            | 45  | 27                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 7.0                      | 48  | 4.6            | 32  | 27                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 7.0                      | 48  | 3.8            | 26  | 28                             | ...                               | ... | ...            | ... | ...                            |
| 700         | 370  | 0.5                    | 6.5                      | 45  | 4.0            | 28  | 28                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10                     | 5.5                      | 38  | 3.2            | 22  | 29                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 4.5                      | 31  | 2.5            | 17  | 30                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 4.5                      | 31  | 2.5            | 17  | 30                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 4.5                      | 31  | 2.5            | 17  | 30                             | ...                               | ... | ...            | ... | ...                            |

Source data are in English units; metric values are converted and rounded.

Table D4.36 380.0-F Die castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                                | At room temperature after heating |     |                |     |                                |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|--------------------------------|-----------------------------------|-----|----------------|-----|--------------------------------|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 2 in. (50 mm), % | Tensile strength                  |     | Yield strength |     | Elongation in 2 in. (50 mm), % |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                                | ksi                               | MPa | ksi            | MPa |                                |
| -320        | -196 | ...                    | 58                       | 400 | 29             | 200 | 3                              | ...                               | ... | ...            | ... | ...                            |
| -112        | -80  | ...                    | 48                       | 330 | 21             | 145 | 3                              | ...                               | ... | ...            | ... | ...                            |
| -18         | -28  | ...                    | 48                       | 330 | 22             | 150 | 3.5                            | ...                               | ... | ...            | ... | ...                            |
| 75          | 25   | ...                    | 47                       | 325 | 23             | 160 | 4                              | 47                                | 325 | 23             | 160 | 4                              |
| 212         | 100  | 0.5                    | 44                       | 305 | 23             | 160 | 7                              | 46                                | 315 | 23             | 160 | 4                              |
|             |      | 10                     | 44                       | 305 | 24             | 165 | 7                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 45                       | 310 | 25             | 170 | 7                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 45                       | 310 | 29             | 200 | 7                              | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 46                       | 315 | 30             | 205 | 7                              | ...                               | ... | ...            | ... | ...                            |
| 300         | 150  | 0.5                    | 37                       | 255 | 23             | 160 | 10                             | 45                                | 310 | 20             | 140 | 4                              |
|             |      | 10                     | 39                       | 270 | 25             | 170 | 10                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 35                       | 240 | 24             | 165 | 10                             | 49                                | 340 | 29             | 200 | 3.5                            |
|             |      | 1,000                  | 33                       | 230 | 22             | 150 | 10                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 31                       | 215 | 21             | 145 | 10                             | ...                               | ... | ...            | ... | ...                            |
| 350         | 177  | 0.5                    | 33                       | 230 | 22             | 150 | 11                             | 46                                | 315 | 22             | 150 | 4                              |
|             |      | 10                     | 34                       | 235 | 22             | 150 | 11                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 30                       | 205 | 20             | 140 | 12                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 29                       | 200 | 19             | 130 | 12                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 27                       | 185 | 18             | 125 | 13                             | ...                               | ... | ...            | ... | ...                            |
| 400         | 205  | 0.5                    | 28                       | 195 | 20             | 140 | 13                             | 47                                | 325 | 23             | 160 | 4                              |
|             |      | 10                     | 26                       | 180 | 18             | 125 | 13                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 25                       | 170 | 17             | 115 | 14                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 24                       | 165 | 16             | 110 | 15                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 23                       | 160 | 15             | 105 | 16                             | ...                               | ... | ...            | ... | ...                            |
| 500         | 260  | 0.5                    | 19                       | 130 | 14             | 95  | 17                             | 44                                | 305 | 21             | 145 | 5                              |
|             |      | 10                     | 19                       | 130 | 14             | 95  | 18                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 18                       | 125 | 12             | 85  | 20                             | 38                                | 260 | 17             | 115 | 6                              |
|             |      | 1,000                  | 15                       | 105 | 9.5            | 66  | 30                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 11                       | 75  | 7.0            | 48  | 31                             | ...                               | ... | ...            | ... | ...                            |
| 600         | 315  | 0.5                    | 11                       | 75  | 8.0            | 55  | 26                             | 43                                | 295 | 21             | 145 | 5                              |
|             |      | 10                     | 11                       | 75  | 7.5            | 52  | 29                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 9.0                      | 62  | 6.0            | 41  | 31                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 6.5                      | 45  | 4.7            | 32  | 45                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 5.5                      | 38  | 4.2            | 29  | 45                             | ...                               | ... | ...            | ... | ...                            |
| 700         | 370  | 0.5                    | 6.0                      | 41  | 3.9            | 27  | 45                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10                     | 5.0                      | 34  | 3.2            | 22  | 46                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 100                    | 4.7                      | 32  | 2.8            | 19  | 47                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 1,000                  | 4.4                      | 30  | 2.8            | 19  | 50                             | ...                               | ... | ...            | ... | ...                            |
|             |      | 10,000                 | 4.1                      | 28  | 2.8            | 19  | 50                             | ...                               | ... | ...            | ... | ...                            |

Source data are in English units; metric values are converted and rounded.

Table D4.37 384.0-F Die castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                                   |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|-----------------------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in<br>2 in. (50 mm), % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                                   | 10 <sup>6</sup> psi      | GPa |
| -320        | -196 | ...                    | 58                       | 400 | 31             | 215 | 1                                 | ...                      | ... |
| -112        | -80  | ...                    | 48                       | 330 | 23             | 160 | 1                                 | ...                      | ... |
| -18         | -28  | ...                    | 48                       | 330 | 24             | 165 | 1                                 | ...                      | ... |
| 75          | 25   | ...                    | 47                       | 325 | 25             | 170 | 1                                 | 10.8                     | 74  |
| 212         | 100  | 0.5                    | 46                       | 315 | 25             | 170 | 1                                 | 10.6                     | 73  |
|             |      | 10                     | 46                       | 315 | 25             | 170 | 1                                 | 10.6                     | 73  |
|             |      | 100                    | 46                       | 315 | 26             | 180 | 1                                 | 10.6                     | 73  |
|             |      | 1,000                  | 48                       | 330 | 29             | 200 | 1                                 | 10.6                     | 73  |
|             |      | 10,000                 | 47                       | 325 | 31             | 215 | 1                                 | 10.6                     | 73  |
| 300         | 150  | 0.5                    | 43                       | 295 | 25             | 170 | 2                                 | 10.3                     | 71  |
|             |      | 10                     | 44                       | 305 | 28             | 195 | 2                                 | 10.3                     | 71  |
|             |      | 100                    | 41                       | 285 | 26             | 180 | 2                                 | 10.3                     | 71  |
|             |      | 1,000                  | 39                       | 270 | 25             | 170 | 2                                 | 10.3                     | 71  |
|             |      | 10,000                 | 37                       | 255 | 23             | 160 | 2                                 | 10.3                     | 71  |
| 350         | 177  | 0.5                    | 40                       | 275 | 25             | 170 | 4                                 | 10.0                     | 69  |
|             |      | 10                     | 37                       | 255 | 26             | 180 | 4                                 | 10.0                     | 69  |
|             |      | 100                    | 35                       | 240 | 23             | 160 | 4                                 | 10.0                     | 69  |
|             |      | 1,000                  | 33                       | 230 | 22             | 150 | 4                                 | 10.0                     | 69  |
|             |      | 10,000                 | 32                       | 220 | 20             | 140 | 4                                 | 10.0                     | 69  |
| 400         | 205  | 0.5                    | 33                       | 230 | 23             | 160 | 6                                 | 9.7                      | 67  |
|             |      | 10                     | 31                       | 215 | 22             | 150 | 6                                 | 9.7                      | 67  |
|             |      | 100                    | 30                       | 205 | 21             | 145 | 6                                 | 9.7                      | 67  |
|             |      | 1,000                  | 29                       | 200 | 19             | 130 | 6                                 | 9.7                      | 67  |
|             |      | 10,000                 | 28                       | 195 | 18             | 125 | 6                                 | 9.7                      | 67  |
| 450         | 230  | 0.5                    | 28                       | 195 | 20             | 140 | 8                                 | 9.3                      | 64  |
|             |      | 10                     | 27                       | 185 | 19             | 130 | 8                                 | 9.3                      | 64  |
|             |      | 100                    | 27                       | 185 | 17             | 115 | 8                                 | 9.3                      | 64  |
|             |      | 1,000                  | 25                       | 170 | 15             | 105 | 8                                 | 9.3                      | 64  |
|             |      | 10,000                 | 21                       | 145 | 13             | 90  | 12                                | 9.3                      | 64  |
| 500         | 260  | 0.5                    | 24                       | 165 | 17             | 115 | 10                                | 8.6                      | 59  |
|             |      | 10                     | 24                       | 165 | 16             | 110 | 10                                | 8.6                      | 59  |
|             |      | 100                    | 23                       | 160 | 14             | 95  | 10                                | 8.6                      | 59  |
|             |      | 1,000                  | 18                       | 125 | 11             | 75  | 14                                | 8.6                      | 59  |
|             |      | 10,000                 | 13                       | 90  | 8.5            | 59  | 23                                | 8.6                      | 59  |
| 600         | 315  | 0.5                    | 16                       | 110 | 11             | 75  | 16                                | 7.0                      | 48  |
|             |      | 10                     | 13                       | 90  | 8.0            | 55  | 22                                | 7.0                      | 48  |
|             |      | 100                    | 10                       | 70  | 6.5            | 45  | 26                                | 7.0                      | 48  |
|             |      | 1,000                  | 8.0                      | 55  | 5.0            | 34  | 35                                | 7.0                      | 48  |
|             |      | 10,000                 | 7.0                      | 48  | 4.2            | 29  | 50                                | 7.0                      | 48  |
| 700         | 370  | 0.5                    | 7.0                      | 48  | 3.9            | 27  | 28                                | ...                      | ... |
|             |      | 10                     | 6.0                      | 41  | 3.2            | 22  | 40                                | ...                      | ... |
|             |      | 100                    | 5.0                      | 34  | 2.9            | 20  | 50                                | ...                      | ... |
|             |      | 1,000                  | 4.8                      | 33  | 2.9            | 20  | 50                                | ...                      | ... |
|             |      | 10,000                 | 4.8                      | 33  | 2.9            | 20  | 50                                | ...                      | ... |

(a) The modulus of elasticity in compression is about 2% greater than in tension.  
Source data are in English units; metric values are converted and rounded.

Table D4.38 B443.0-F Sand castings: typical tensile properties

|             |      |                        | At temperature indicated |     |                |     |                     |                          |     |
|-------------|------|------------------------|--------------------------|-----|----------------|-----|---------------------|--------------------------|-----|
| Temperature |      | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Modulus of elasticity(a) |     |
| °F          | °C   |                        | ksi                      | MPa | ksi            | MPa |                     | 10 <sup>6</sup> psi      | GPa |
| -320        | -196 | ...                    | 25                       | 170 | 10             | 70  | ...                 | ...                      | ... |
| -112        | -80  | ...                    | 19                       | 130 | 8.0            | 55  | ...                 | ...                      | ... |
| -18         | -28  | ...                    | 19                       | 130 | 8.0            | 55  | ...                 | ...                      | ... |
| 75          | 25   | ...                    | 19                       | 130 | 8.0            | 55  | 8                   | 10.3                     | 71  |
| 212         | 100  | 0.5                    | 16                       | 110 | 8.0            | 55  | 12                  | ...                      | ... |
|             |      | 10                     | 16                       | 110 | 8.0            | 55  | 12                  | ...                      | ... |
|             |      | 100                    | 16                       | 110 | 8.0            | 55  | 10                  | ...                      | ... |
|             |      | 1,000                  | 16                       | 110 | 8.5            | 59  | 8                   | ...                      | ... |
|             |      | 10,000                 | 16                       | 110 | 11             | 75  | 7                   | ...                      | ... |
|             |      | 0.5                    | 14                       | 95  | 8.0            | 55  | 22                  | ...                      | ... |
|             |      | 10                     | 14                       | 95  | 9.0            | 62  | 21                  | ...                      | ... |
|             |      | 100                    | 14                       | 95  | 10             | 70  | 20                  | ...                      | ... |
|             |      | 1,000                  | 14                       | 95  | 10             | 70  | 19                  | ...                      | ... |
|             |      | 10,000                 | 14                       | 95  | 9.0            | 62  | 18                  | ...                      | ... |
| 300         | 150  | 0.5                    | 11                       | 75  | 7.5            | 52  | 25                  | ...                      | ... |
|             |      | 10                     | 11                       | 75  | 8.5            | 59  | 24                  | ...                      | ... |
|             |      | 100                    | 11                       | 75  | 8.0            | 55  | 25                  | ...                      | ... |
|             |      | 1,000                  | 11                       | 75  | 7.5            | 52  | 25                  | ...                      | ... |
|             |      | 10,000                 | 11                       | 75  | 7.5            | 52  | 28                  | ...                      | ... |
|             |      | 0.5                    | 9.0                      | 62  | 6.0            | 41  | 30                  | ...                      | ... |
|             |      | 10                     | 9.0                      | 62  | 6.0            | 41  | 30                  | ...                      | ... |
|             |      | 100                    | 9.0                      | 62  | 6.0            | 41  | 30                  | ...                      | ... |
|             |      | 1,000                  | 9.0                      | 62  | 6.0            | 41  | 30                  | ...                      | ... |
|             |      | 10,000                 | 9.0                      | 62  | 6.0            | 41  | 30                  | ...                      | ... |
| 400         | 205  | 0.5                    | 6.5                      | 45  | 4.8            | 33  | 30                  | ...                      | ... |
|             |      | 10                     | 6.5                      | 45  | 4.8            | 33  | 32                  | ...                      | ... |
|             |      | 100                    | 6.5                      | 45  | 4.8            | 33  | 35                  | ...                      | ... |
|             |      | 1,000                  | 5.5                      | 38  | 4.2            | 29  | 40                  | ...                      | ... |
|             |      | 10,000                 | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 0.5                    | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 10                     | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 1,000                  | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 10,000                 | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
| 500         | 260  | 0.5                    | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 10                     | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 100                    | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 1,000                  | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 10,000                 | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 0.5                    | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 10                     | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 100                    | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |
| 600         | 315  | 0.5                    | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 10                     | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 100                    | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 1,000                  | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 10,000                 | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 0.5                    | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 10                     | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 100                    | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |
| 700         | 370  | 0.5                    | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 10                     | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 100                    | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 1,000                  | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 10,000                 | 3.2                      | 22  | 2.3            | 16  | 55                  | ...                      | ... |
|             |      | 0.5                    | 4.0                      | 28  | 2.8            | 19  | 50                  | ...                      | ... |
|             |      | 10                     | 4.7                      | 32  | 3.4            | 23  | 35                  | ...                      | ... |
|             |      | 100                    | 3.8                      | 26  | 2.6            | 18  | 40                  | ...                      | ... |
|             |      | 100                    | 3.4                      | 23  | 2.3            | 16  | 55                  | ...                      | ... |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.

Table D4.39 518.0-F (A218) Sand castings (results of tests made on sand cast test bars): representative tensile properties

|             |     |                        | At temperature indicated |     |                |     |                     | At room temperature after heating |     |                |     |                     |
|-------------|-----|------------------------|--------------------------|-----|----------------|-----|---------------------|-----------------------------------|-----|----------------|-----|---------------------|
| Temperature |     | Time at temperature, h | Tensile strength         |     | Yield strength |     | Elongation in 4D, % | Tensile strength                  |     | Yield strength |     | Elongation in 4D, % |
| °F          | °C  |                        | ksi                      | MPa | ksi            | MPa |                     | ksi                               | MPa | ksi            | MPa |                     |
| 75          | 25  | ...                    | 36.2                     | 250 | 20.1           | 140 | 8.8                 | 36.2                              | 250 | 20.1           | 140 | 8.8                 |
| 300         | 150 | 100                    | 31.3                     | 215 | 20.7           | 145 | 9                   | 37.1                              | 255 | 21.9           | 150 | 6.5                 |
|             |     | 1000                   | 32.5                     | 225 | 21.6           | 150 | 6.5                 | 31.5                              | 215 | 23.2           | 160 | 2.8                 |
|             |     | 5000                   | 34.3                     | 235 | 20             | 140 | 7.4                 | 31.6                              | 220 | 23.7           | 165 | 1.8                 |
| 400         | 205 | 100                    | 25.7                     | 175 | 18.8           | 130 | 9.5                 | 28.3                              | 195 | 21.5           | 150 | 2                   |
|             |     | 1000                   | 24.5                     | 170 | 17.2           | 120 | 11                  | 24.3                              | 170 | 19.2           | 130 | 1                   |
|             |     | 5000                   | 23.2                     | 160 | 15             | 105 | 15.5                | 22.6                              | 155 | 17.5           | 120 | 1.5                 |
| 500         | 260 | 100                    | 19.9                     | 135 | 13.9           | 95  | 14.5                | 22                                | 150 | 19.3           | 135 | 1                   |
|             |     | 1000                   | 19.1                     | 130 | 13.1           | 90  | 14                  | 20                                | 140 | 17.9           | 125 | 0.8                 |
|             |     | 5000                   | 17.8                     | 125 | 13             | 90  | 22                  | 19.6                              | 135 | 17.7           | 120 | 1                   |
| 600         | 315 | 100                    | 13.3                     | 90  | 9.6            | 66  | 18                  | 26.2                              | 180 | 20.3           | 140 | 2.5                 |
|             |     | 1000                   | 14.9                     | 105 | 10             | 70  | 14.5                | 34.3                              | 235 | 21.2           | 145 | 6.5                 |
|             |     | 5000                   | 14.4                     | 100 | 8.8            | 61  | 18                  | 36                                | 250 | 21.3           | 145 | 8                   |

Source data are in English units; metric values are converted and rounded.

Table D4.40 520.0-T4 Sand castings: typical tensile properties

| Temperature |     |                           | At temperature indicated |     |                |     |                        |                          |     | At room temperature after heating |     |                |     |                        |
|-------------|-----|---------------------------|--------------------------|-----|----------------|-----|------------------------|--------------------------|-----|-----------------------------------|-----|----------------|-----|------------------------|
|             |     |                           | Tensile strength         |     | Yield strength |     | Elongation<br>in 4D, % | Modulus of elasticity(a) |     | Tensile strength                  |     | Yield strength |     | Elongation<br>in 4D, % |
|             |     |                           | ksi                      | MPa | ksi            | MPa |                        | 10 <sup>6</sup> psi      | GPa | ksi                               | MPa | ksi            | MPa |                        |
| °F          | °C  | Time at<br>temperature, h |                          |     |                |     |                        |                          |     |                                   |     |                |     |                        |
| 75          | 25  | ...                       | 48                       | 330 | 26             | 180 | 16                     | 9.5                      | 66  | 48                                | 330 | 26             | 180 | 16                     |
| 212         | 100 | 0.5                       | 42                       | 290 | 24             | 165 | ...                    | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10                        | 43                       | 295 | 24             | 165 | ...                    | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 100                       | 44                       | 305 | 25             | 170 | ...                    | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 1,000                     | 44                       | 305 | 25             | 170 | ...                    | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10,000                    | 44                       | 305 | 25             | 170 | ...                    | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 300         | 150 | 0.5                       | 36                       | 250 | 22             | 150 | 13                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10                        | 38                       | 260 | 23             | 160 | 14                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 100                       | 39                       | 270 | 23             | 160 | 10                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 1,000                     | 37                       | 255 | 20             | 140 | 13                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 6,500                     | ...                      | ... | ...            | ... | ...                    | ...                      | ... | 30                                | 205 | 29             | 200 | 0.5                    |
|             |     | 10,000                    | 37                       | 255 | 20             | 140 | 13                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 400         | 205 | 0.5                       | 29                       | 200 | 20             | 140 | 11                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10                        | 27                       | 185 | 15             | 105 | 25                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 100                       | 24                       | 165 | 12             | 85  | 30                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 1,000                     | 22                       | 150 | 12             | 85  | 34                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 2,000                     | ...                      | ... | ...            | ... | ...                    | ...                      | ... | 28                                | 195 | 19             | 130 | 1                      |
|             |     | 10,000                    | 21                       | 145 | 12             | 85  | 35                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
| 500         | 260 | 0.5                       | 21                       | 145 | 7.0            | 48  | 20                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10                        | 16                       | 110 | 7.0            | 48  | 40                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 100                       | 15                       | 105 | 7.0            | 48  | 42                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 1,000                     | 15                       | 105 | 7.0            | 48  | 48                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 3,000                     | ...                      | ... | ...            | ... | ...                    | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10,000                    | 15                       | 105 | 7.0            | 48  | 50                     | ...                      | ... | 26                                | 180 | 19             | 130 | 1.5                    |
| 600         | 315 | 0.5                       | 11                       | 75  | 4.0            | 28  | 28                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10                        | 11                       | 75  | 4.0            | 28  | 48                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 100                       | 11                       | 75  | 4.0            | 28  | 52                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 1,000                     | 11                       | 75  | 4.0            | 28  | 60                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10,000                    | 11                       | 75  | 4.0            | 28  | 60                     | ...                      | ... | 26                                | 180 | 19             | 130 | 1.5                    |
| 700         | 370 | 0.5                       | 6.5                      | 45  | 2.0            | 14  | 50                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10                        | 6.5                      | 45  | 2.0            | 14  | 55                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 100                       | 6.5                      | 45  | 2.0            | 14  | 60                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 1,000                     | 6.5                      | 45  | 2.0            | 14  | 70                     | ...                      | ... | ...                               | ... | ...            | ... | ...                    |
|             |     | 10,000                    | 6.5                      | 45  | 2.0            | 14  | 70                     | ...                      | ... | 26                                | 180 | 19             | 130 | 1.5                    |

(a) Average of tensile and compressive moduli

Source data are in English units; metric values are converted and rounded.

Table D4.41 710.0-F Sand castings: typical tensile properties

| Temperature |      |                           | At temperature indicated |        |                |        |                        | At room temperature after heating |        |                |        |                        |
|-------------|------|---------------------------|--------------------------|--------|----------------|--------|------------------------|-----------------------------------|--------|----------------|--------|------------------------|
|             |      |                           | Tensile strength         |        | Yield strength |        | Elongation<br>in 4D, % | Tensile strength                  |        | Yield strength |        | Elongation<br>in 4D, % |
|             |      |                           | ksi                      | MPa    | ksi            | MPa    |                        | ksi                               | MPa    | ksi            | MPa    |                        |
| °F          | °C   | Time at<br>temperature, h |                          |        |                |        |                        |                                   |        |                |        |                        |
| -320        | -196 | ...                       | 42(a)                    | 290(a) | 35(a)          | 240(a) | 4(a)                   | ...                               | ...    | ...            | ...    | ...                    |
| -112        | -80  | ...                       | 37(a)                    | 255(a) | 28(a)          | 195(a) | 5(a)                   | ...                               | ...    | ...            | ...    | ...                    |
| -18         | -28  | ...                       | 37(a)                    | 255(a) | 26(a)          | 180(a) | 6(a)                   | ...                               | ...    | ...            | ...    | ...                    |
| 75          | 25   | ...                       | 35(a)                    | 240(a) | 25(a)          | 170(a) | 5(a)                   | 35(a)                             | 240(a) | 25(a)          | 170(a) | 5                      |
| 212         | 100  | 0.5                       | 34                       | 235    | 25             | 170    | 5                      | 34                                | 235    | 25             | 170    | 5                      |
|             |      | 10                        | 35                       | 240    | 30             | 205    | 5                      | 35                                | 240    | 30             | 205    | 5                      |
|             |      | 100                       | 43                       | 295    | 38             | 260    | 4                      | 44                                | 305    | 38             | 260    | 4                      |
|             |      | 1,000                     | 46                       | 315    | 42             | 290    | 3                      | 48                                | 330    | 46             | 315    | 3                      |
|             |      | 10,000                    | 43                       | 295    | 40             | 275    | 3                      | 47                                | 325    | 44             | 305    | 3                      |
| 300         | 150  | 0.5                       | 33                       | 230    | 25             | 170    | 5                      | 35                                | 240    | 25             | 170    | 5                      |
|             |      | 10                        | 37                       | 255    | 33             | 230    | 3                      | 42                                | 290    | 38             | 260    | 3                      |
|             |      | 100                       | 34                       | 235    | 32             | 220    | 3                      | 41                                | 285    | 37             | 255    | 3                      |
|             |      | 1,000                     | 28                       | 195    | 26             | 180    | 6                      | 36                                | 250    | 30             | 205    | 4                      |
|             |      | 10,000                    | 20                       | 140    | 17             | 115    | 12                     | 29                                | 200    | 21             | 145    | 6                      |
| 400         | 205  | 0.5                       | 24                       | 165    | 20             | 140    | 10                     | 31                                | 215    | 22             | 150    | 5                      |
|             |      | 10                        | 19                       | 130    | 17             | 115    | 10                     | 30                                | 205    | 21             | 145    | 6                      |
|             |      | 100                       | 15                       | 105    | 14             | 95     | 14                     | 28                                | 195    | 19             | 130    | 7                      |
|             |      | 1,000                     | 12                       | 85     | 10             | 70     | 22                     | 23                                | 160    | 13             | 90     | 9                      |
|             |      | 10,000                    | 10                       | 70     | 8.0            | 55     | 30                     | 21                                | 145    | 11             | 75     | 10                     |
| 500         | 260  | 0.5                       | 13                       | 90     | 11             | 75     | 12                     | 27                                | 185    | 16             | 110    | 10                     |
|             |      | 10                        | 10                       | 70     | 8.5            | 59     | 23                     | 24                                | 165    | 11             | 75     | 11                     |
|             |      | 100                       | 8.0                      | 55     | 7.0            | 48     | 33                     | 22                                | 150    | 9.0            | 62     | 12                     |
|             |      | 1,000                     | 7.0                      | 48     | 6.0            | 41     | 45                     | 20                                | 140    | 8.0            | 55     | 12                     |
|             |      | 10,000                    | 6.5                      | 45     | 5.0            | 34     | 60                     | 19                                | 130    | 7.0            | 48     | 12                     |

(a) 30 days after casting

Source data are in English units; metric values are converted and rounded.



## DATA SET 5

# Creep Rupture Properties

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This data set contains the results of uniaxial creep rupture tests of a wide range of aluminum casting alloys conducted at temperatures from 212 to 600 °F (100 to 315 °C).

These data were developed at the Alcoa Research Laboratories in New Kensington, PA, from 1950 through about 1985. The early generation and analysis of the data was led by Kenneth O. Bogardus and Robert C. Malcolm, Jr., with principal testing support from Robert C. Faulk and George Schofield. In more recent years, the activity has been led by Robert J. Bucci and Daniel Lege. Most of the data included here were originally published in Ref 1, although some additional data have been added for this publication.

The tensile tests were made in accordance with ASTM E 139, with ½ in. (12.5 mm) diam tensile specimens per Appendix 3, Fig. A3.1. In most cases, the specimens were as-cast test bars.

Strain measurements were made with autographic extensometers used in conjunction with strain-transfer devices.

In most cases, tests were made of several lots of material of each alloy and temper, and the results analyzed and the averages normalized to the room-temperature typical values; in these cases the values are identified as typical values in the table. In some cases, too few data, perhaps only for a single lot, were available, and these are reported as representative rather than typical values.

## REFERENCE

1. *Properties of Aluminum Alloys: Tensile, Creep and Fatigue Data at High and Low Temperatures*, J.G. Kaufman, Ed., ASM International, 1999

Table D5.1 201.0-T7 Sand castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 10                   | 57             | 395 | 56                   | 385 | 56                   | 385 | 53                   | 365 | 52                   | 360 |
|             |     | 100                  | 51             | 350 | 51                   | 350 | 50                   | 345 | 49                   | 340 | 47                   | 325 |
|             |     | 1000                 | 45             | 310 | 45                   | 310 | 45                   | 310 | 44                   | 305 | 41                   | 285 |
| 350         | 177 | 1                    | ...            | ... | ...                  | ... | ...                  | ... | 50                   | 345 | 48                   | 330 |
|             |     | 10                   | 48             | 330 | 47                   | 325 | 46                   | 315 | 45                   | 310 | 43                   | 295 |
|             |     | 100                  | 42             | 290 | 42                   | 290 | 41                   | 285 | 39                   | 270 | 38                   | 260 |
|             |     | 1000                 | 35             | 240 | 35                   | 240 | 35                   | 240 | 34                   | 235 | ...                  | ... |
| 400         | 205 | 1                    | 42             | 290 | 42                   | 290 | 41                   | 285 | 40                   | 275 | 39                   | 270 |
|             |     | 10                   | 39             | 270 | 38                   | 260 | 38                   | 260 | 36                   | 250 | 32                   | 220 |
|             |     | 100                  | 33             | 230 | 33                   | 230 | 32                   | 220 | 30                   | 205 | 25                   | 170 |
|             |     | 1000                 | 25             | 170 | 25                   | 170 | 25                   | 170 | ...                  | ... | ...                  | ... |
| 450         | 230 | 10                   | ...            | ... | ...                  | ... | ...                  | ... | 27                   | 185 | 24                   | 165 |
|             |     | 100                  | 24             | 165 | 24                   | 165 | 23                   | 160 | ...                  | ... | ...                  | ... |
| 500         | 260 | 1                    | ...            | ... | ...                  | ... | ...                  | ... | ...                  | ... | 21                   | 145 |
|             |     | 10                   | 21             | 145 | 20                   | 140 | 20                   | 140 | 18                   | 125 | ...                  | ... |

Source data are in English units; metric values are converted and rounded.

Table D5.2 224.0-T7: Creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 0.1                  | 50             | 345 | 46                   | 315 | 44                   | 305 | 42                   | 290 | 41                   | 285 |
|             |     | 1                    | 46             | 315 | 43                   | 295 | 41                   | 285 | 40                   | 275 | 39                   | 270 |
|             |     | 10                   | 41             | 285 | 40                   | 275 | 39                   | 270 | 37                   | 255 | 36                   | 250 |
|             |     | 100                  | 37             | 255 | 36                   | 250 | 35                   | 240 | 31                   | 215 | ...                  | ... |
| 400         | 205 | 1000                 | 30             | 205 | 28                   | 195 | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 0.1                  | 39             | 270 | 34                   | 235 | 32                   | 220 | 28                   | 195 | 26                   | 180 |
|             |     | 1                    | 34             | 235 | 29                   | 200 | 26                   | 180 | 22                   | 150 | 20                   | 140 |
|             |     | 10                   | 28             | 195 | 24                   | 165 | 21                   | 145 | 17                   | 115 | 15                   | 105 |
| 450         | 230 | 100                  | 23             | 160 | 21                   | 145 | 18                   | 125 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 19             | 130 | 18                   | 125 | 16                   | 110 | ...                  | ... | ...                  | ... |
|             |     | 0.1                  | 32             | 220 | 29                   | 200 | 26                   | 180 | 23                   | 160 | 20                   | 140 |
|             |     | 1                    | 28             | 195 | 25                   | 170 | 22                   | 150 | 16                   | 110 | 14                   | 95  |
| 500         | 260 | 10                   | 23             | 160 | 21                   | 145 | 18                   | 125 | 13                   | 90  | 11                   | 75  |
|             |     | 100                  | 19             | 130 | 18                   | 125 | 15                   | 105 | 11                   | 75  | 8.5                  | 59  |
|             |     | 1000                 | 15             | 105 | 14                   | 95  | 12                   | 85  | ...                  | ... | ...                  | ... |
|             |     | 0.1                  | 26             | 180 | 24                   | 165 | 23                   | 160 | 20                   | 140 | 18                   | 125 |
| 550         | 290 | 1                    | 23             | 160 | 21                   | 145 | 19                   | 130 | 16                   | 110 | 13                   | 90  |
|             |     | 10                   | 20             | 140 | 18                   | 125 | 16                   | 110 | 13                   | 90  | 10                   | 70  |
|             |     | 100                  | 16             | 110 | 15                   | 105 | 13                   | 90  | 10                   | 70  | 8.0                  | 55  |
|             |     | 1000                 | 11             | 75  | 10                   | 70  | 9.0                  | 62  | ...                  | ... | ...                  | ... |
| 600         | 315 | 0.1                  | 22             | 150 | 20                   | 140 | 20                   | 140 | 17                   | 115 | 15                   | 105 |
|             |     | 1                    | 20             | 140 | 18                   | 125 | 16                   | 110 | 14                   | 95  | 12                   | 85  |
|             |     | 10                   | 17             | 115 | 15                   | 105 | 14                   | 95  | 12                   | 85  | 9.5                  | 66  |
|             |     | 100                  | 13             | 90  | 12                   | 85  | 10                   | 70  | 8.0                  | 55  | 7.0                  | 48  |
| 650         | 345 | 1000                 | 8.0            | 55  | 6.5                  | 45  | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 0.1                  | 19             | 130 | 17                   | 115 | 17                   | 115 | 15                   | 105 | 13                   | 90  |
|             |     | 1                    | 17             | 115 | 15                   | 105 | 14                   | 95  | 13                   | 90  | 11                   | 75  |
|             |     | 10                   | 14             | 95  | 12                   | 85  | 12                   | 85  | 10                   | 70  | 8.0                  | 55  |
| 700         | 370 | 100                  | 10             | 70  | 9.0                  | 62  | 6.5                  | 45  | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 5.0            | 34  | 3.5                  | 24  | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 0.1                  | 16             | 110 | 15                   | 105 | 14                   | 95  | 12                   | 85  | 11                   | 75  |
|             |     | 1                    | 14             | 95  | 12                   | 85  | 12                   | 85  | 9.5                  | 66  | 8.0                  | 55  |
| 750         | 400 | 10                   | 10             | 70  | 9.5                  | 66  | 8.0                  | 55  | 6.0                  | 41  | 5.5                  | 38  |
|             |     | 100                  | 7.0            | 48  | 6.0                  | 41  | 4.3                  | 30  | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 3.0            | 21  | 2.0                  | 14  | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 0.1                  | 14             | 95  | 12                   | 85  | 11                   | 75  | 8.5                  | 59  | 7.5                  | 52  |
| 800         | 427 | 1                    | 11             | 75  | 10                   | 70  | 8.0                  | 55  | 6.3                  | 43  | 5.0                  | 34  |
|             |     | 10                   | 7.0            | 48  | 6.5                  | 45  | 4.3                  | 30  | 3.3                  | 23  | 2.5                  | 17  |
|             |     | 100                  | 4.0            | 28  | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |

Source data are in English units; metric values are converted and rounded.

Table D5.3 240.0-F Sand castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 400         | 205 | 0.1                  | 31             | 215 | 30                   | 205 | 29                   | 200 | 28                   | 195 | 23                   | 160 |
|             |     | 1                    | 30             | 205 | 29                   | 200 | 28                   | 195 | 22                   | 150 | 18                   | 125 |
|             |     | 10                   | 28             | 195 | 26                   | 180 | 22                   | 150 | 18                   | 125 | 14                   | 95  |
|             |     | 100                  | 22             | 150 | 18                   | 125 | 16                   | 110 | 13                   | 90  | 11                   | 75  |
|             |     | 1000                 | 16             | 110 | 12                   | 85  | 11                   | 75  | 10                   | 70  | 8.5                  | 59  |
| 500         | 260 | 0.1                  | 27             | 185 | 20                   | 140 | 17                   | 115 | 13                   | 90  | 10                   | 70  |
|             |     | 1                    | 20             | 140 | 15                   | 105 | 13                   | 90  | 9.0                  | 62  | 6.5                  | 45  |
|             |     | 10                   | 15             | 105 | 11                   | 75  | 9.0                  | 62  | 6.5                  | 45  | 5.0                  | 34  |
|             |     | 100                  | 11             | 75  | 7.5                  | 52  | 6.5                  | 45  | 4.5                  | 31  | 4.0                  | 28  |
|             |     | 1000                 | 8.0            | 55  | 5.5                  | 38  | 4.5                  | 31  | 4.0                  | 28  | 3.0                  | 21  |
| 600         | 315 | 0.1                  | 19             | 130 | 13                   | 90  | 10                   | 70  | 6.5                  | 45  | 4.5                  | 31  |
|             |     | 1                    | 13             | 90  | 8.0                  | 55  | 6.5                  | 45  | 4.0                  | 28  | 2.5                  | 17  |
|             |     | 10                   | 8.0            | 55  | 5.0                  | 34  | 4.0                  | 28  | 2.5                  | 17  | 1.5                  | 10  |
|             |     | 100                  | 5.0            | 34  | 3.0                  | 21  | 2.5                  | 17  | 1.5                  | 10  | 1.0                  | 7.0 |
|             |     | 1000                 | 3.0            | 21  | 2.0                  | 14  | 1.5                  | 10  | 1.0                  | 7.0 | 0.5                  | 3.0 |

Source data are in English units; metric values are converted and rounded.

Table D5.4 242.0-T77 Sand castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 1                    | ...            | ... | 26                   | 180 | 21                   | 145 | ...                  | ... | ...                  | ... |
|             |     | 10                   | ...            | ... | 26                   | 180 | 21                   | 145 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 27             | 185 | 25                   | 170 | 21                   | 145 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 22             | 150 | 20                   | 140 | 18                   | 125 | ...                  | ... | ...                  | ... |
| 400         | 205 | 1                    | ...            | ... | 20                   | 140 | 17                   | 115 | 14                   | 95  | ...                  | ... |
|             |     | 10                   | 19             | 130 | 17                   | 115 | 15                   | 105 | 12                   | 85  | ...                  | ... |
|             |     | 100                  | 16             | 110 | 14                   | 95  | 12                   | 85  | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 13             | 90  | 12                   | 85  | ...                  | ... | ...                  | ... | ...                  | ... |
| 600         | 315 | 1                    | ...            | ... | ...                  | ... | ...                  | ... | 3.5                  | 24  | 2.8                  | 19  |
|             |     | 10                   | ...            | ... | ...                  | ... | ...                  | ... | 3.1                  | 21  | 2.4                  | 17  |
|             |     | 100                  | 3.8            | 26  | 3.6                  | 25  | 3.3                  | 23  | 2.6                  | 18  | 1.9                  | 13  |
|             |     | 1000                 | 3.2            | 22  | 2.7                  | 19  | 2.3                  | 16  | 1.5                  | 10  | 1.2                  | 8.0 |

Source data are in English units; metric values are converted and rounded.

Table D5.5 249.0-T7: Creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 0.1                  | 53             | 365 | 51                   | 350 | 51                   | 350 | 50                   | 345 | 50                   | 345 |
|             |     | 1                    | 51             | 350 | 50                   | 345 | 49                   | 340 | 49                   | 340 | 48                   | 330 |
|             |     | 10                   | 48             | 330 | 48                   | 330 | 47                   | 325 | 47                   | 325 | 44                   | 305 |
|             |     | 100                  | 43             | 295 | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
| 350         | 177 | 0.1                  | 48             | 330 | 47                   | 325 | 46                   | 315 | 45                   | 310 | 45                   | 310 |
|             |     | 1                    | 46             | 315 | 45                   | 310 | 44                   | 305 | 43                   | 295 | 41                   | 285 |
|             |     | 10                   | 41             | 285 | 40                   | 275 | 39                   | 270 | 38                   | 260 | 35                   | 240 |
|             |     | 100                  | 33             | 230 | 33                   | 230 | 32                   | 220 | 30                   | 205 | 25                   | 170 |
| 400         | 205 | 1000                 | 25             | 170 | 24                   | 165 | 24                   | 165 | 20                   | 140 | 17                   | 115 |
|             |     | 0.1                  | 42             | 290 | 41                   | 285 | 40                   | 275 | 39                   | 270 | 37                   | 255 |
|             |     | 1                    | 38             | 260 | 37                   | 255 | 36                   | 250 | 35                   | 240 | 33                   | 230 |
|             |     | 10                   | 32             | 220 | 31                   | 215 | 31                   | 215 | 29                   | 200 | 25                   | 170 |
|             |     | 100                  | 26             | 180 | 25                   | 170 | 24                   | 165 | 21                   | 145 | 15                   | 105 |
|             |     | 1000                 | 20             | 140 | 19                   | 130 | 18                   | 125 | 15                   | 105 | 12                   | 85  |

Source data are in English units; metric values are converted and rounded.

Table D5.6 295.0-T6 Sand castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |        | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|--------|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa    | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 75          | 25  | 100                  | 40(a)          | 275(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 39(a)          | 270(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1                    | ...            | ...    | 31                   | 215 | 27                   | 185 | ...                  | ... | ...                  | ... |
| 212         | 100 | 10                   | ...            | ...    | 30                   | 205 | 26                   | 180 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 32             | 220    | 30                   | 205 | 26                   | 180 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 31             | 215    | ...                  | ... | 26                   | 180 | ...                  | ... | ...                  | ... |
| 300         | 150 | 1                    | ...            | ...    | 28                   | 195 | 26                   | 180 | 17                   | 115 | ...                  | ... |
|             |     | 10                   | 30             | 205    | 28                   | 195 | 25                   | 170 | 17                   | 115 | ...                  | ... |
|             |     | 100                  | 27             | 185    | 27                   | 185 | 24                   | 165 | 15                   | 105 | ...                  | ... |
| 400         | 205 | 1000                 | 20             | 140    | ...                  | ... | 16                   | 110 | ...                  | ... | ...                  | ... |
|             |     | 1                    | ...            | ...    | ...                  | ... | ...                  | ... | 15                   | 105 | 8.0                  | 55  |
|             |     | 10                   | ...            | ...    | 18                   | 125 | 16                   | 110 | 8.0                  | 55  | ...                  | ... |
|             |     | 100                  | 16             | 110    | 14                   | 95  | 9.5                  | 66  | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 11             | 75     | 11                   | 75  | 5.8                  | 40  | ...                  | ... | ...                  | ... |

(a) Tested at 90 °F (32 °C)  
Source data are in English units; metric values are converted and rounded.

Table D5.7 333.0-T533 Permanent mold castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa | ksi                  | MPa | ksi                  | MPa |
| 212         | 100 | 1                    | 28             | 195 | 28                   | 195 | 25                   | 170 |
|             |     | 10                   | 27             | 185 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 26             | 180 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 26             | 180 | ...                  | ... | ...                  | ... |
| 300         | 150 | 1                    | 23             | 160 | 23                   | 160 | 22                   | 150 |
|             |     | 10                   | 22             | 150 | 22                   | 150 | 22                   | 150 |
|             |     | 100                  | 22             | 150 | 22                   | 150 | 22                   | 150 |
|             |     | 1000                 | 22             | 150 | 21                   | 145 | ...                  | ... |
| 400         | 205 | 1                    | 21             | 145 | 21                   | 145 | 17                   | 115 |
|             |     | 10                   | 19             | 130 | 19                   | 130 | 15                   | 105 |
|             |     | 100                  | 17             | 115 | 16                   | 110 | ...                  | ... |
|             |     | 1000                 | 14             | 95  | ...                  | ... | ...                  | ... |

Source data are in English units; metric values are converted and rounded.

Table D5.8 336.0-T551 Permanent mold castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |     |
|-------------|-----|----------------------|----------------|-----|
| °F          | °C  |                      | ksi            | MPa |
| 75          | 25  | 0.1                  | 36             | 250 |
|             |     | 1                    | 36             | 250 |
|             |     | 10                   | 36             | 250 |
|             |     | 100                  | 36             | 250 |
|             |     | 1000                 | 36             | 250 |
| 212         | 100 | 0.1                  | 32             | 220 |
|             |     | 1                    | 32             | 220 |
|             |     | 10                   | 32             | 220 |
|             |     | 100                  | 32             | 220 |
|             |     | 1000                 | 32             | 220 |
| 300         | 150 | 0.1                  | 27             | 185 |
|             |     | 1                    | 26             | 180 |
|             |     | 10                   | 26             | 180 |
|             |     | 100                  | 26             | 180 |
|             |     | 1000                 | 25             | 170 |
| 350         | 177 | 0.1                  | 24             | 165 |
|             |     | 1                    | 23             | 160 |
|             |     | 10                   | 23             | 160 |
|             |     | 100                  | 22             | 150 |
|             |     | 1000                 | 20             | 140 |
| 400         | 205 | 0.1                  | 21             | 145 |
|             |     | 1                    | 20             | 140 |
|             |     | 10                   | 19             | 130 |
|             |     | 100                  | 18             | 125 |
|             |     | 1000                 | 15             | 105 |
| 500         | 260 | 1000                 | 7.0            | 48  |
| 600         | 315 | 1000                 | 2.8            | 19  |

Source data are in English units; metric values are converted and rounded.

Table D5.9 A344.0-T4 Permanent mold castings (results of tests on permanent mold test bars): creep rupture and creep properties

| Temperature |    | Time under stress, h | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C |                      | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 75          | 25 | 0.1                  | 22             | 150 | 21                   | 145 | 20                   | 140 | 18                   | 125 | 16                   | 110 |
|             |    | 1                    | 22             | 150 | 19                   | 130 | 18                   | 125 | 16                   | 110 | 15                   | 105 |
|             |    | 10                   | 21             | 145 | 16                   | 110 | 15                   | 105 | 14                   | 95  | 12                   | 85  |
|             |    | 100                  | 19             | 130 | 14                   | 95  | 13                   | 90  | 11                   | 75  | 10                   | 70  |
|             |    | 1000                 | 17             | 115 | 12                   | 85  | 11                   | 75  | 10                   | 70  | 9.5                  | 66  |

Source data are in English units; metric values are converted and rounded.

Table D5.10 354.0-T6, -T61 Permanent mold castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 350         | 177 | 0.1                  | 44             | 305 | 43                   | 295 | 41                   | 285 | 39                   | 270 | 37                   | 255 |
|             |     | 1                    | 43             | 295 | 42                   | 290 | 41                   | 285 | 39                   | 270 | 37                   | 255 |
|             |     | 10                   | 41             | 285 | 41                   | 285 | 40                   | 275 | 37                   | 255 | 35                   | 240 |
|             |     | 100                  | 35             | 240 | 34                   | 235 | 33                   | 230 | 30                   | 205 | 17                   | 115 |
|             |     | 1000                 | 25             | 170 | 24                   | 165 | 24                   | 165 | 20                   | 140 | 11                   | 75  |
| 400         | 205 | 0.1                  | 41             | 285 | 40                   | 275 | 39                   | 270 | 37                   | 255 | 35                   | 240 |
|             |     | 1                    | 37             | 255 | 36                   | 250 | 36                   | 250 | 34                   | 235 | 31                   | 215 |
|             |     | 10                   | 32             | 220 | 31                   | 215 | 30                   | 205 | 26                   | 180 | 18                   | 125 |
|             |     | 100                  | 23             | 160 | 23                   | 160 | 22                   | 150 | 18                   | 125 | 10                   | 70  |
|             |     | 1000                 | 13             | 90  | 13                   | 90  | 12                   | 85  | 12                   | 85  | 7.0                  | 48  |

Source data are in English units; metric values are converted and rounded.

Table D5.11 355.0-T51 Sand castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |       | Stress at 1.0% creep |       | Stress at 0.5% creep |       | Stress at 0.2% creep |       | Stress at 0.1% creep |       |
|-------------|-----|----------------------|----------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|
| °F          | °C  |                      | ksi            | MPa   | ksi                  | MPa   | ksi                  | MPa   | ksi                  | MPa   | ksi                  | MPa   |
| 400         | 205 | 1                    | ...            | ...   | 10(a)                | 70(a) | 9.6(a)               | 66(a) | 8.6(a)               | 59(a) | ...                  | ...   |
|             |     | 10                   | 10(a)          | 70(a) | 9.6(a)               | 66(a) | 9.0(a)               | 62(a) | 8.0(a)               | 55(a) | ...                  | ...   |
|             |     | 100                  | 9.6(a)         | 66(a) | 8.9(a)               | 61(a) | 8.2(a)               | 57(a) | 7.0(a)               | 48(a) | ...                  | ...   |
|             |     | 1000                 | 8.6(a)         | 59(a) | 7.8(a)               | 54(a) | 7.0(a)               | 48(a) | 5.0(a)               | 34(a) | ...                  | ...   |
| 600         | 315 | 1                    | ...            | ...   | 3.0(b)               | 21(b) | 2.9(b)               | 20(b) | 2.5(b)               | 17(b) | 2.0(b)               | 14(b) |
|             |     | 10                   | 3.2(b)         | 22(b) | 2.7(b)               | 19(b) | 2.5(b)               | 17(b) | 2.1(b)               | 14(b) | 1.7(b)               | 12(b) |
|             |     | 100                  | 2.6(b)         | 18(b) | 2.4(b)               | 17(b) | 2.2(b)               | 15(b) | 1.8(b)               | 12(b) | 1.4(b)               | 10(b) |
|             |     | 1000                 | 2.1(b)         | 14(b) | 1.9(b)               | 13(b) | 1.7(b)               | 12(b) | 1.5(b)               | 10(b) | ...                  | ...   |

(a) Heated for 100 days at 400 °F (205 °C) before testing. (b) Heated for 40 days at 600 °F (315 °C) before testing  
Source data are in English units; metric values are converted and rounded.

Table D5.12 355.0-T62 Permanent mold castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |        | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|--------|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa    | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 75          | 25  | 0.1                  | 43(a)          | 295(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1                    | 42(a)          | 290(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 41(a)          | 285(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 40(a)          | 275(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 40(a)          | 275(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
| 212         | 100 | 1                    | 39             | 270    | 38                   | 260 | 36                   | 250 | ...                  | ... | ...                  | ... |
|             |     | 10                   | 38             | 260    | 37                   | 255 | 35                   | 240 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 38             | 260    | 36                   | 250 | 34                   | 235 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 37             | 255    | 35                   | 240 | 33                   | 230 | ...                  | ... | ...                  | ... |
|             |     | 1                    | 34             | 235    | ...                  | ... | 32                   | 220 | 20                   | 140 | ...                  | ... |
| 300         | 150 | 10                   | 32             | 220    | ...                  | ... | 31                   | 215 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 31             | 215    | ...                  | ... | 30                   | 205 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 29             | 200    | ...                  | ... | 25                   | 170 | ...                  | ... | ...                  | ... |
|             |     | 1                    | ...            | ...    | ...                  | ... | 19                   | 130 | 15                   | 105 | 10                   | 70  |
| 400         | 205 | 10                   | ...            | ...    | ...                  | ... | 18                   | 125 | 13                   | 90  | 8.0                  | 55  |
|             |     | 100                  | 18             | 125    | ...                  | ... | 16                   | 110 | 9.5                  | 66  | ...                  | ... |
|             |     | 1000                 | 13             | 90     | ...                  | ... | 12                   | 85  | 8.0                  | 55  | ...                  | ... |

(a) Tested at 90 °F (32 °C)  
Source data are in English units; metric values are converted and rounded.

Table D5.13 355.0-T71 Permanent mold castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |        | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|--------|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa    | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 75          | 25  | 1                    | 38(a)          | 260(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 38(a)          | 260(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 37(a)          | 255(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 37(a)          | 255(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
| 212         | 100 | 1                    | ...            | ...    | 29                   | 200 | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 32             | 220    | 29                   | 200 | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 31             | 215    | 28                   | 195 | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 29             | 200    | 27                   | 185 | ...                  | ... | ...                  | ... | ...                  | ... |
| 300         | 150 | 1                    | 28             | 195    | 26                   | 180 | 24                   | 165 | ...                  | ... | ...                  | ... |
|             |     | 10                   | 27             | 185    | 25                   | 170 | 23                   | 160 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 25             | 170    | 24                   | 165 | 22                   | 150 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 24             | 165    | 22                   | 150 | 21                   | 145 | ...                  | ... | ...                  | ... |
| 400         | 205 | 1                    | ...            | ...    | ...                  | ... | 20                   | 140 | 15                   | 105 | 12                   | 85  |
|             |     | 10                   | 21             | 145    | 20                   | 140 | 18                   | 125 | 14                   | 95  | 11                   | 75  |
|             |     | 100                  | 18             | 125    | 17                   | 115 | 16                   | 110 | 13.5                 | 95  | ...                  | ... |
|             |     | 1000                 | 14             | 95     | 13                   | 90  | 12.5                 | 85  | ...                  | ... | ...                  | ... |

(a) Tested at 90 °F (32 °C)  
Source data are in English units; metric values are converted and rounded.

Table D5.14 355.0-T71 Sand castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |        | Stress at 1.0% creep |        | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|--------|----------------------|--------|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa    | ksi                  | MPa    | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 75          | 25  | 0.1                  | 32(a)          | 220(a) | 31(a)                | 215(a) | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1                    | 32(a)          | 220(a) | 31(a)                | 215(a) | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 32(a)          | 220(a) | 31(a)                | 215(a) | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 32(a)          | 220(a) | 31(a)                | 215(a) | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 31(a)          | 215(a) | 31(a)                | 215(a) | ...                  | ... | ...                  | ... | ...                  | ... |
| 212         | 100 | 1                    | ...            | ...    | 28                   | 195    | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 28             | 195    | 27.5                 | 190    | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 27.5           | 190    | 27                   | 185    | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 27             | 185    | 26                   | 180    | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1                    | 25             | 170    | 24                   | 165    | 22                   | 150 | ...                  | ... | ...                  | ... |
| 300         | 150 | 10                   | 24             | 165    | 23                   | 160    | 21                   | 145 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 23             | 160    | 22                   | 150    | 20                   | 140 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 22             | 150    | 21                   | 145    | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1                    | 21             | 145    | 21                   | 145    | 19                   | 130 | 15                   | 105 | 12                   | 85  |
|             |     | 10                   | 20             | 140    | 19                   | 130    | 17                   | 115 | 14                   | 95  | ...                  | ... |
| 400         | 205 | 100                  | 18             | 125    | 17                   | 115    | 16                   | 110 | 13.5                 | 95  | ...                  | ... |
|             |     | 1000                 | 14             | 95     | ...                  | ...    | ...                  | ... | ...                  | ... | ...                  | ... |

(a) Tested at 90 °F (32 °C)

Source data are in English units; metric values are converted and rounded.

Table D5.15 A355.0-T51 Sand castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 400         | 205 | 1                    | ...            | ... | ...                  | ... | 16                   | 110 | 10.5                 | 70  | ...                  | ... |
|             |     | 10                   | 16.8           | 115 | 16                   | 110 | 15                   | 105 | 10                   | 70  | ...                  | ... |
|             |     | 100                  | 15             | 105 | 14.5                 | 100 | 13                   | 90  | 9.4                  | 65  | ...                  | ... |
|             |     | 1000                 | 12.3           | 85  | 11                   | 75  | ...                  | ... | 8.8                  | 61  | ...                  | ... |
| 600         | 315 | 0.1                  | 10             | 70  | 9.0                  | 62  | 8.0                  | 55  | 6.0                  | 41  | 4.4                  | 30  |
|             |     | 1                    | 8.5            | 59  | 7.0                  | 48  | 6.5                  | 45  | 4.8                  | 33  | 3.8                  | 26  |
|             |     | 10                   | 7.0            | 48  | 5.5                  | 38  | 5.0                  | 34  | 3.9                  | 27  | 3.3                  | 23  |
|             |     | 100                  | 5.5            | 38  | 4.6                  | 32  | 4.0                  | 28  | 3.2                  | 22  | 2.9                  | 20  |
|             |     | 1000                 | 4.2            | 29  | 3.7                  | 26  | 3.2                  | 22  | 2.7                  | 19  | 2.5                  | 17  |

Source data are in English units; metric values are converted and rounded.

Table D5.16 C355.0-T6: Creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 0.1                  | 41             | 285 | 39                   | 270 | 38                   | 260 | 36                   | 250 | 34                   | 235 |
|             |     | 1                    | 40             | 275 | 39                   | 270 | 38                   | 260 | 35                   | 240 | 33                   | 230 |
|             |     | 10                   | 39             | 270 | 38                   | 260 | 37                   | 255 | 34                   | 235 | 32                   | 220 |
|             |     | 100                  | 38             | 260 | 37                   | 255 | 36                   | 250 | 33                   | 230 | 31                   | 215 |
|             |     | 1000                 | 33             | 230 | 33                   | 230 | 32                   | 220 | 28                   | 195 | 27                   | 185 |
| 350         | 177 | 0.1                  | 39             | 270 | 38                   | 260 | 38                   | 260 | 35                   | 240 | 34                   | 235 |
|             |     | 1                    | 37             | 255 | 37                   | 255 | 36                   | 250 | 34                   | 235 | 33                   | 230 |
|             |     | 10                   | 35             | 240 | 35                   | 240 | 35                   | 240 | 32                   | 220 | 31                   | 215 |
|             |     | 100                  | 32             | 220 | 32                   | 220 | 31                   | 215 | 30                   | 205 | 28                   | 195 |
|             |     | 1000                 | 22             | 150 | 22                   | 150 | 21                   | 145 | 19                   | 130 | 16                   | 110 |
| 400         | 205 | 0.1                  | 37             | 255 | 36                   | 250 | 36                   | 250 | 34                   | 235 | 33                   | 230 |
|             |     | 1                    | 35             | 240 | 35                   | 240 | 34                   | 235 | 31                   | 215 | 30                   | 205 |
|             |     | 10                   | 30             | 205 | 30                   | 205 | 29                   | 200 | 26                   | 180 | 21                   | 145 |
|             |     | 100                  | 22             | 150 | 22                   | 150 | 21                   | 145 | 19                   | 130 | 9.5                  | 66  |
|             |     | 1000                 | 14             | 95  | 14                   | 95  | 14                   | 95  | 13                   | 90  | ...                  | ... |
| 500         | 260 | 0.1                  | 24             | 165 | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1                    | 18             | 125 | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 13             | 90  | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 9.0            | 62  | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 6.5            | 45  | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |

Source data are in English units; metric values are converted and rounded.



Table D5.17 356.0-T7 Sand castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |        | Stress at 1.0% creep |        | Stress at 0.5% creep |        | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|--------|----------------------|--------|----------------------|--------|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa    | ksi                  | MPa    | ksi                  | MPa    | ksi                  | MPa | ksi                  | MPa |
| 75          | 25  | 1                    | 30(a)          | 205(a) | 28(a)                | 195(a) | 26(a)                | 180(a) | ...                  | ... | ...                  | ... |
|             |     | 10                   | 29(a)          | 200(a) | 28(a)                | 195(a) | 26(a)                | 180(a) | ...                  | ... | ...                  | ... |
|             |     | 100                  | 28(a)          | 195(a) | 27(a)                | 185(a) | 25(a)                | 170(a) | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 28(a)          | 195(a) | 26(a)                | 180(a) | 25(a)                | 170(a) | ...                  | ... | ...                  | ... |
| 212         | 100 | 1                    | ...            | ...    | 25                   | 170    | 23.5                 | 160    | ...                  | ... | ...                  | ... |
|             |     | 10                   | 25             | 170    | 24.5                 | 170    | 23.5                 | 160    | ...                  | ... | ...                  | ... |
|             |     | 100                  | 24.5           | 169    | 24                   | 165    | 22.5                 | 155    | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 24             | 165    | 23.5                 | 160    | 22                   | 150    | ...                  | ... | ...                  | ... |
| 300         | 150 | 1                    | 23             | 160    | 22.5                 | 155    | 21.5                 | 150    | 17                   | 115 | ...                  | ... |
|             |     | 10                   | 22.5           | 155    | 22                   | 150    | 21                   | 145    | 16.5                 | 115 | ...                  | ... |
|             |     | 100                  | 22             | 150    | 21.5                 | 150    | 20.5                 | 140    | 16                   | 110 | ...                  | ... |
|             |     | 1000                 | 20             | 140    | 19.5                 | 135    | 19                   | 130    | 15                   | 105 | ...                  | ... |
| 400         | 205 | 0.1                  | 21             | 145    | ...                  | ...    | ...                  | ...    | ...                  | ... | ...                  | ... |
|             |     | 1                    | 20             | 140    | ...                  | ...    | ...                  | ...    | 15                   | 105 | 9.5                  | 66  |
|             |     | 10                   | 18             | 125    | 18                   | 125    | 17                   | 115    | 14                   | 95  | 7.8                  | 54  |
|             |     | 100                  | 15             | 105    | 15                   | 105    | 14                   | 95     | 10                   | 70  | 5.0                  | 34  |
|             |     | 1000                 | 8.5            | 59     | ...                  | ...    | ...                  | ...    | 5.5                  | 38  | ...                  | ... |

(a) Tested at 90 °F (32 °C)  
Source data are in English units; metric values are converted and rounded.

Table D5.18 A356.0-T6, -T61 Permanent mold castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 0.1                  | 34             | 235 | 31                   | 215 | 30                   | 205 | 28                   | 195 | 27                   | 185 |
|             |     | 1                    | 34             | 235 | 31                   | 215 | 29                   | 200 | 27                   | 185 | 26                   | 180 |
|             |     | 10                   | 33             | 230 | 30                   | 205 | 28                   | 195 | 26                   | 180 | 25                   | 170 |
|             |     | 100                  | 29             | 200 | 28                   | 195 | 27                   | 185 | 25                   | 170 | 24                   | 165 |
|             |     | 1000                 | 24             | 165 | 24                   | 165 | 23                   | 160 | ...                  | ... | ...                  | ... |

Source data are in English units; metric values are converted and rounded.

Table D5.19 A357.0-T6, -T61, -T62 Permanent mold castings: creep rupture and creep properties

| Temperature |     | Time under stress, h | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  |                      | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 350         | 177 | 0.1                  | 36             | 250 | 35                   | 240 | 35                   | 240 | 32                   | 220 | 31                   | 215 |
|             |     | 1                    | 35             | 240 | 34                   | 235 | 34                   | 235 | 31                   | 215 | 30                   | 205 |
|             |     | 10                   | 33             | 230 | 32                   | 220 | 31                   | 215 | 29                   | 200 | 26                   | 180 |
|             |     | 100                  | 25             | 170 | 25                   | 170 | 24                   | 165 | 20                   | 140 | ...                  | ... |
|             |     | 1000                 | 16             | 110 | 16                   | 110 | 16                   | 110 | ...                  | ... | ...                  | ... |

Source data are in English units; metric values are converted and rounded.

Table D5.20 360.0-F Die castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |       |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-------|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa   |
| 212         | 100 | 0.1                  | 43             | 295 | 42                   | 290 | 41                   | 285 | 35                   | 240 | 28                   | 195   |
|             |     | 1                    | 43             | 295 | 42                   | 290 | 38                   | 260 | 32                   | 220 | 27                   | 185   |
|             |     | 10                   | 42             | 290 | 40                   | 275 | 37                   | 255 | 30                   | 205 | 26                   | 180   |
|             |     | 100                  | 42             | 290 | 38                   | 260 | 35                   | 240 | 28                   | 195 | 25                   | 170   |
|             |     | 1000                 | 41             | 285 | 36                   | 250 | 33                   | 230 | 26                   | 180 | 24                   | 165   |
| 300         | 150 | 0.1                  | 39             | 270 | 37                   | 255 | 35                   | 240 | 32                   | 220 | 29                   | 200   |
|             |     | 1                    | 38             | 260 | 35                   | 240 | 33                   | 230 | 29                   | 200 | 27                   | 185   |
|             |     | 10                   | 35             | 240 | 33                   | 230 | 31                   | 215 | 26                   | 180 | 18                   | 125   |
|             |     | 100                  | 32             | 220 | 30                   | 205 | 27                   | 185 | 17                   | 115 | 4.0                  | 28    |
|             |     | 1000                 | 27             | 185 | 25                   | 170 | 22                   | 150 | 18                   | 125 | ...                  | ...   |
| 400         | 205 | 0.1                  | 33             | 230 | 31                   | 215 | 29                   | 200 | 26                   | 180 | 23                   | 160   |
|             |     | 1                    | 29             | 200 | 27                   | 185 | 25                   | 170 | 21                   | 145 | 18                   | 125   |
|             |     | 10                   | 25             | 170 | 23                   | 160 | 21                   | 145 | 17                   | 115 | 13                   | 90    |
|             |     | 100                  | 21             | 145 | 19                   | 130 | 17                   | 115 | 13                   | 90  | 8.5(a)               | 59(a) |
|             |     | 1000                 | 16             | 110 | 15                   | 105 | 13                   | 90  | 10                   | 70  | 7.0(a)               | 48(a) |

(a) These values are higher than the corresponding values for 300 °F (150 °C). This behavior is probably associated with aging.  
Source data are in English units; metric values are converted and rounded.

Table D5.21 380.0-F Die castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |       | Stress at 0.1% creep |       |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-------|----------------------|-------|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa   | ksi                  | MPa   |
| 212         | 100 | 0.1                  | 45             | 310 | 44                   | 305 | 42                   | 290 | 38                   | 260   | 31                   | 215   |
|             |     | 1                    | 44             | 305 | 43                   | 295 | 40                   | 275 | 35                   | 240   | 28                   | 195   |
|             |     | 10                   | 42             | 290 | 41                   | 285 | 38                   | 260 | 31                   | 215   | 25                   | 170   |
|             |     | 100                  | 41             | 285 | 38                   | 260 | 35                   | 240 | 27                   | 185   | 23                   | 160   |
|             |     | 1000                 | 39             | 270 | 36                   | 250 | 31                   | 215 | 23                   | 160   | 21                   | 145   |
| 300         | 150 | 0.1                  | 39             | 270 | 38                   | 260 | 36                   | 250 | 31                   | 215   | 25                   | 170   |
|             |     | 1                    | 37             | 255 | 36                   | 250 | 33                   | 230 | 27                   | 185   | 23                   | 160   |
|             |     | 10                   | 34             | 235 | 31                   | 215 | 28                   | 195 | 23                   | 160   | 20                   | 140   |
|             |     | 100                  | 29             | 200 | 26                   | 180 | 23                   | 160 | 16                   | 110   | 5.0                  | 34    |
|             |     | 1000                 | 24             | 165 | 23                   | 160 | 20                   | 140 | 10                   | 70    | ...                  | ...   |
| 400         | 205 | 0.1                  | 28             | 195 | 26                   | 180 | 23                   | 160 | 19                   | 130   | 17                   | 115   |
|             |     | 1                    | 25             | 170 | 21                   | 145 | 20                   | 140 | 17                   | 115   | 15                   | 105   |
|             |     | 10                   | 22             | 150 | 19                   | 130 | 17                   | 115 | 15                   | 105   | 13                   | 90    |
|             |     | 100                  | 19             | 130 | 17                   | 115 | 15                   | 105 | 13                   | 90    | 11(a)                | 75(a) |
|             |     | 1000                 | 16             | 110 | 15                   | 105 | 13                   | 90  | 11(a)                | 75(a) | 10(a)                | 70(a) |

(a) These values are higher than the corresponding values for 300 °F (150 °C). This behavior is probably associated with aging.  
Source data are in English units; metric values are converted and rounded.

Table D5.22 384.0-F Die castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |     | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 300         | 150 | 0.1                  | 43             | 295 | 41                   | 285 | 37                   | 255 | 30                   | 205 | ...                  | ... |
|             |     | 1                    | 42             | 290 | 37                   | 255 | 34                   | 235 | ...                  | ... | ...                  | ... |
|             |     | 10                   | 38             | 260 | 33                   | 230 | 30                   | 205 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 33             | 230 | 29                   | 200 | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 28             | 195 | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
| 400         | 205 | 0.1                  | 31             | 215 | 29                   | 200 | 26                   | 180 | 21                   | 145 | 18                   | 125 |
|             |     | 1                    | 29             | 200 | 25                   | 170 | 22                   | 150 | 16                   | 110 | ...                  | ... |
|             |     | 10                   | 26             | 180 | 21                   | 145 | 18                   | 125 | ...                  | ... | ...                  | ... |
|             |     | 100                  | 23             | 160 | 19                   | 130 | 16                   | 110 | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 21             | 145 | 17                   | 115 | 14                   | 95  | ...                  | ... | ...                  | ... |

Source data are in English units; metric values are converted and rounded.

Table D5.23 B443.0-F Sand castings: creep rupture and creep properties

| Temperature |     |                      | Rupture stress |        | Stress at 1.0% creep |     | Stress at 0.5% creep |     | Stress at 0.2% creep |     | Stress at 0.1% creep |     |
|-------------|-----|----------------------|----------------|--------|----------------------|-----|----------------------|-----|----------------------|-----|----------------------|-----|
| °F          | °C  | Time under stress, h | ksi            | MPa    | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa | ksi                  | MPa |
| 75          | 25  | 1                    | 19(a)          | 130(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 18(a)          | 125(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 17(a)          | 115(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 16(a)          | 110(a) | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
| 212         | 100 | 1                    | 16             | 110    | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 10                   | 15             | 105    | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 100                  | 14             | 95     | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 14             | 95     | ...                  | ... | ...                  | ... | ...                  | ... | ...                  | ... |
| 300         | 150 | 1                    | 13             | 90     | 10                   | 70  | 9.0                  | 62  | 7.0                  | 48  | ...                  | ... |
|             |     | 10                   | 13             | 90     | 10                   | 70  | 9.0                  | 62  | 7.0                  | 48  | ...                  | ... |
|             |     | 100                  | 12             | 85     | 10                   | 70  | 8.5                  | 59  | 6.5                  | 45  | ...                  | ... |
|             |     | 1000                 | 10             | 70     | 9.0                  | 62  | 7.0                  | 48  | ...                  | ... | ...                  | ... |
| 400         | 205 | 1                    | ...            | ...    | 9.0                  | 62  | 8.0                  | 55  | 7.0                  | 48  | 4.9                  | 34  |
|             |     | 10                   | 9.5            | 66     | 8.5                  | 59  | 7.5                  | 52  | 4.9                  | 34  | ...                  | ... |
|             |     | 100                  | 8.0            | 55     | 7.0                  | 48  | 6.0                  | 41  | ...                  | ... | ...                  | ... |
|             |     | 1000                 | 6.5            | 45     | 6.0                  | 41  | 5.0                  | 34  | ...                  | ... | ...                  | ... |

(a) Tested at 90 °F (32 °C)  
Source data are in English units; metric values are converted and rounded.

## DATA SET 6

# Rotating-Beam Reversed-Bending Fatigue Curves

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This data set contains the results of rotating-beam reversed-bending (stress ratio,  $R = -1.0$ ) fatigue tests for a wide range of aluminum casting alloys. All the fatigue curves were developed at Alcoa Laboratories in New Kensington, PA.

These fatigue curves are the results of tests on individual lots of material considered representative of the respective alloys and tempers. The tests were made in R.R. Moore type rotating-beam fatigue machines. The raw data are presented; they have not

been normalized to any typical or average properties for the individual alloys and tempers. In some cases, the results of tests from several lots of the same alloy and temper are included on one figure.

Unless otherwise noted, the tests are performed on smooth and notched specimens as shown in Fig. A3.2 of Appendix 3.

A horizontal arrow on a rightmost data point indicates that the specimen did not fail.

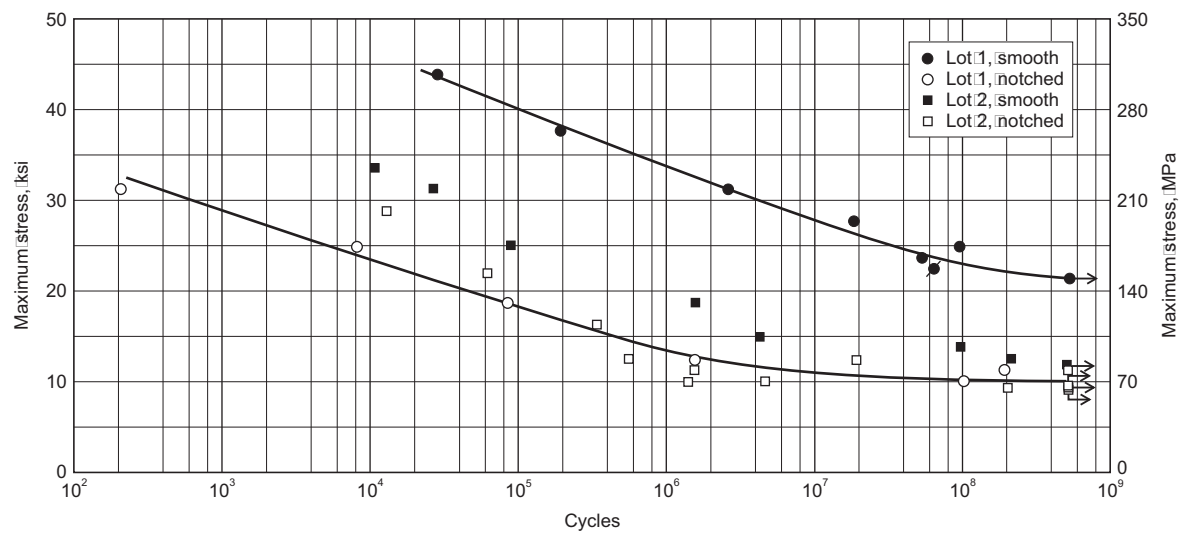


**Fig. D6.1** 213.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots. Line through data point indicates specimen had nonuniform microstructure.

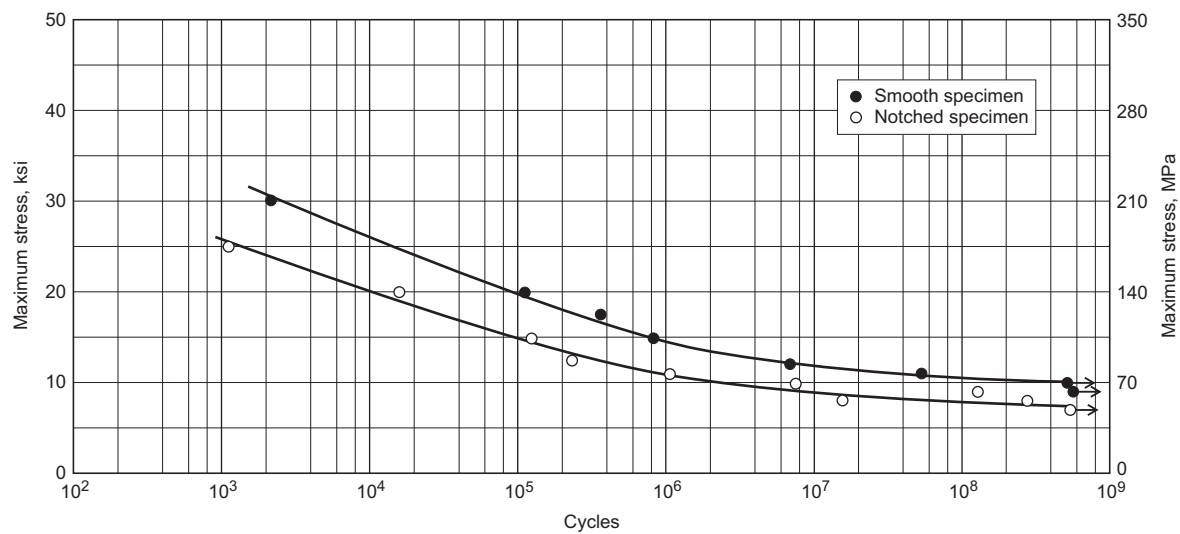


**Fig. D6.2** 213.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

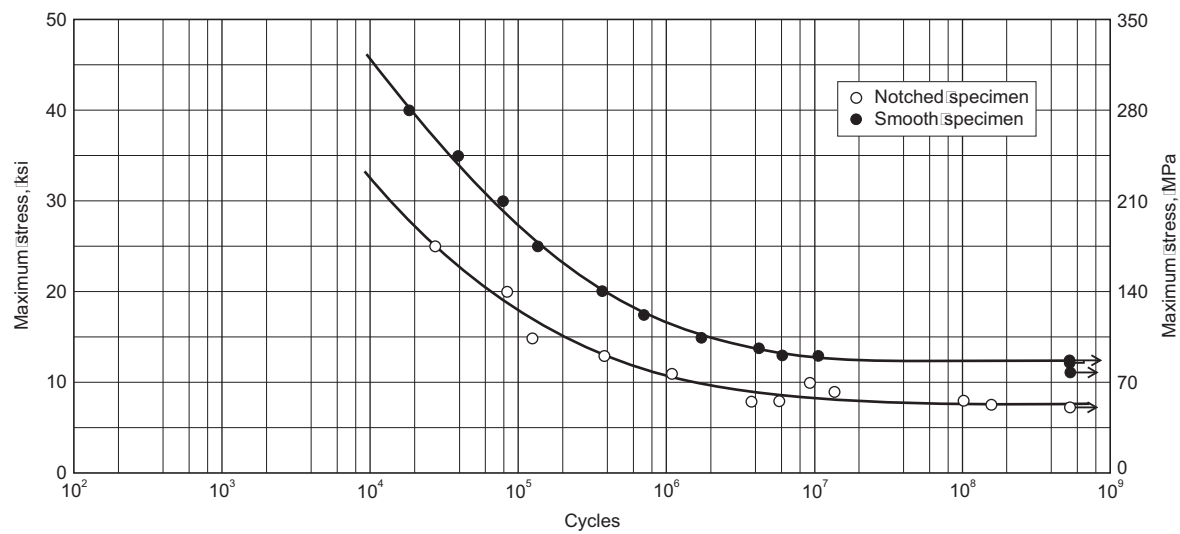


**Fig. D6.3** 224.0-T62, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

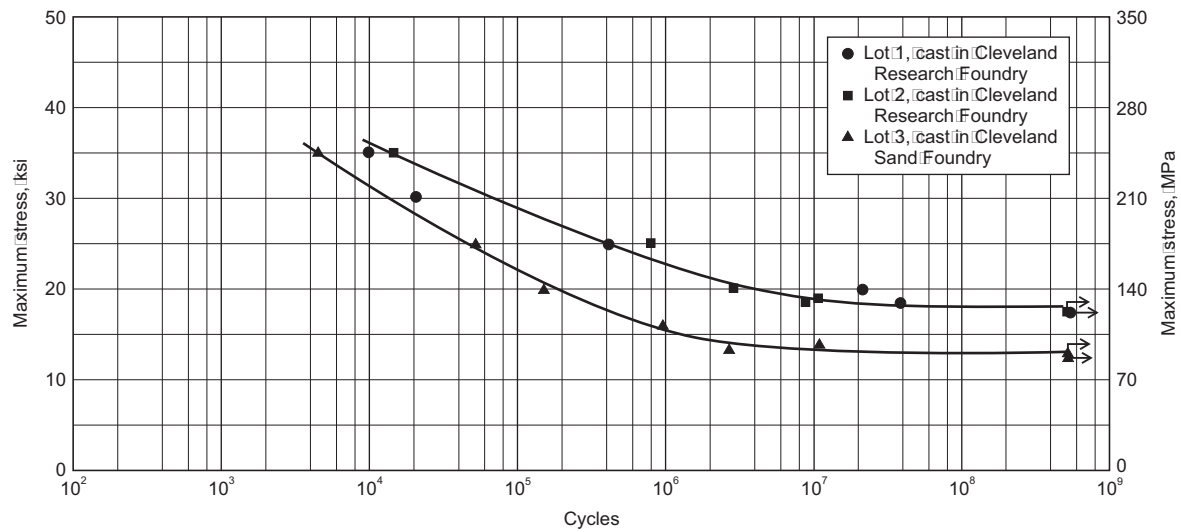


**Fig. D6.4** 240.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from three lots

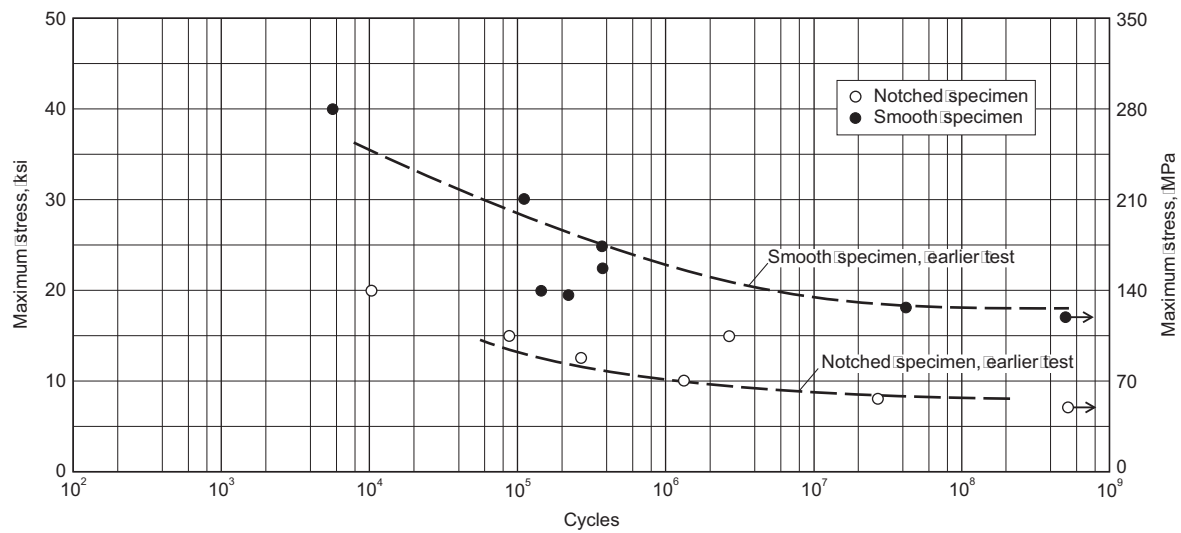


**Fig. D6.5** 240.0-F, sand cast aluminum casting rotating-beam fatigue curve. Data points for smooth and notched specimens from one lot are compared to curves from previous tests.

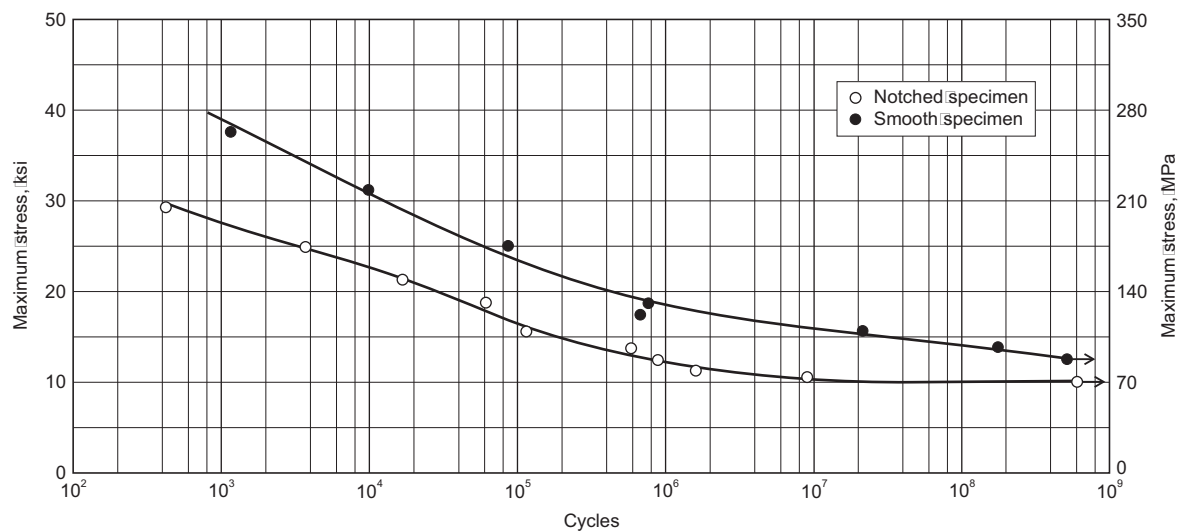


**Fig. D6.6** 242.0-O, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

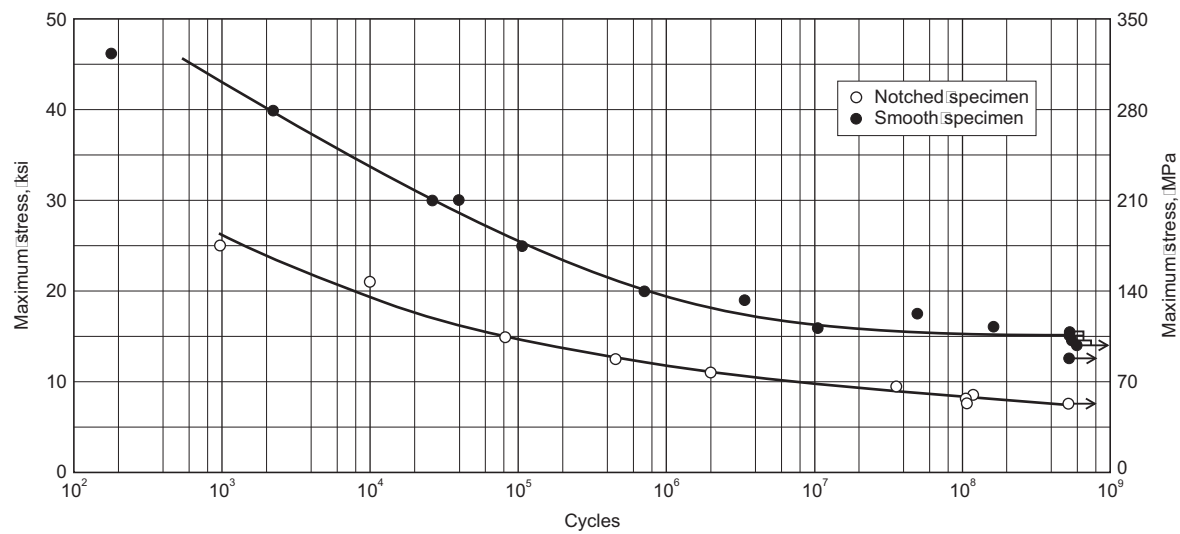


Fig. D6.7 242.0-T571, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

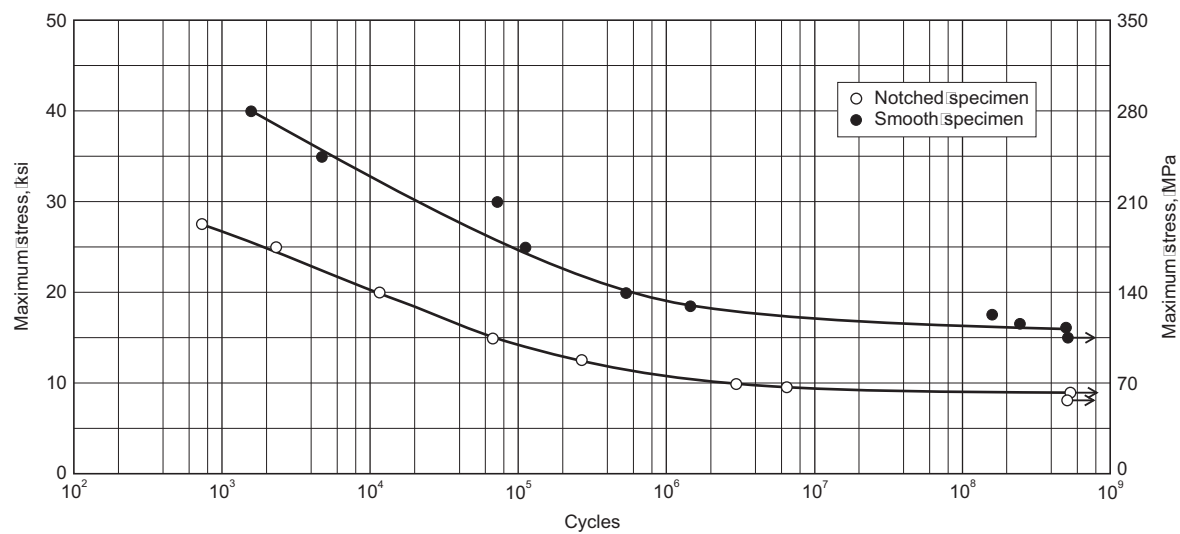


Fig. D6.8 242.0-T571, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

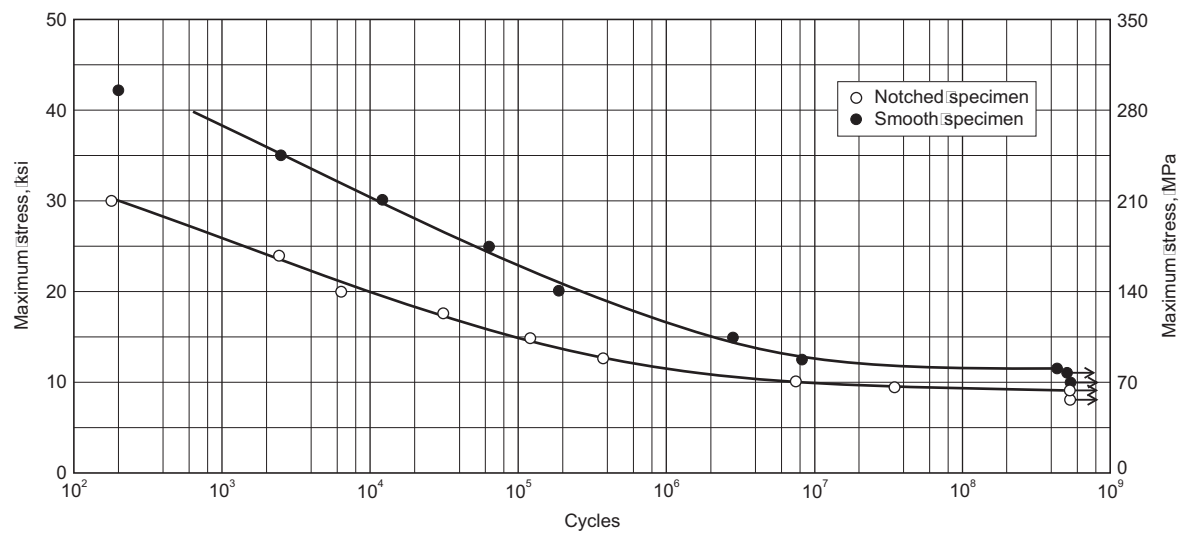


Fig. D6.9 242.0-T571, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot



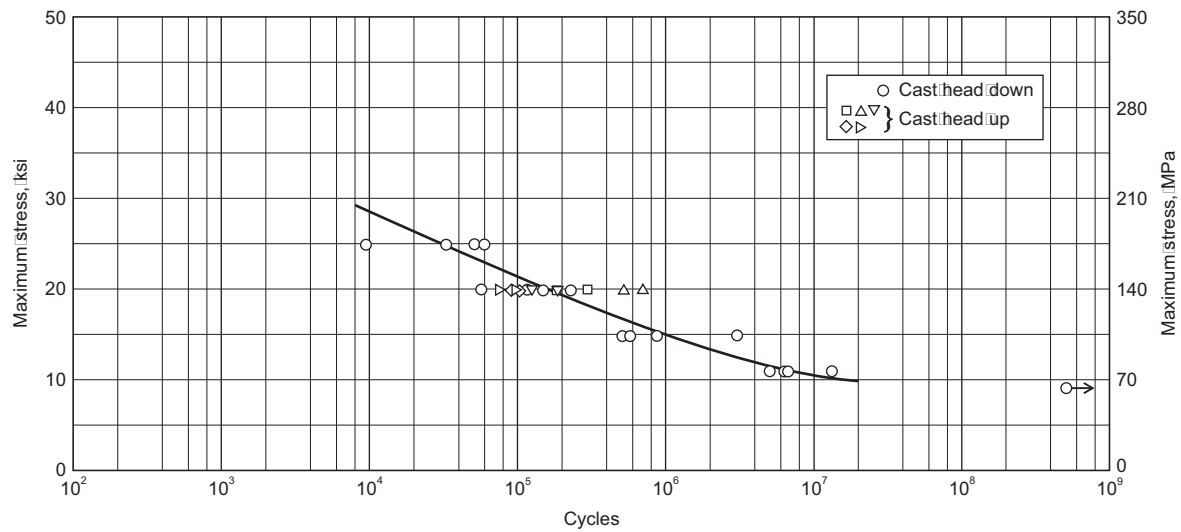


**Fig. D6.10** 242.0-T571, cast pistons aluminum casting rotating-beam fatigue curve. Smooth specimens are from the wrist pin boss, shaped to Fig. A3.2(a), Appendix 3. Open circle symbol, cast head down, others cast head up

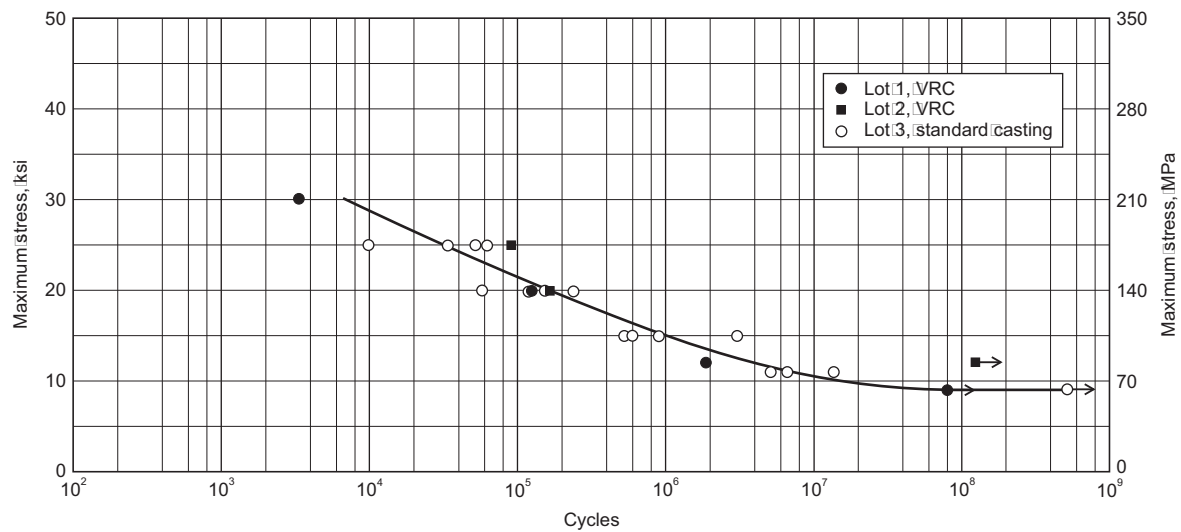


**Fig. D6.11** 242.0-T571, cast pistons aluminum casting rotating-beam fatigue curve. Smooth specimens are from the wrist pin boss, shaped to Fig. A3.2(a), Appendix 3. Solid symbols are vacuum riserless castings (VRC); open symbol is standard.

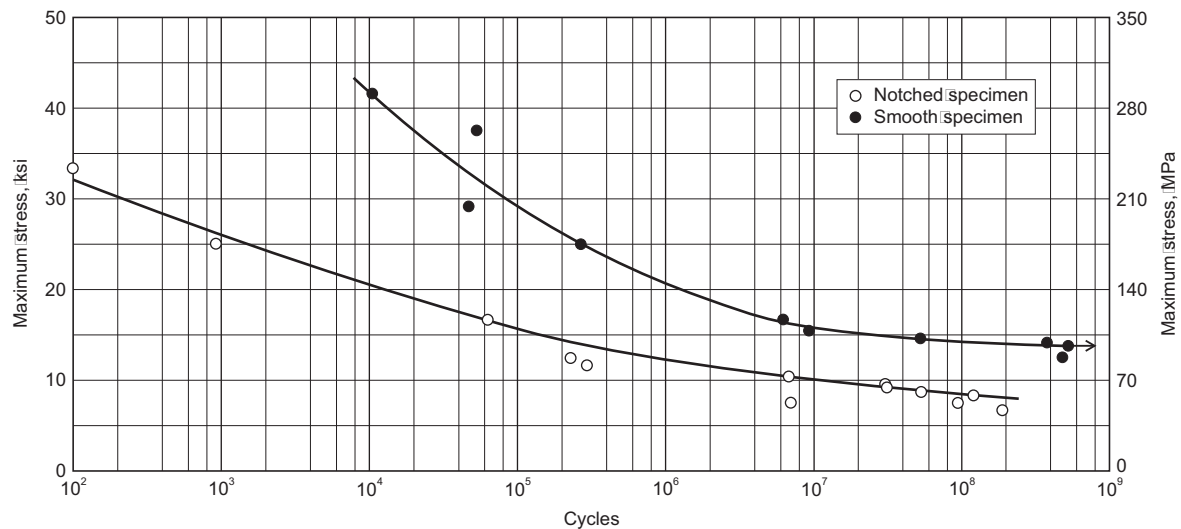


**Fig. D6.12** 242.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

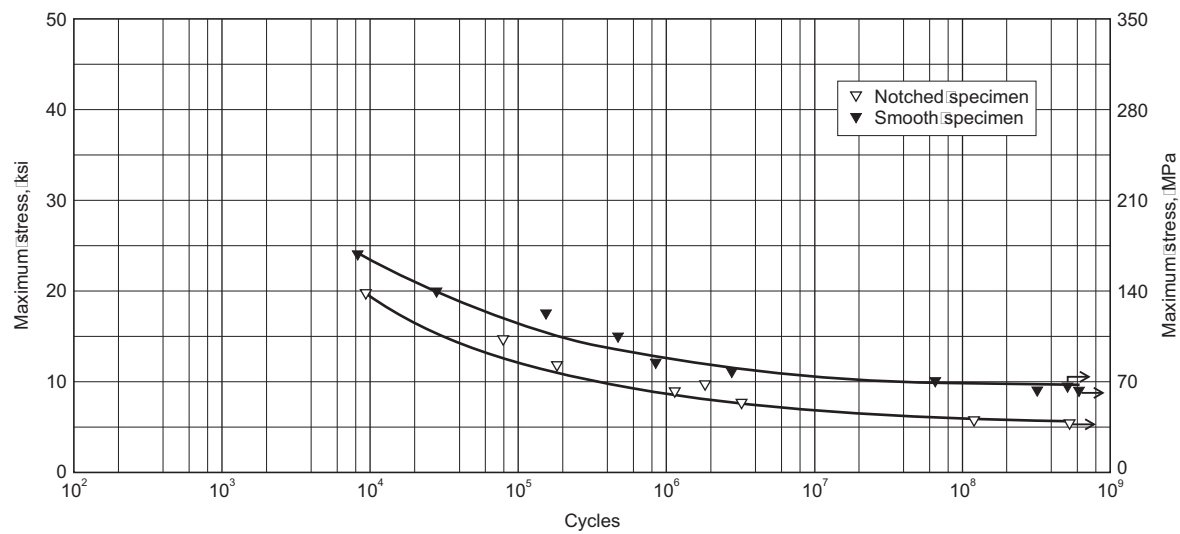


Fig. D6.13 242.0-T75, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

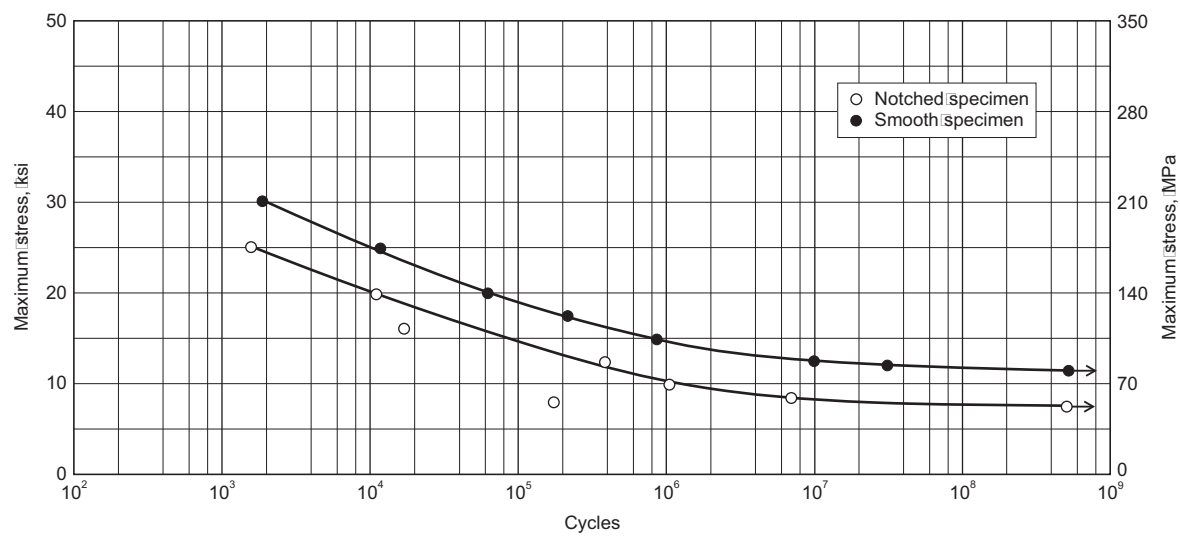


Fig. D6.14 242.0-T77, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

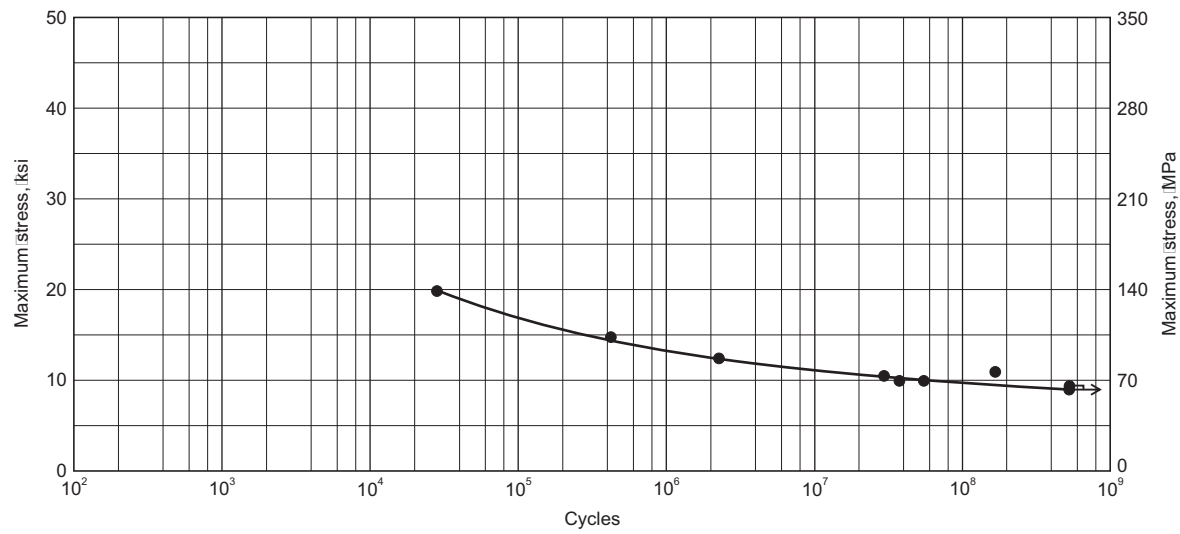


Fig. D6.15 242.0-T77, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

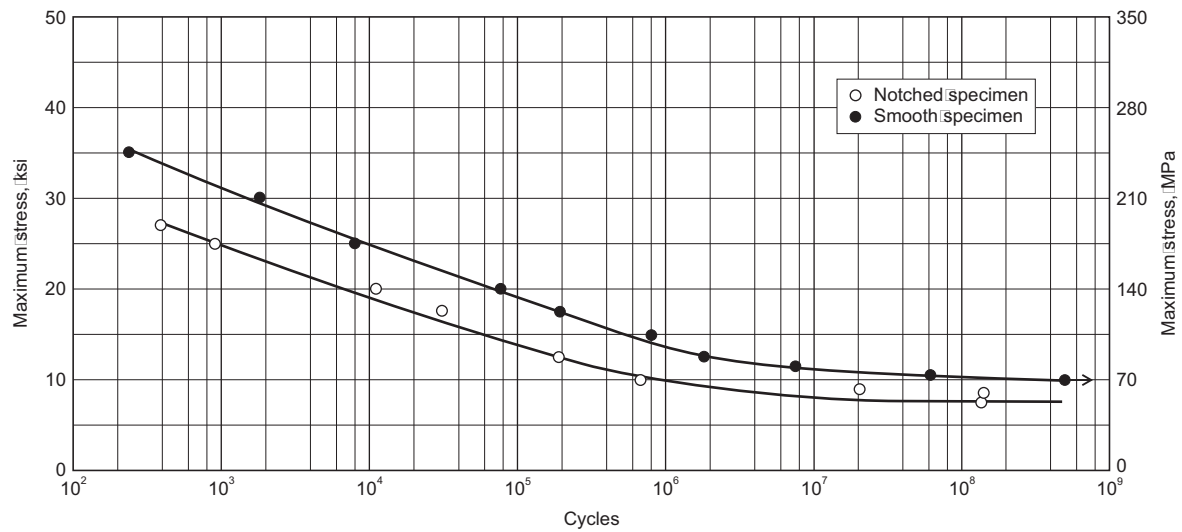


**Fig. D6.16** 242.0-T77, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

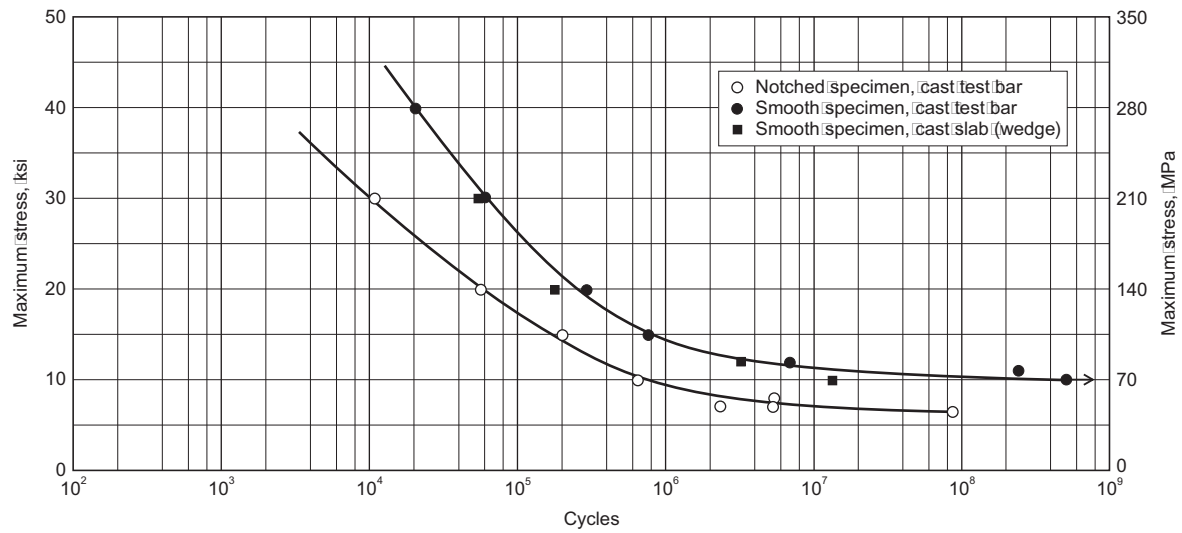


**Fig. D6.17** 249.0-T63, sand cast aluminum casting rotating-beam fatigue curve. Circles are smooth and notched specimens from one lot. Squares are smooth specimens taken from cast slab

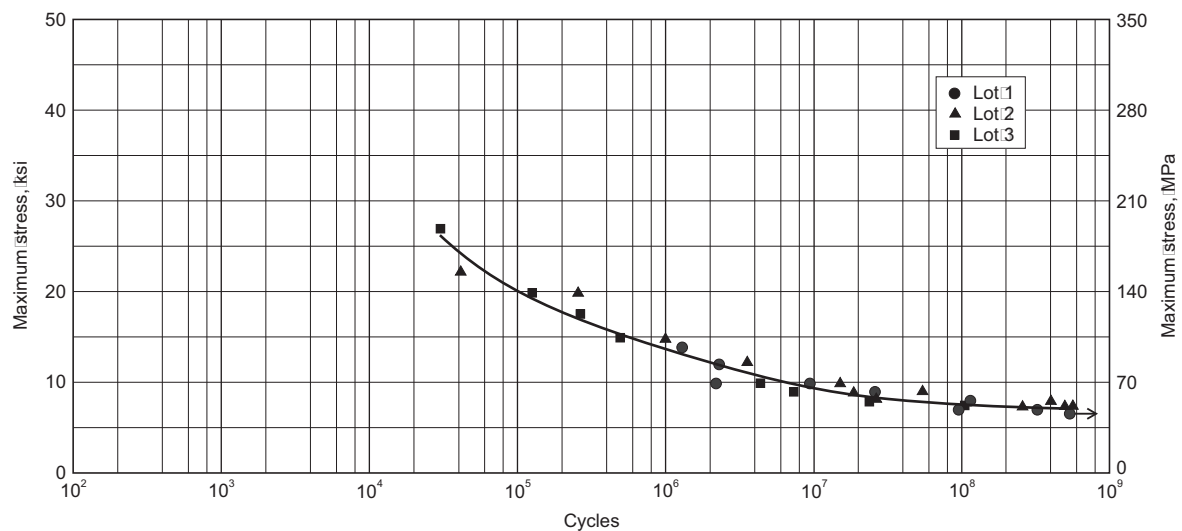


**Fig. D6.18** 295.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from three lots

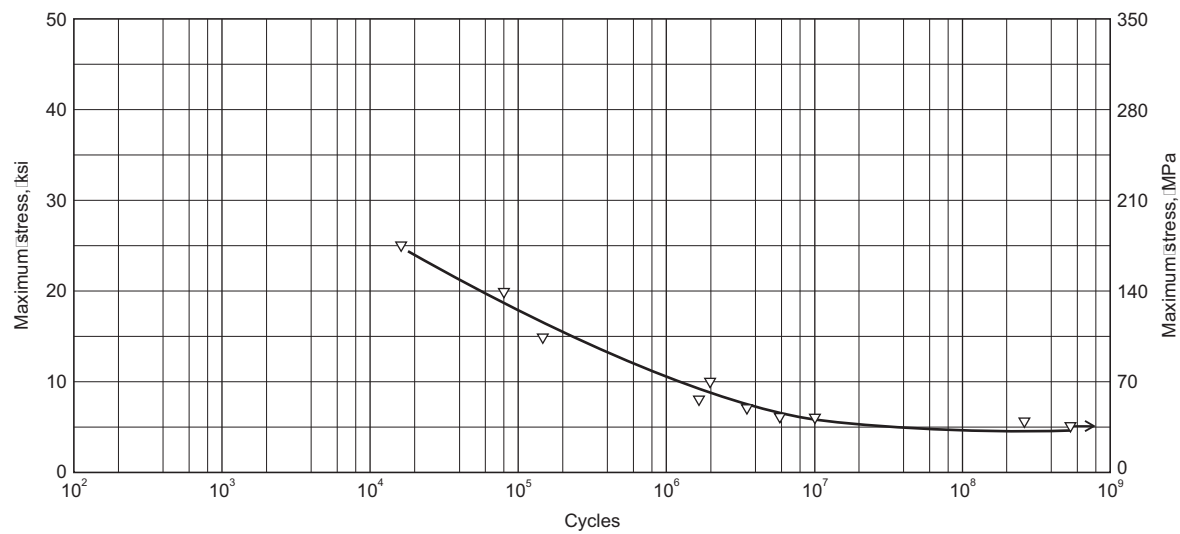


Fig. D6.19 295.0-T62, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

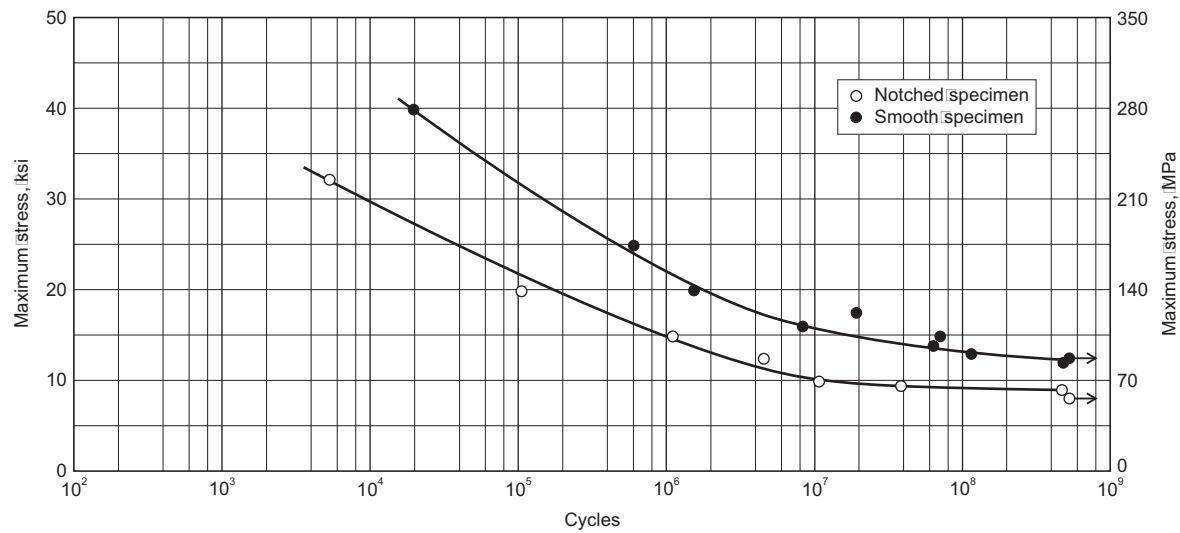


Fig. D6.20 296.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

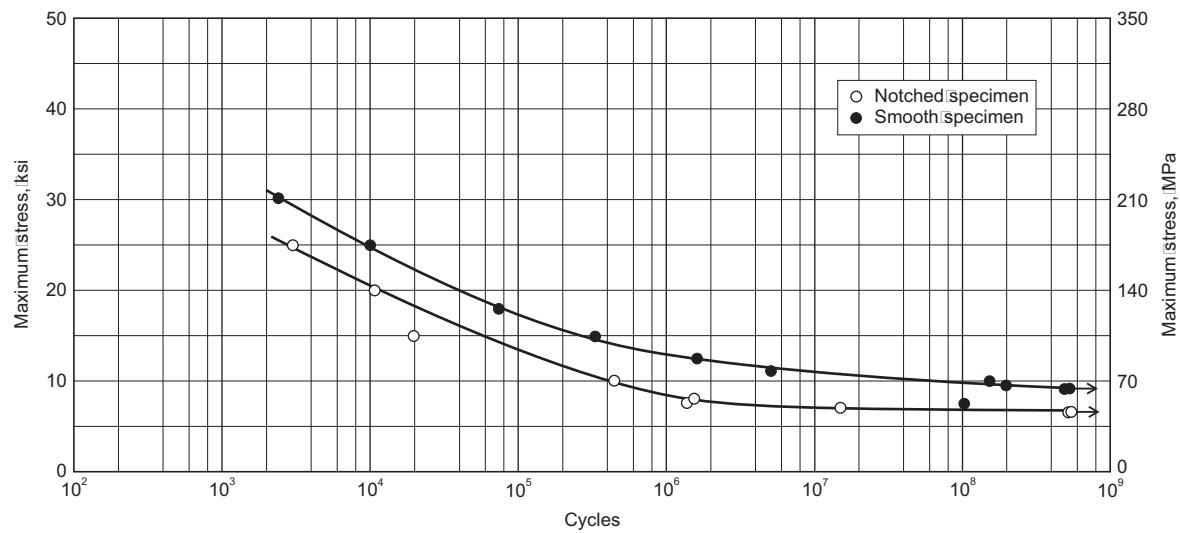


Fig. D6.21 296.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

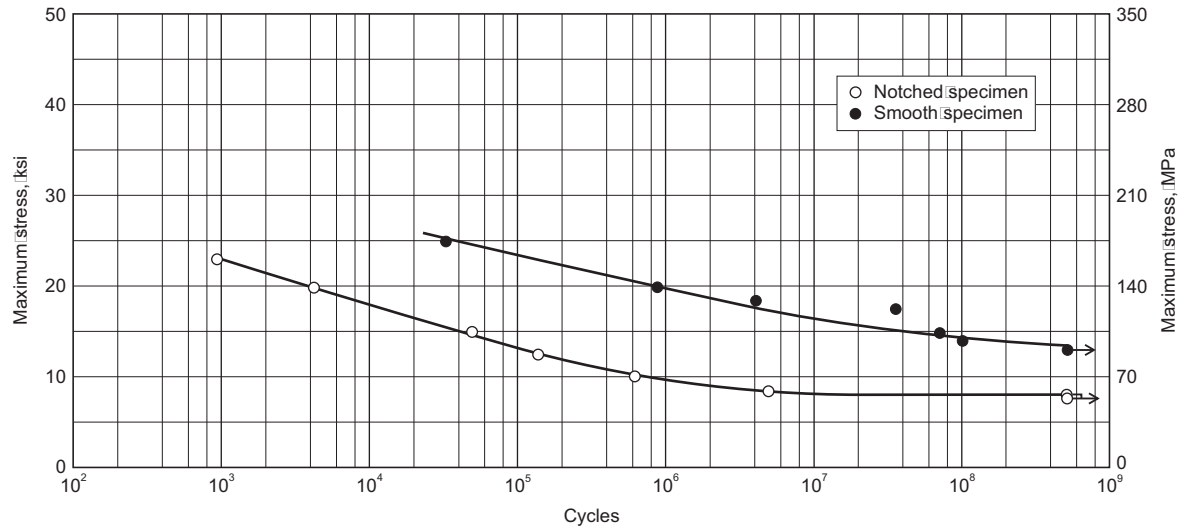


**Fig. D6.22** 308.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

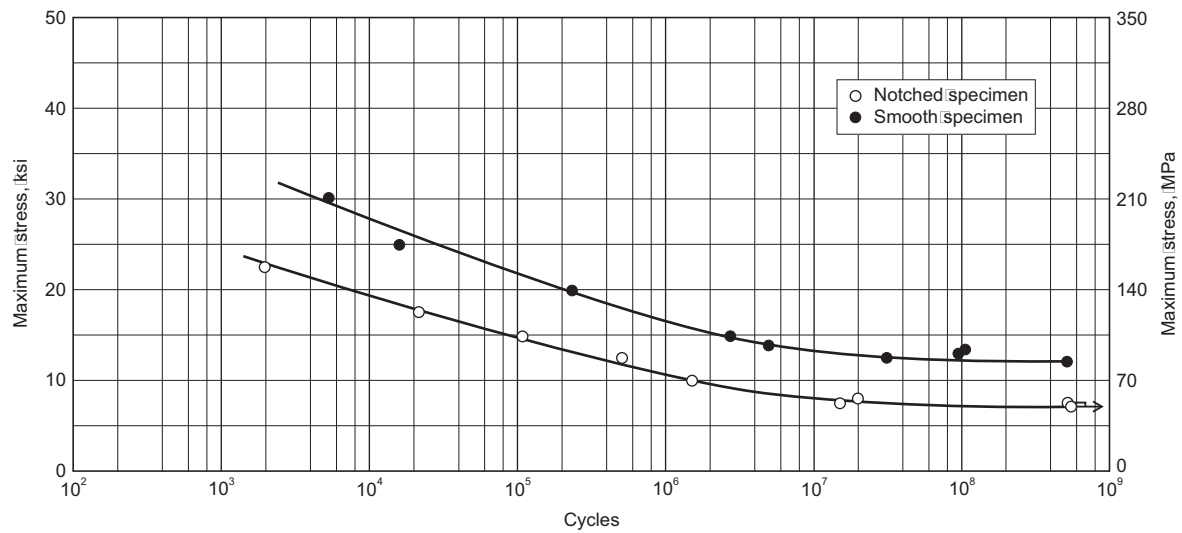


**Fig. D6.23** 308.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

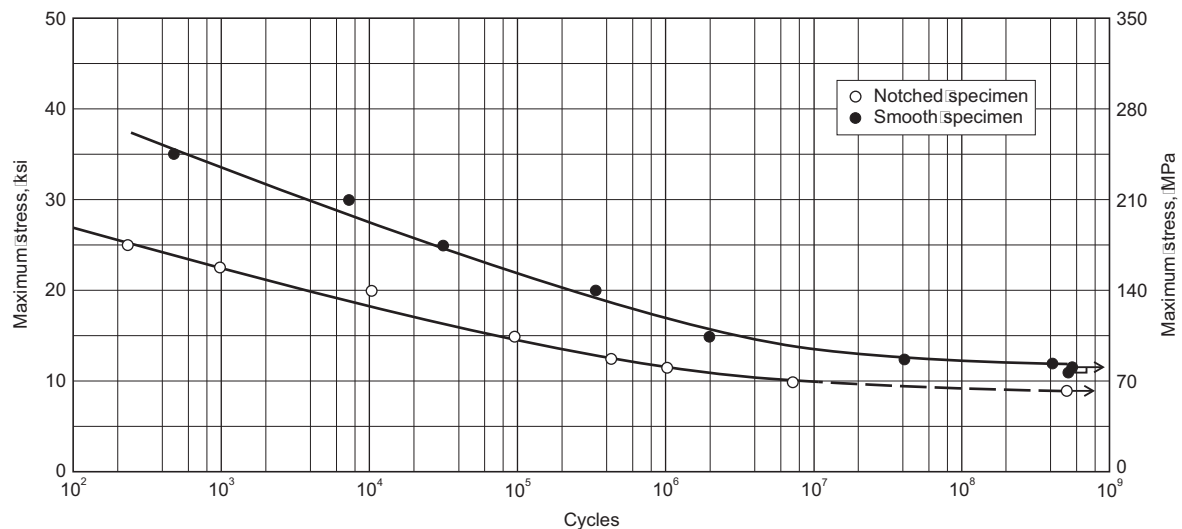


**Fig. D6.24** 319.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

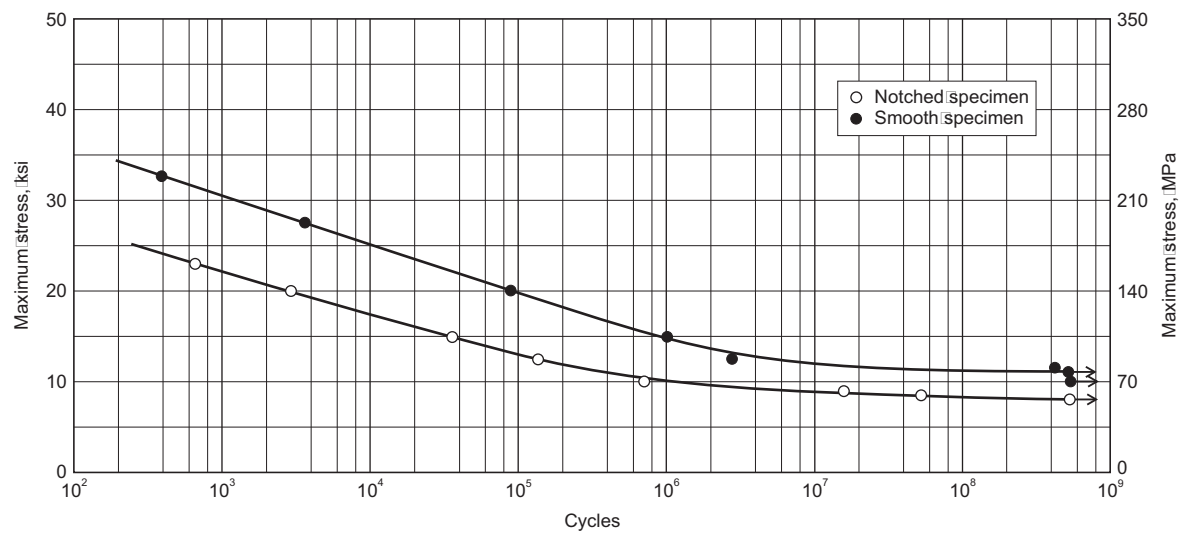


Fig. D6.25 319.0-T5, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

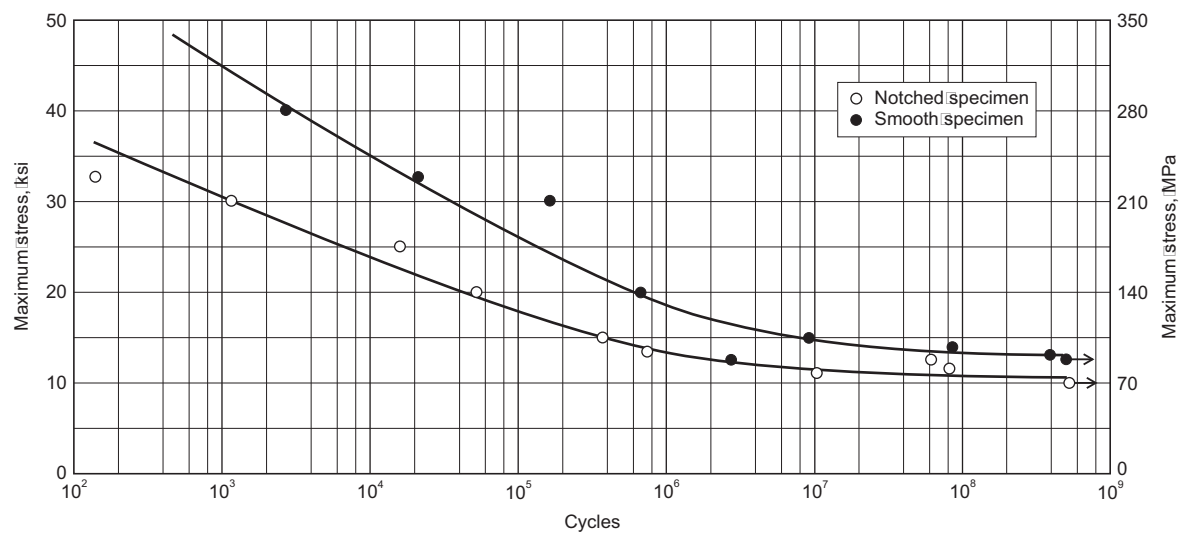


Fig. D6.26 319.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

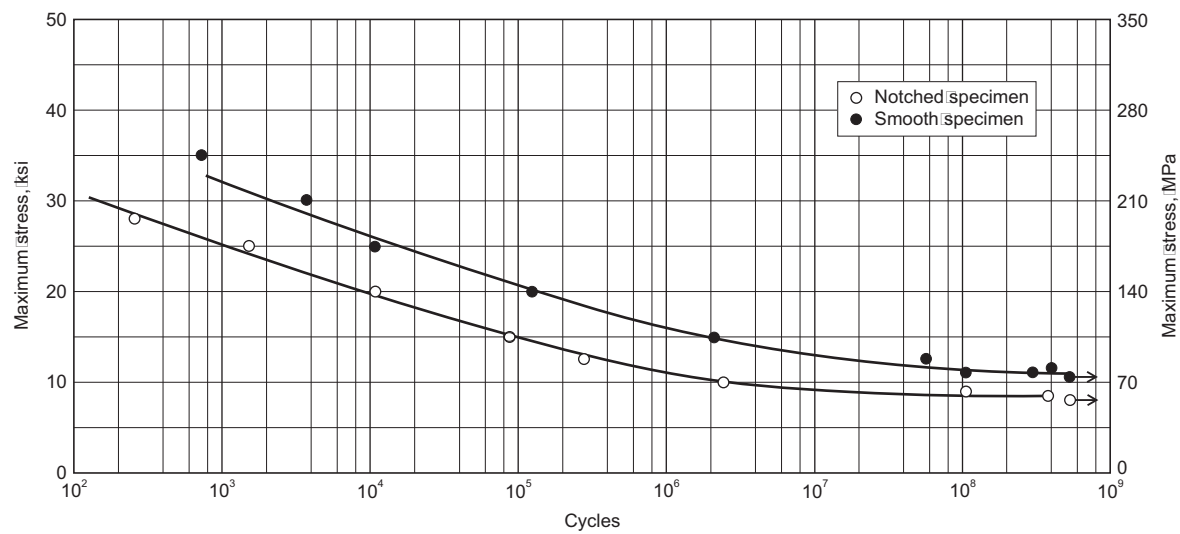


Fig. D6.27 319.0-T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

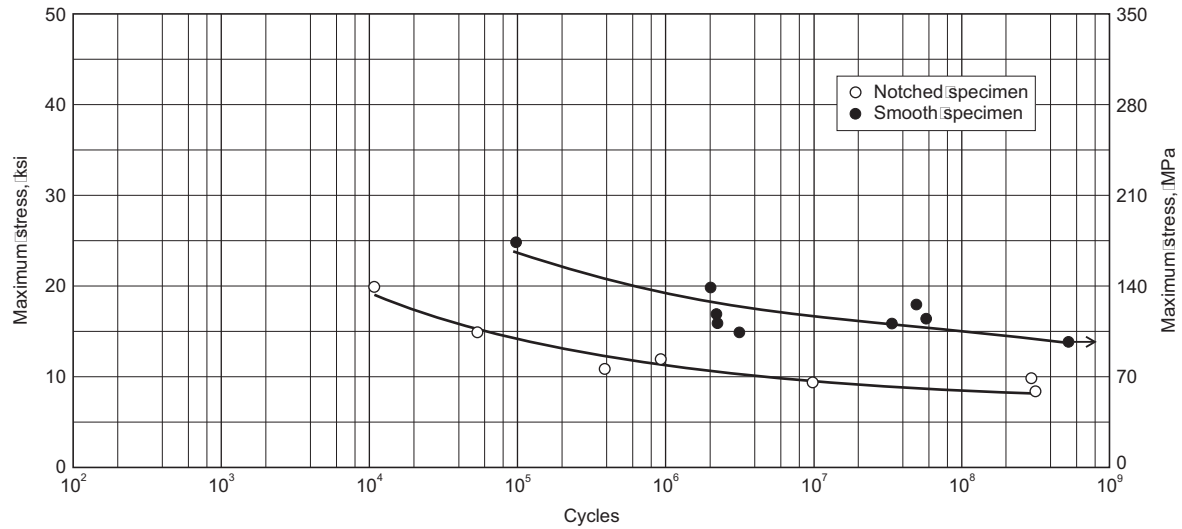


**Fig. D6.28** 332.0-T5, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

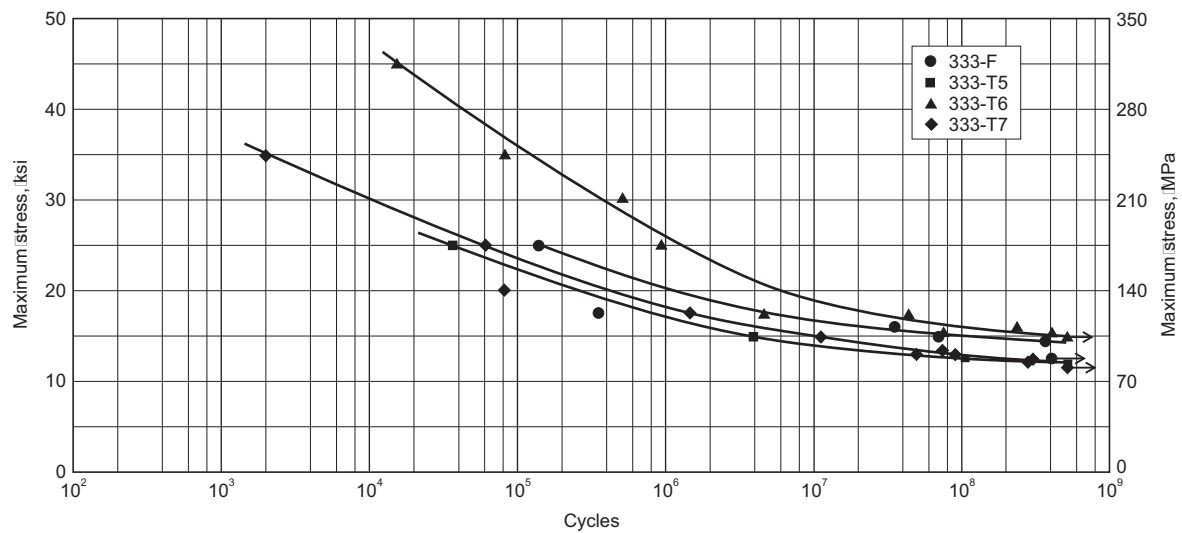


**Fig. D6.29** 333.0-F, -T5, -T6, and -T7, permanent mold aluminum casting rotating-beam fatigue curve. Comparison of smooth specimens as-cast (F) and with three heat treatments

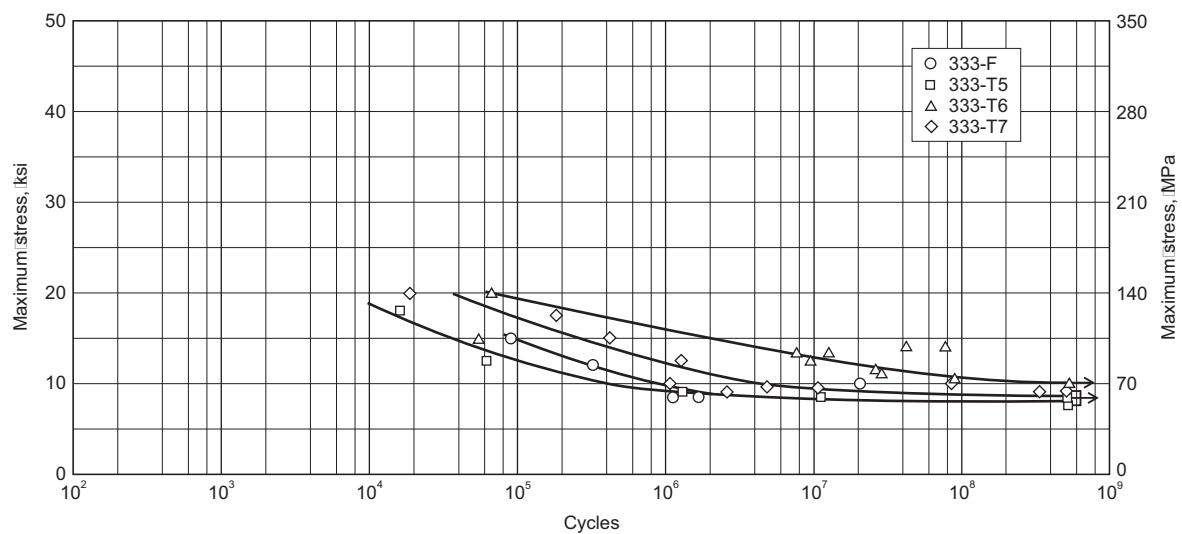


**Fig. D6.30** 333.0-F, -T5, -T6, and -T7, permanent mold aluminum casting rotating-beam fatigue curve. Comparison of notched specimens as-cast (F) and with three heat treatments



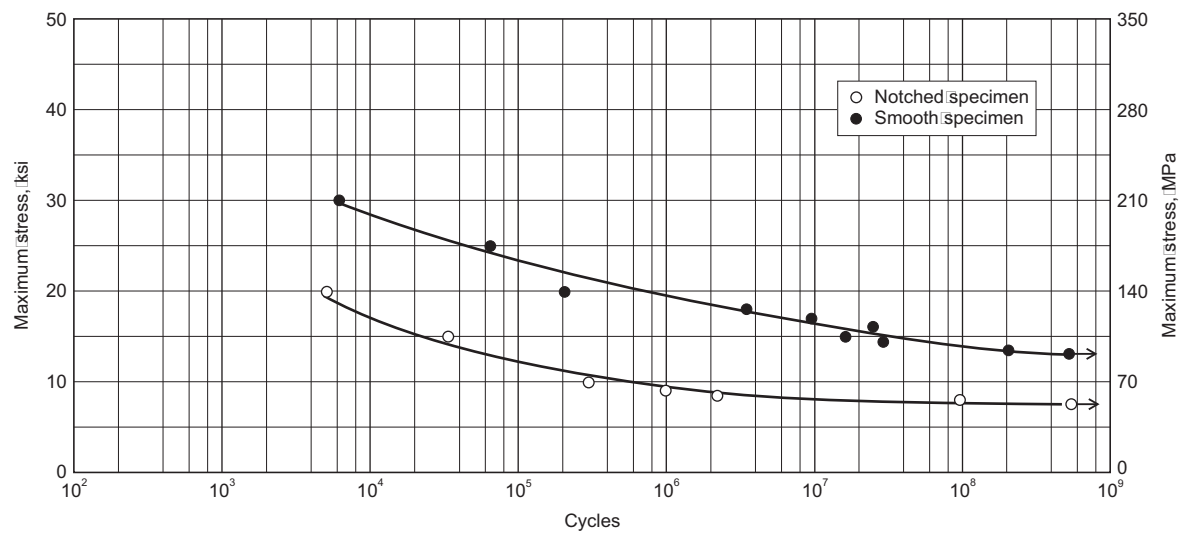


Fig. D6.31 333.0-T5, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

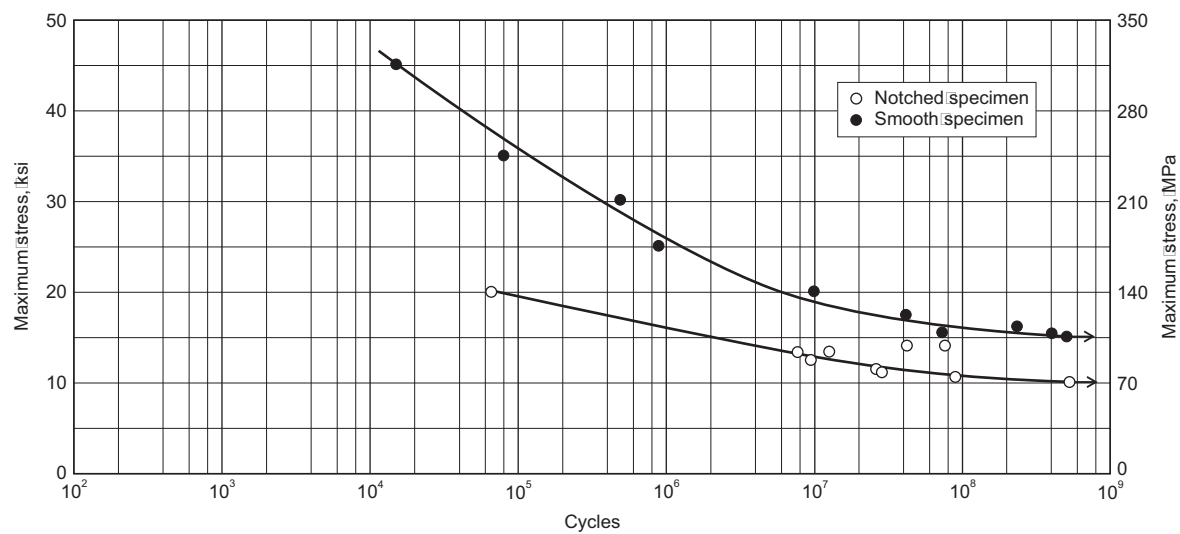


Fig. D6.32 333.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

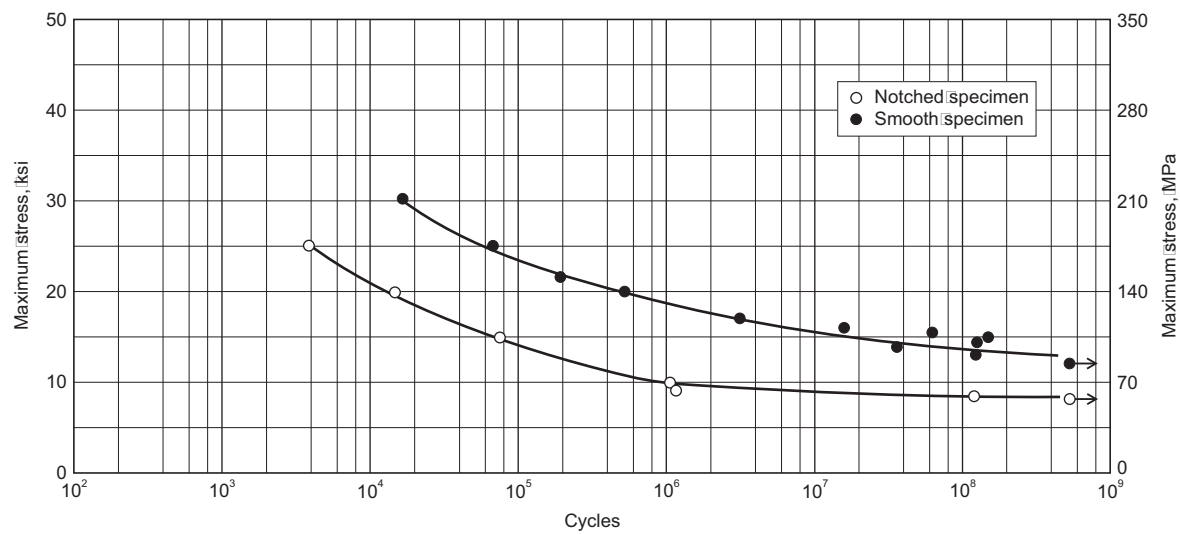


Fig. D6.33 333.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

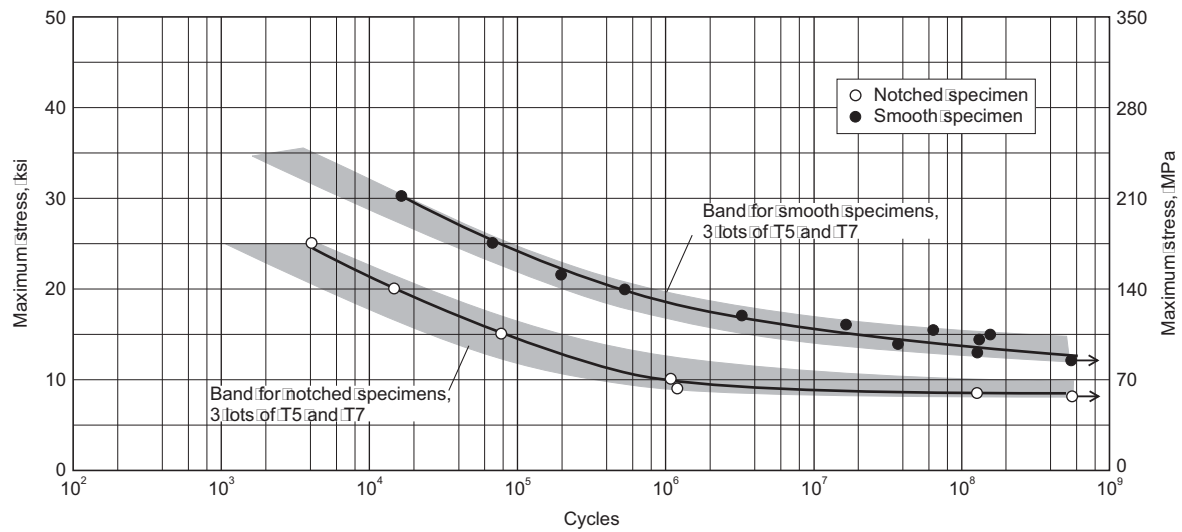


**Fig. D6.34** 333.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Data for smooth and notched specimens from one lot superimposed on bands of data from three lots of T5 and T7 data

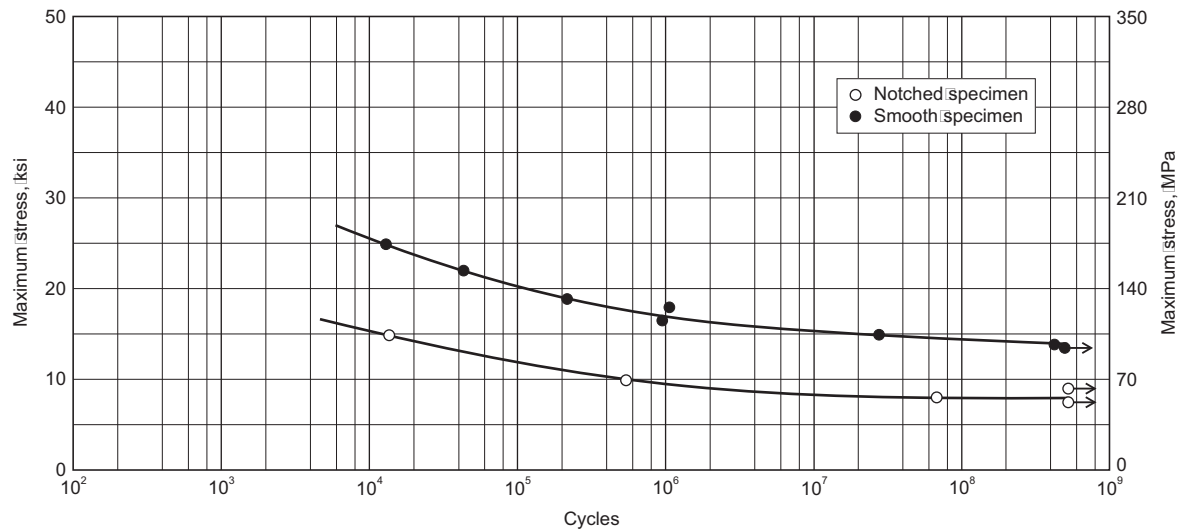


**Fig. D6.35** 336.0-T551, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

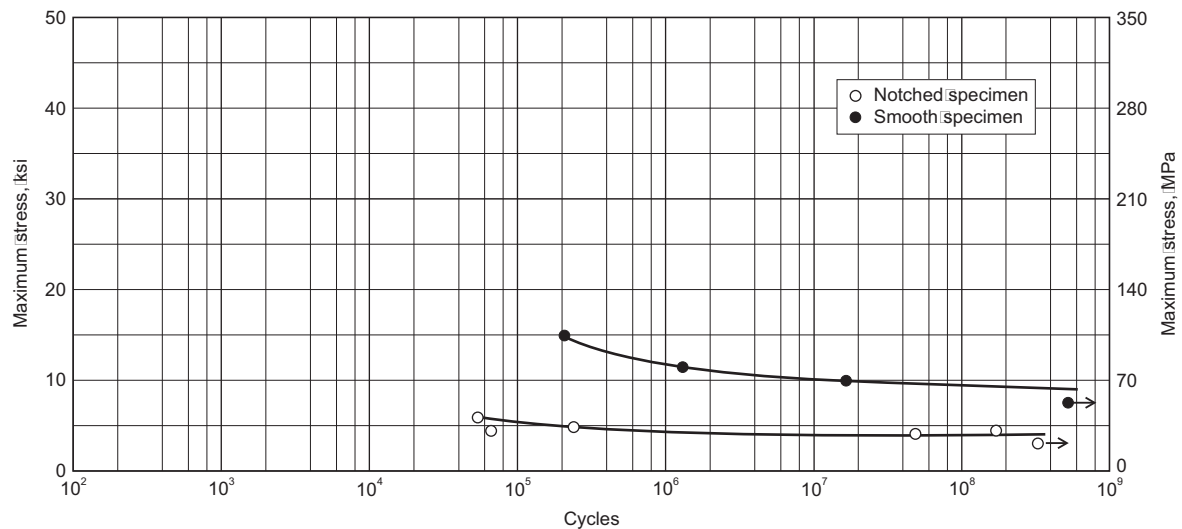


**Fig. D6.36** A344.0-T4, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

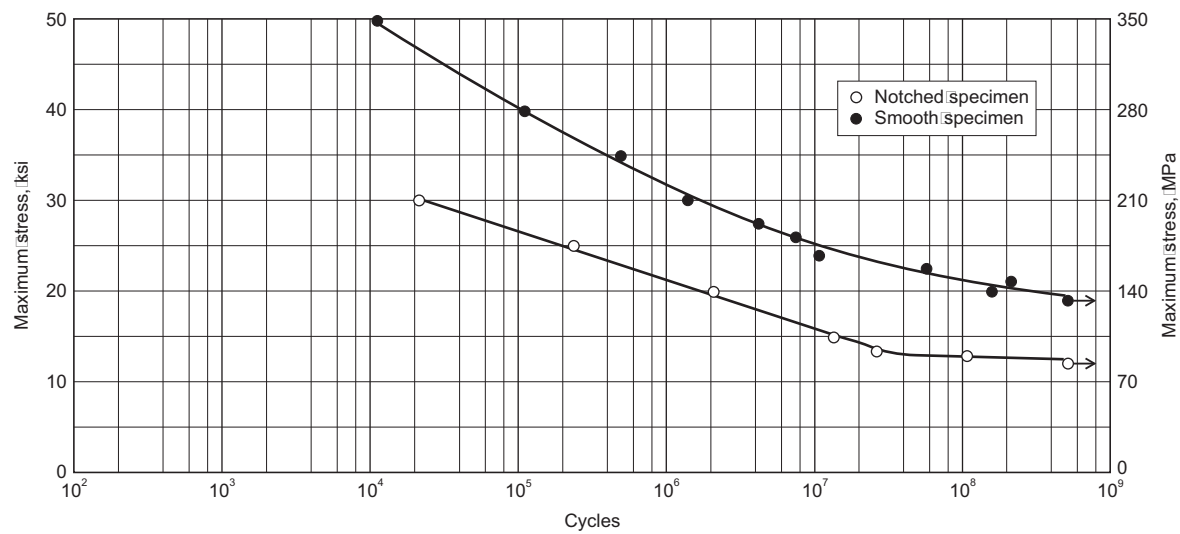


Fig. D6.37 354.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

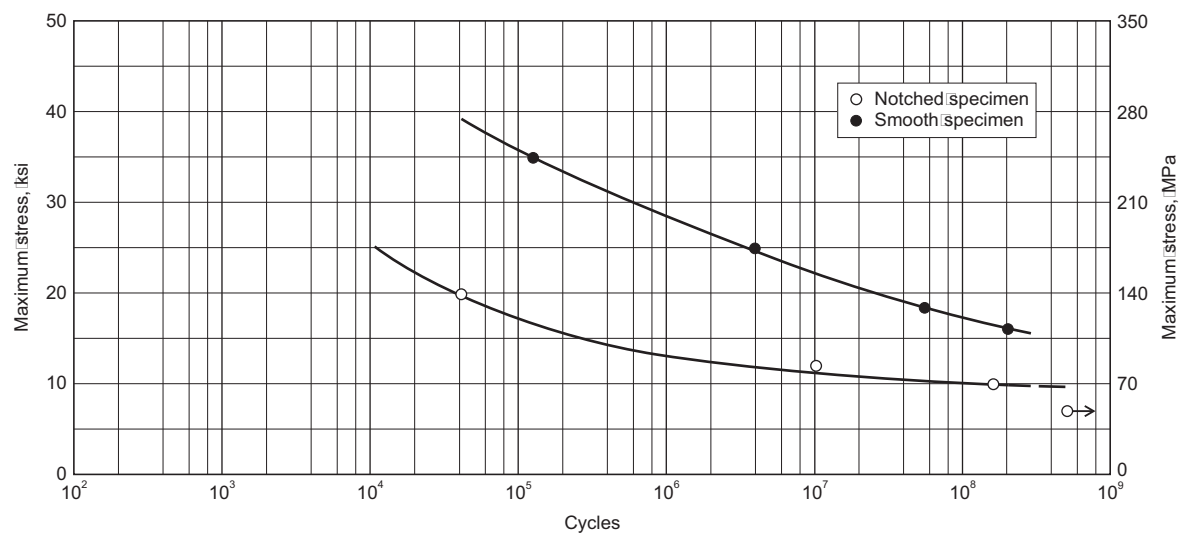


Fig. D6.38 354.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Specimens were machined from cantilever beam cast test bars

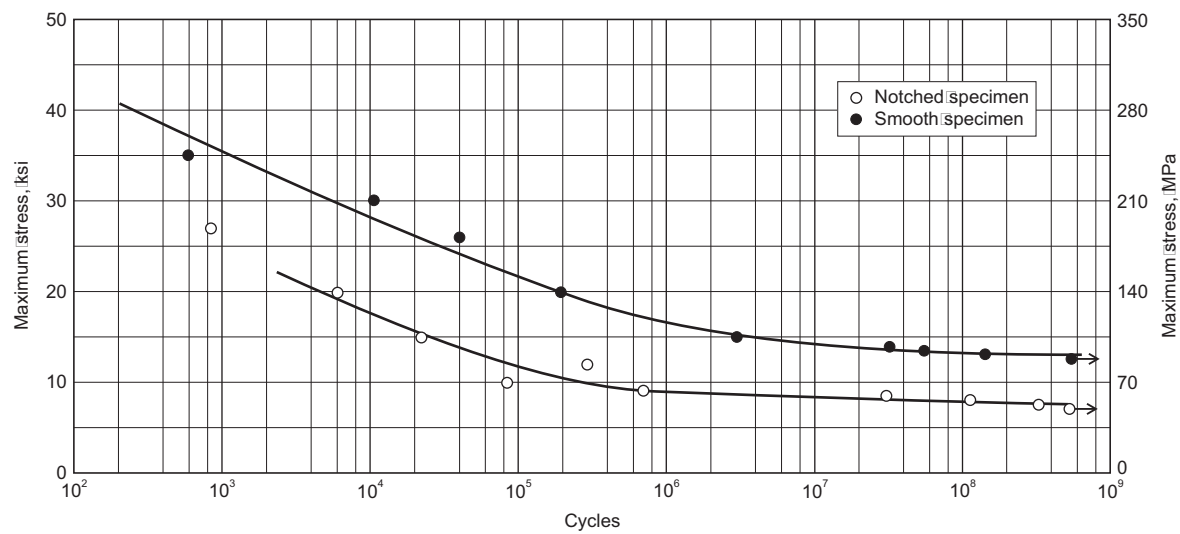


Fig. D6.39 355.0-T51, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

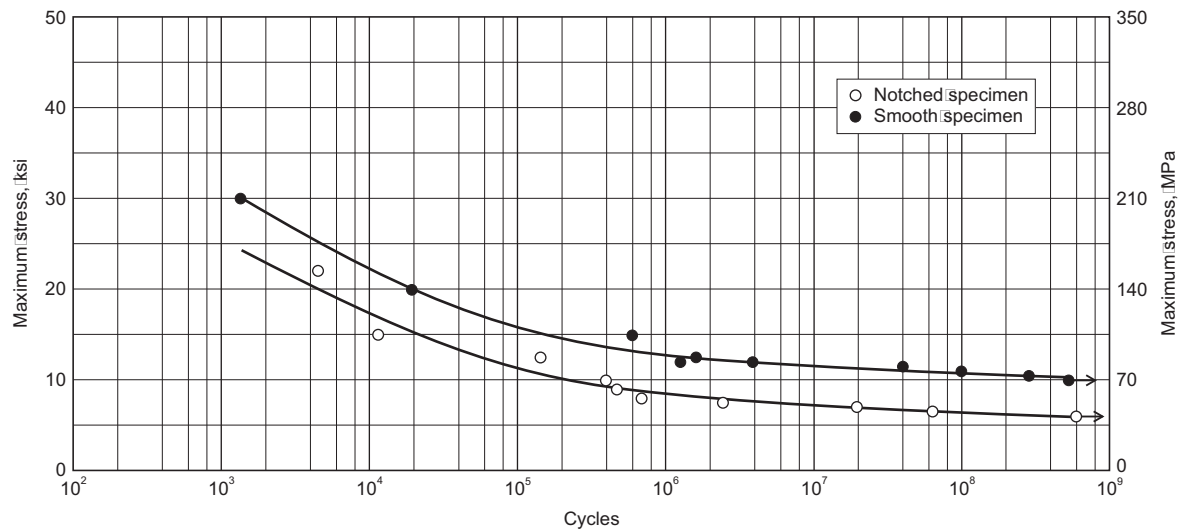


**Fig. D6.40** 355.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

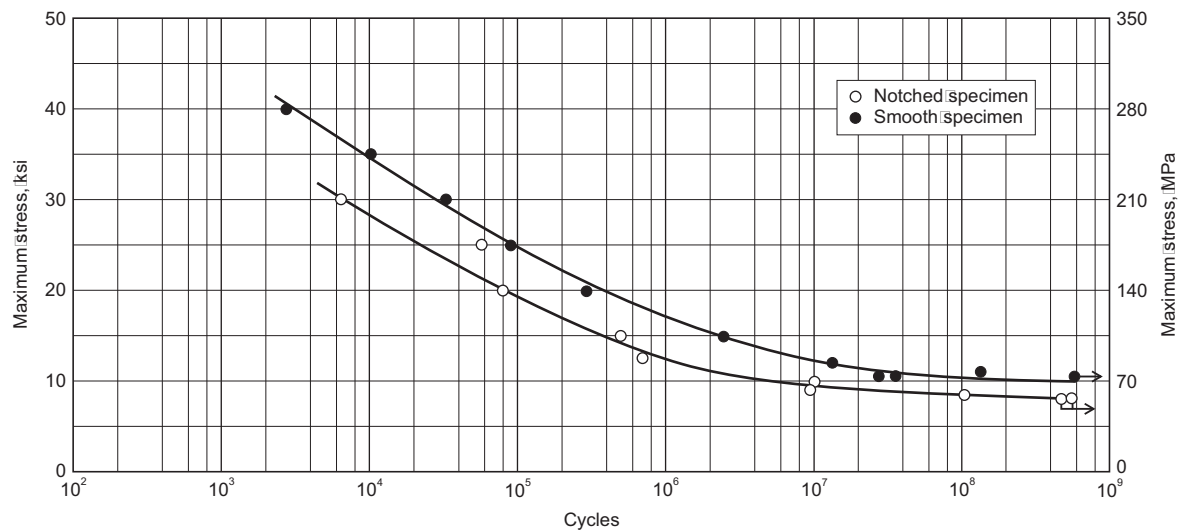


**Fig. D6.41** 355.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

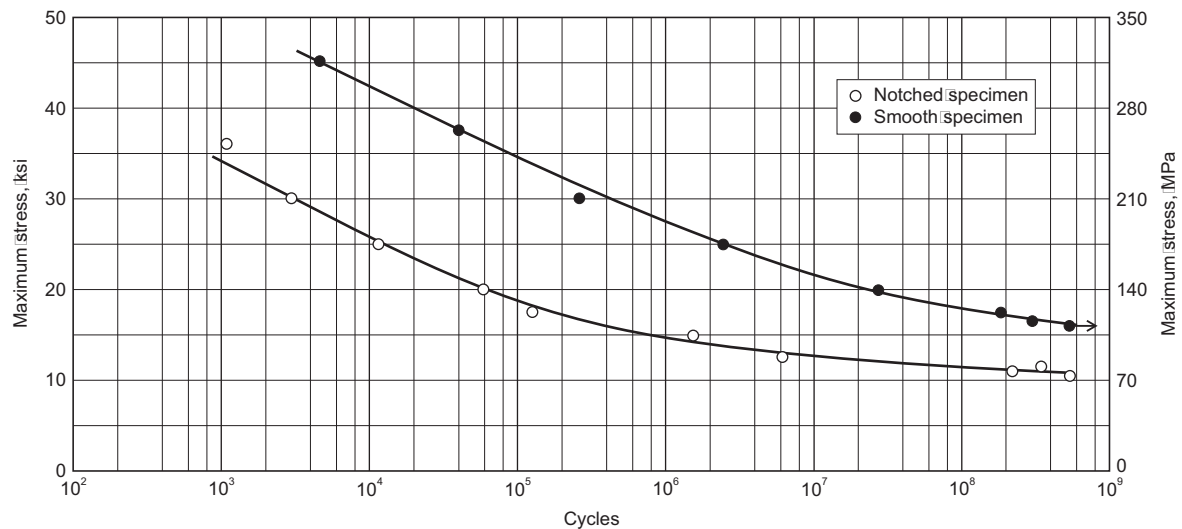


**Fig. D6.42** 355.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

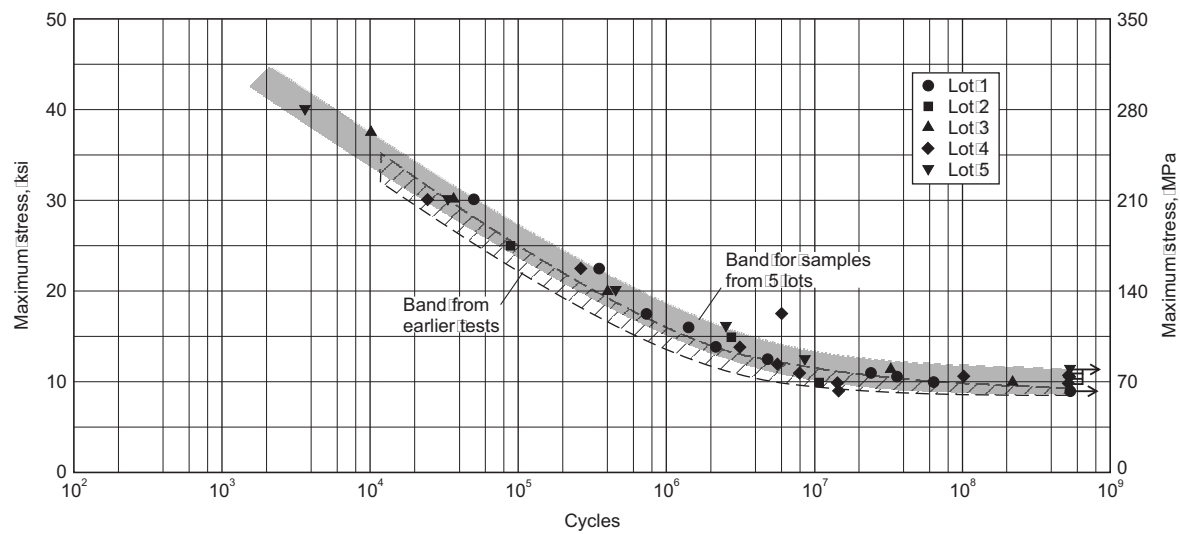


**Fig. D6.43** 355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from five lots. Band of these samples compared to band of samples from earlier tests

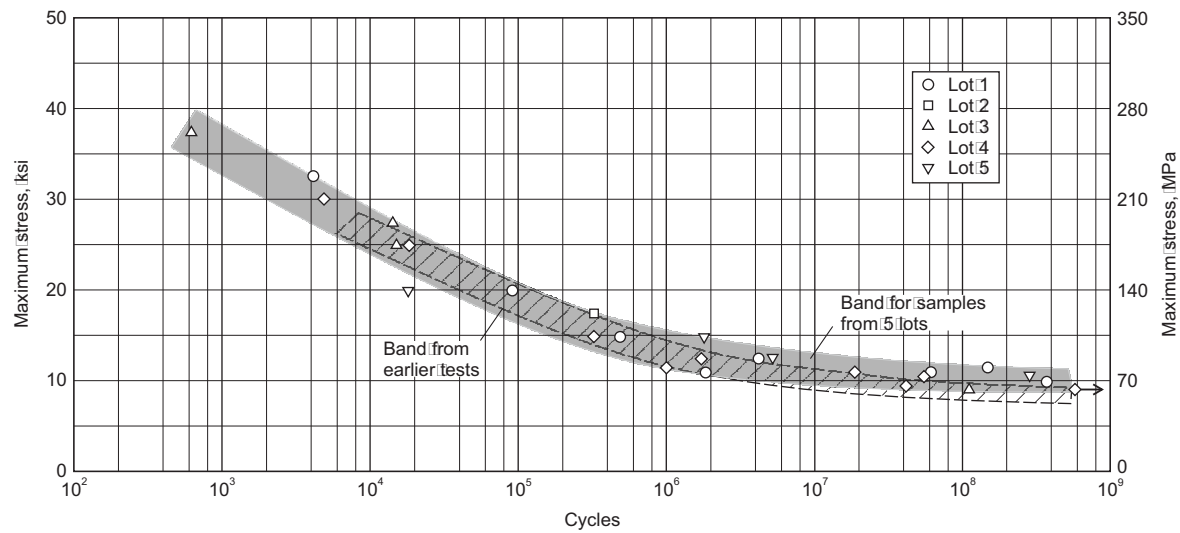


**Fig. D6.44** 355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from five lots. Band of these samples compared to band of samples from earlier tests

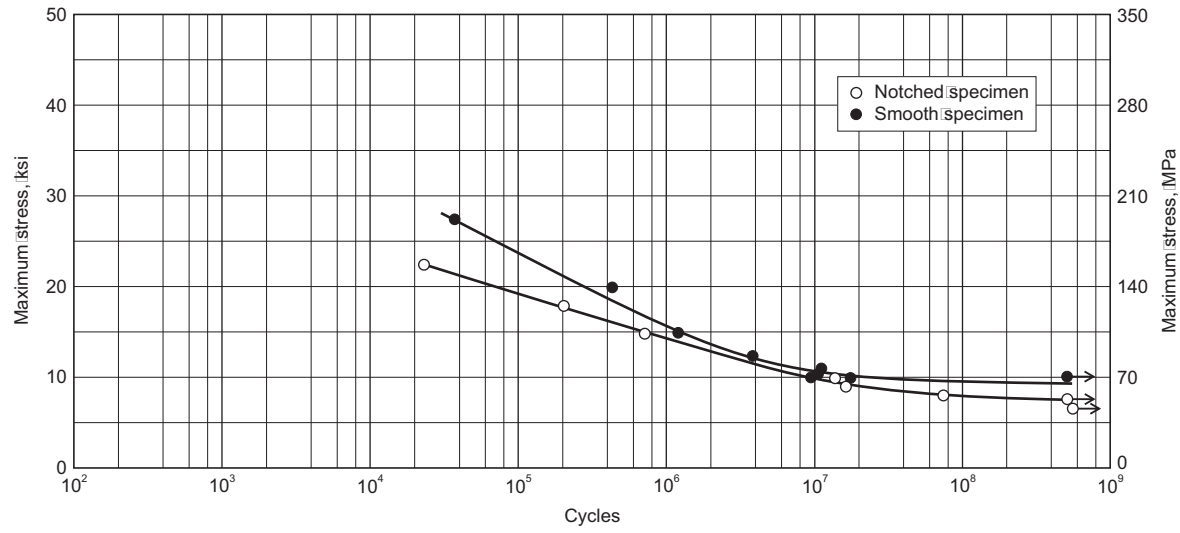


**Fig. D6.45** 355.0-T61, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

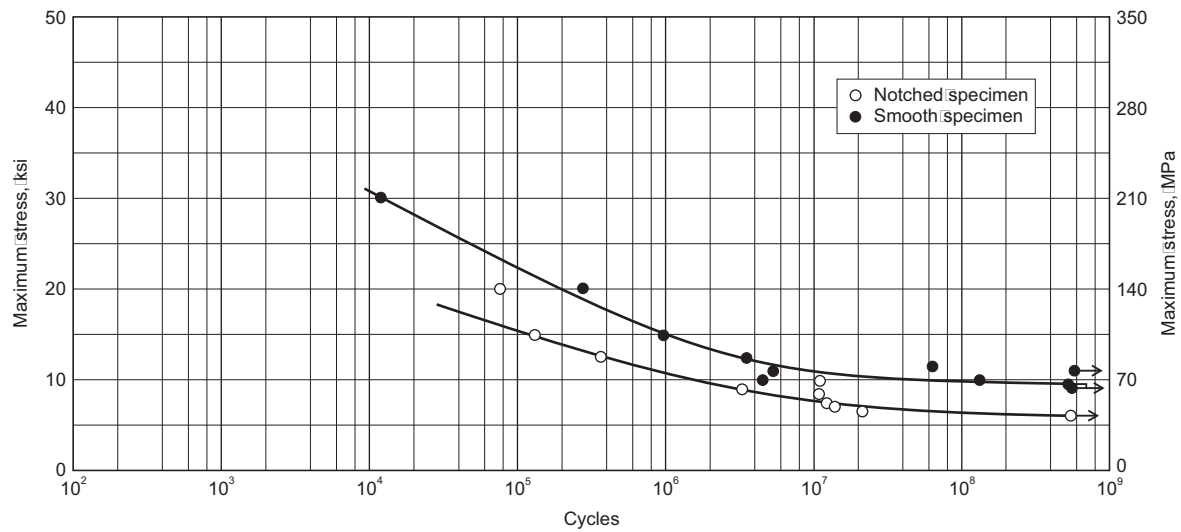


**Fig. D6.46** 355.0-T62, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

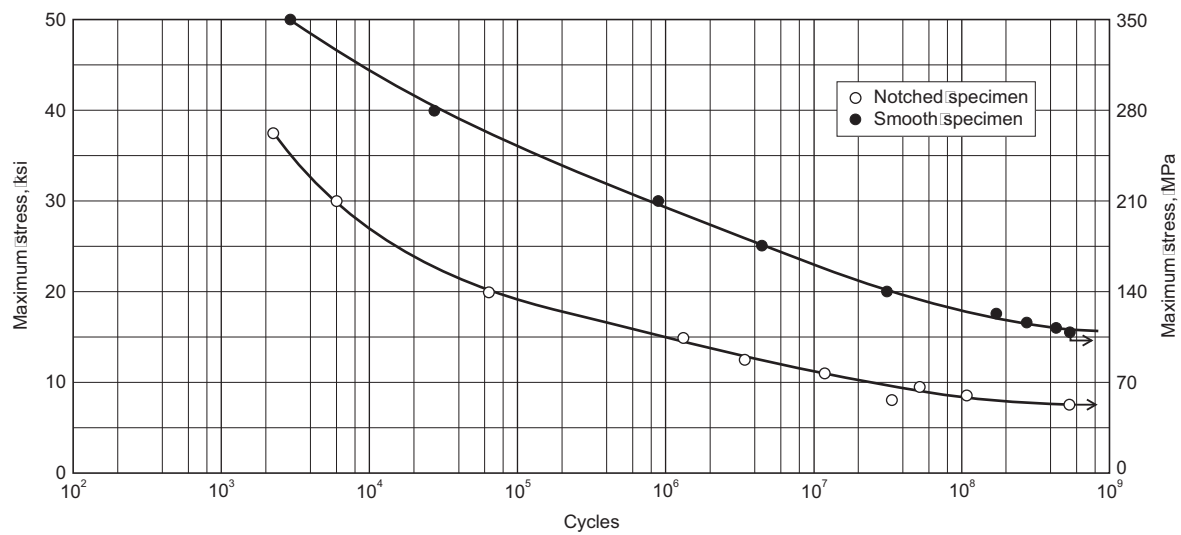


**Fig. D6.47** 355.0-T62, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

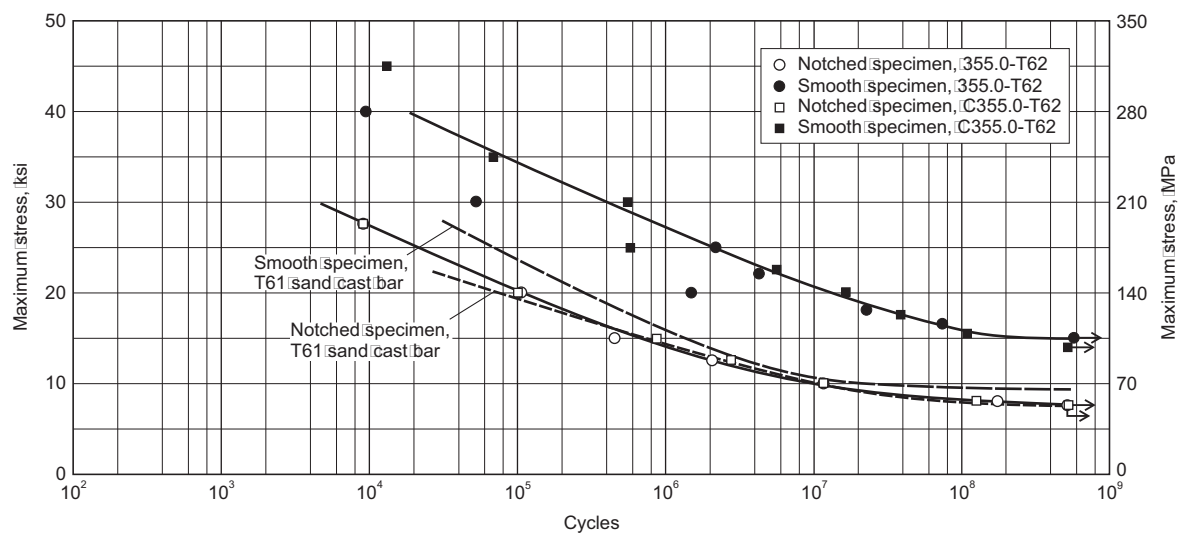


**Fig. D6.48** 355.0-T62, C355.0-T62, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Comparison of smooth and notched specimen data for two lots. Broken lines are data for smooth and notched 355.0-T61 sand cast alloy.

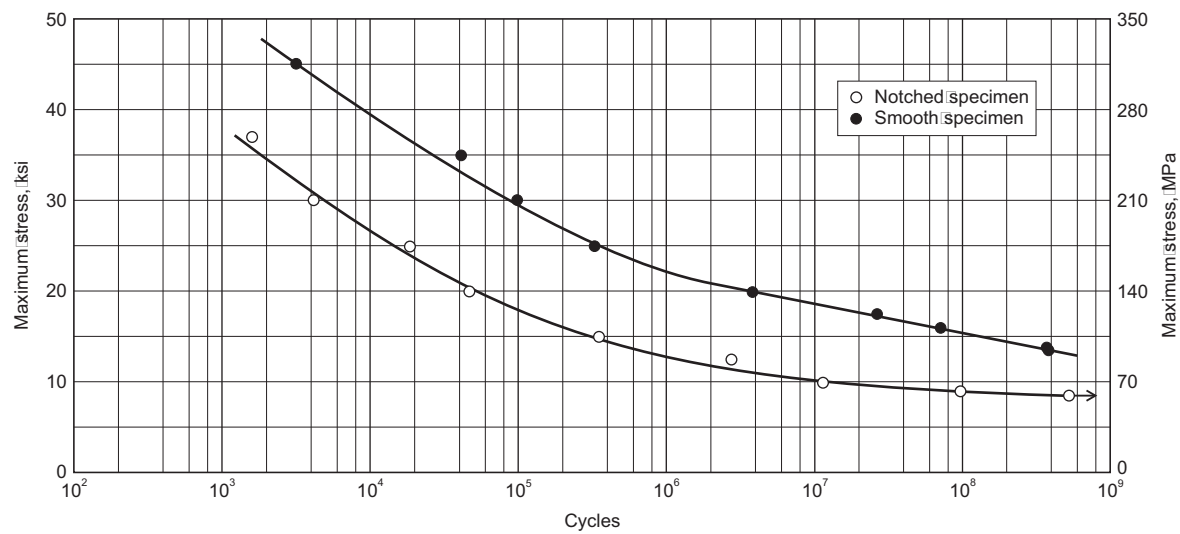


Fig. D6.49 355.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

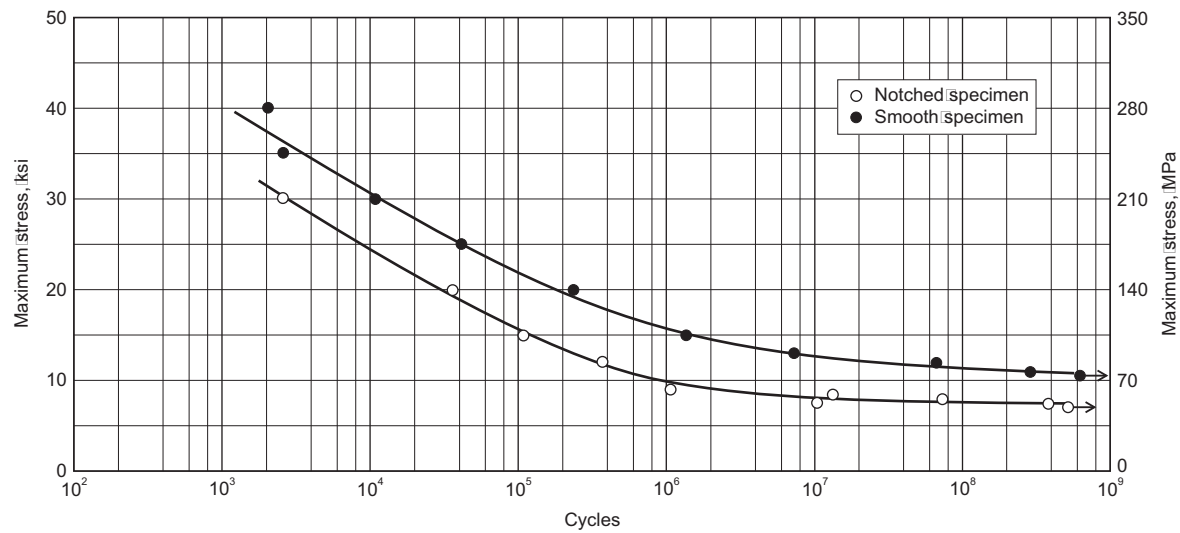


Fig. D6.50 355.0-T7, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

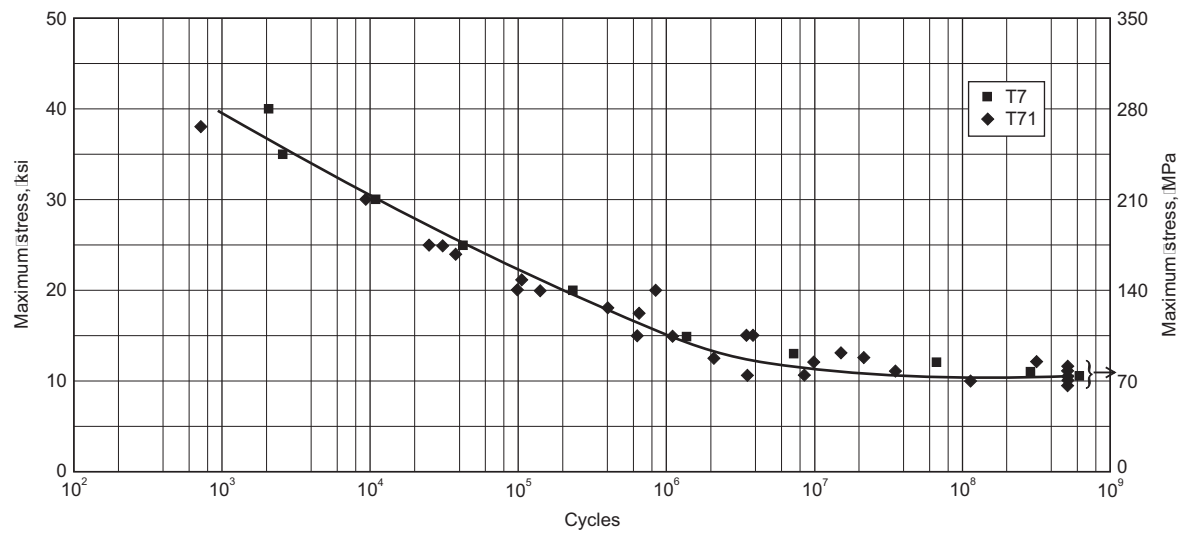


Fig. D6.51 355.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens comparing effects of heat treatment



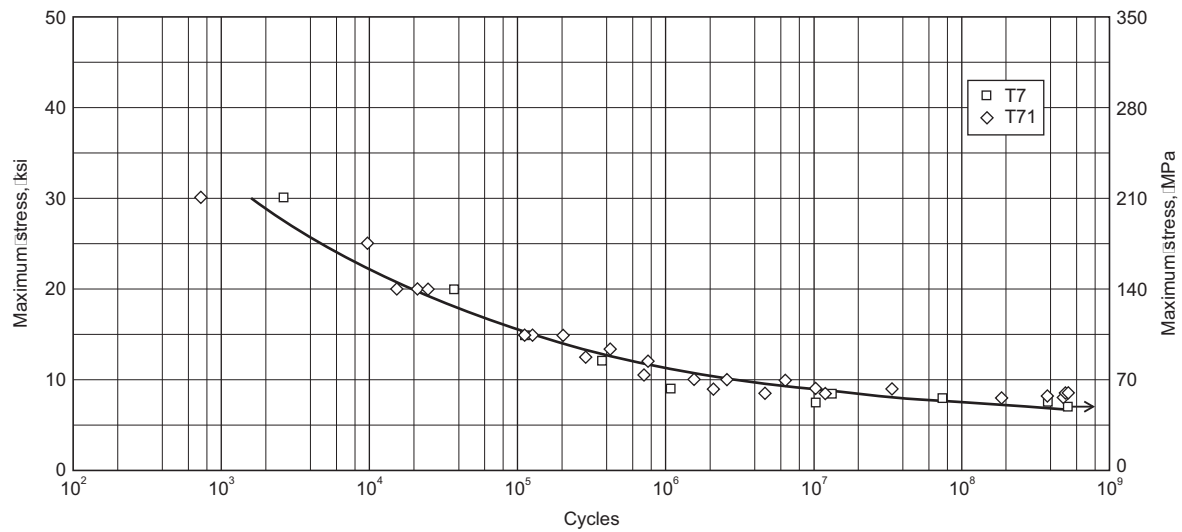


**Fig. D6.52** 355.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens comparing effects of heat treatment

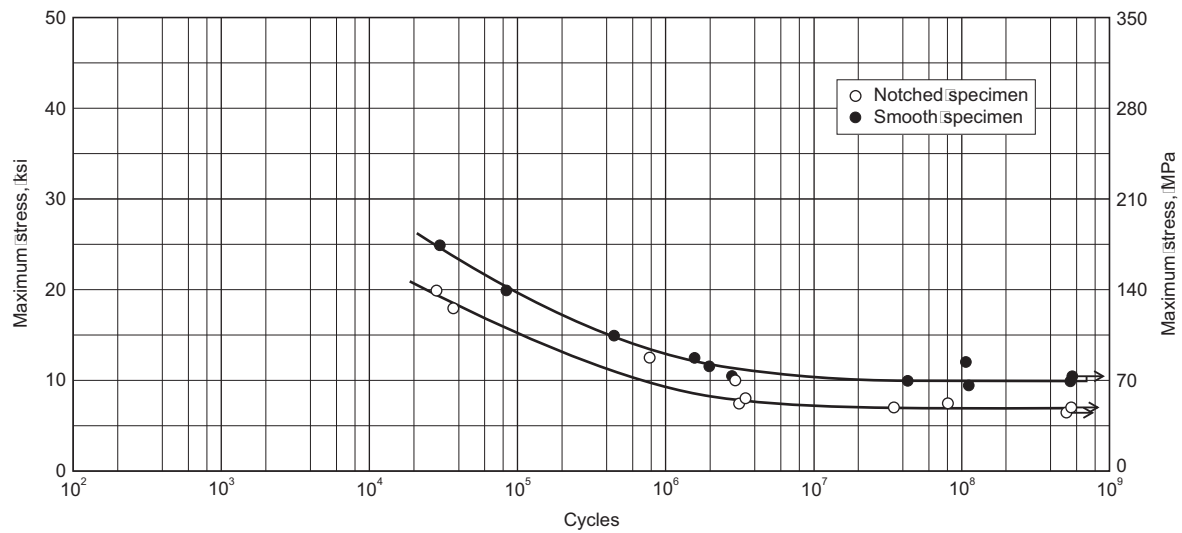


**Fig. D6.53** 355.0-T71, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

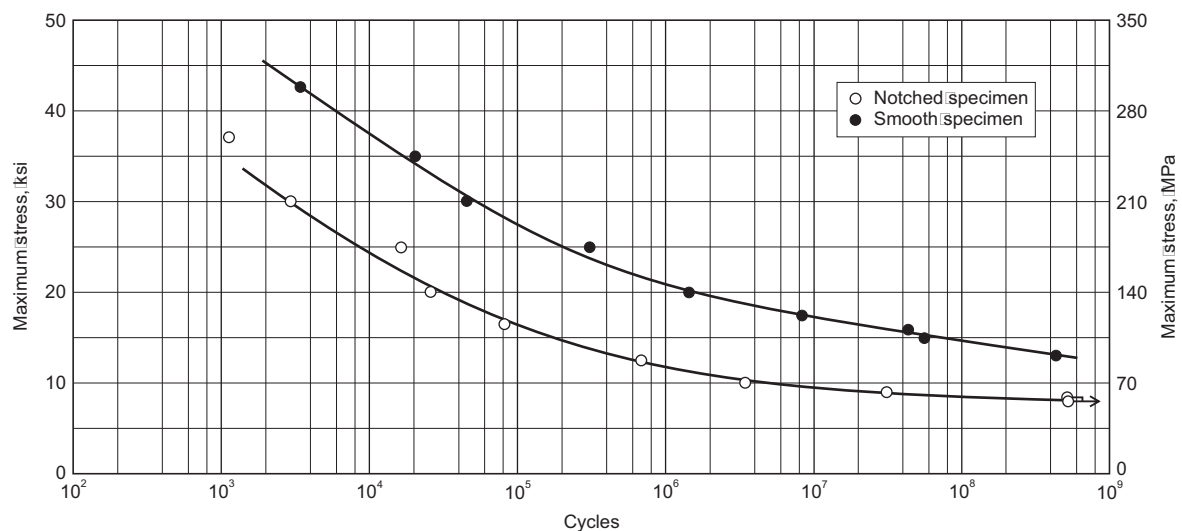


**Fig. D6.54** 355.0-T71, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

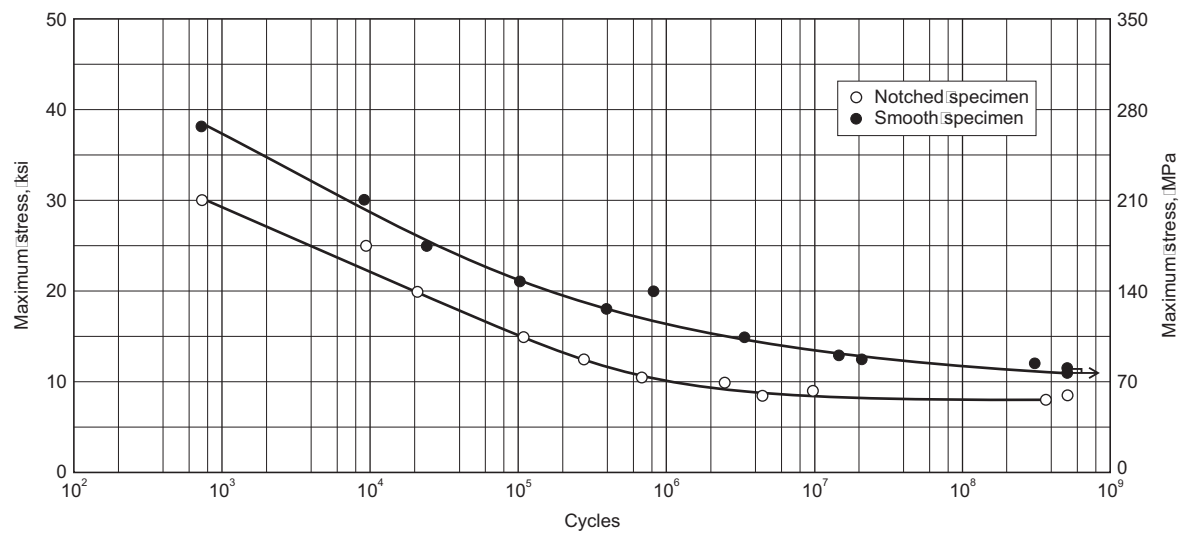


Fig. D6.55 355.0-T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

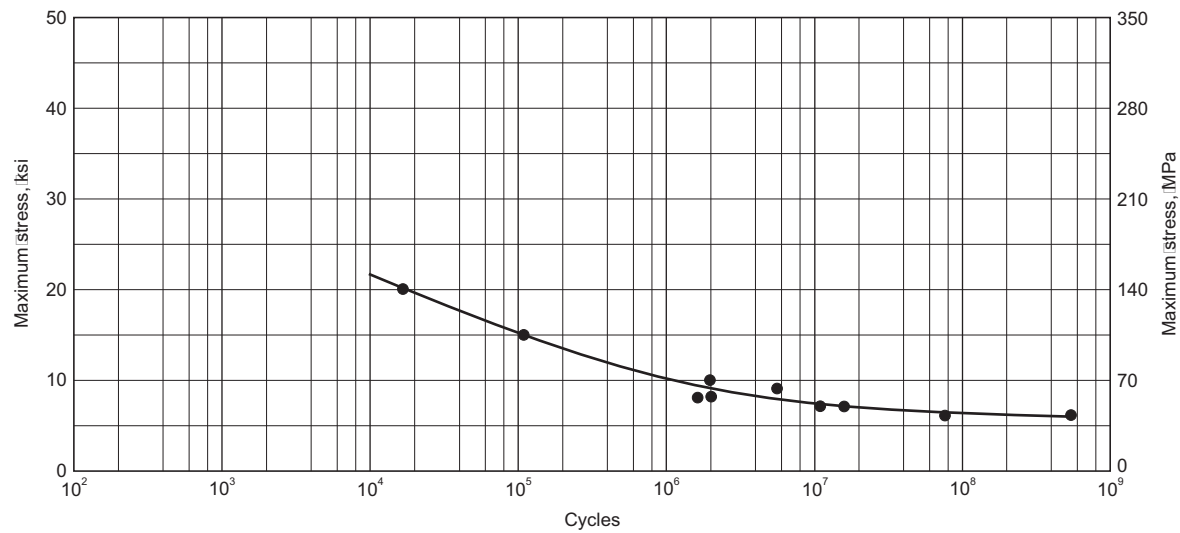


Fig. D6.56 355.0-T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimen from crankshaft casting, Fig. A3.3, Appendix 3

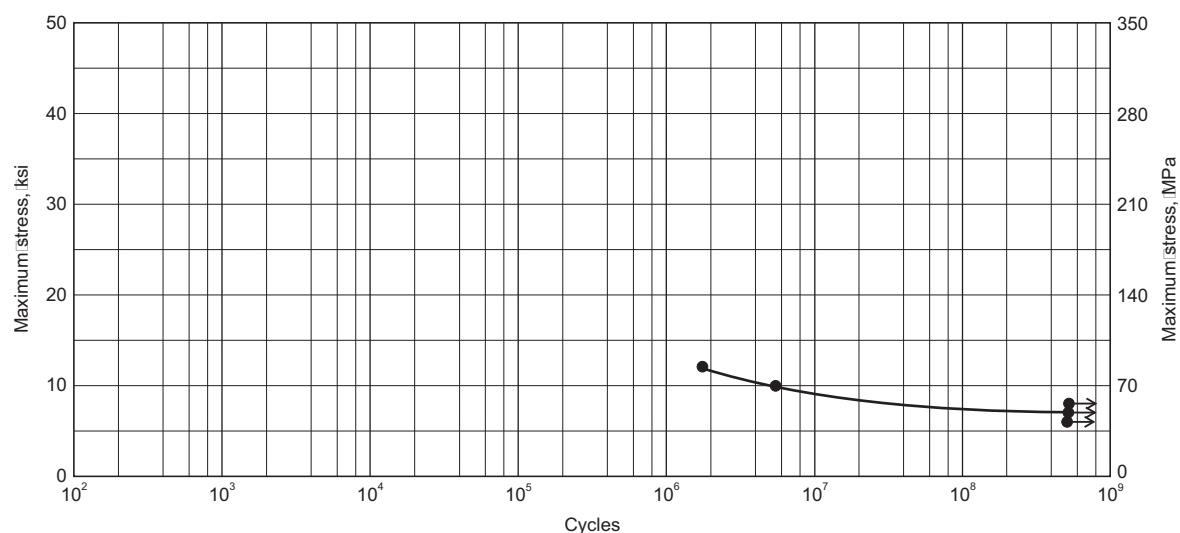


Fig. D6.57 A355.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth, larger-than-standard specimens per Fig. A3.4, Appendix 3, from a single lot

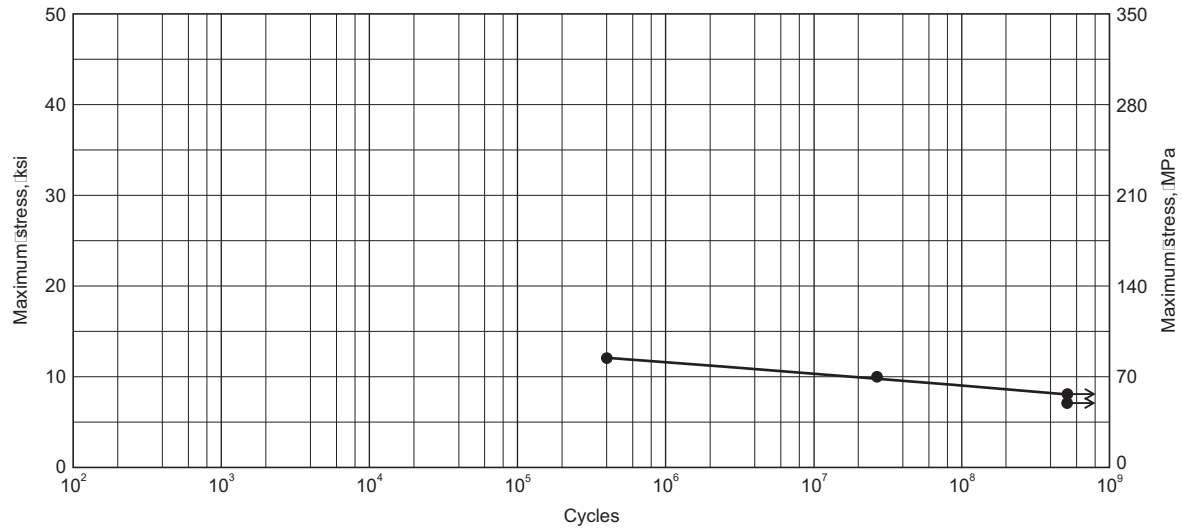


**Fig. D6.58** A355.0-T59, sand cast aluminum casting rotating-beam fatigue curve. Smooth, larger-than-standard specimens per Fig. A3.4, Appendix 3, from a single lot

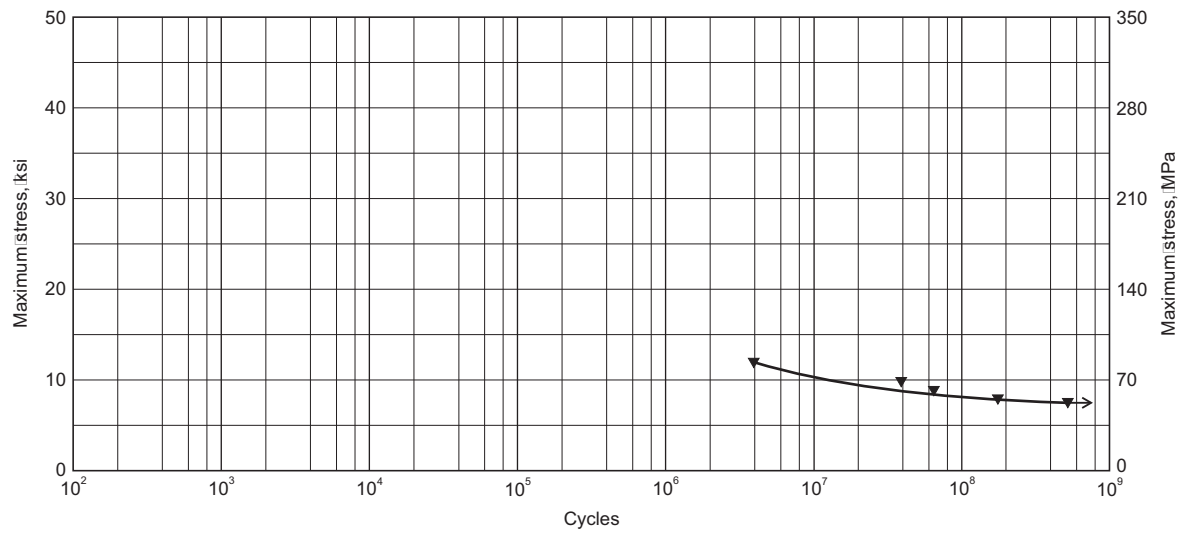


**Fig. D6.59** A355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

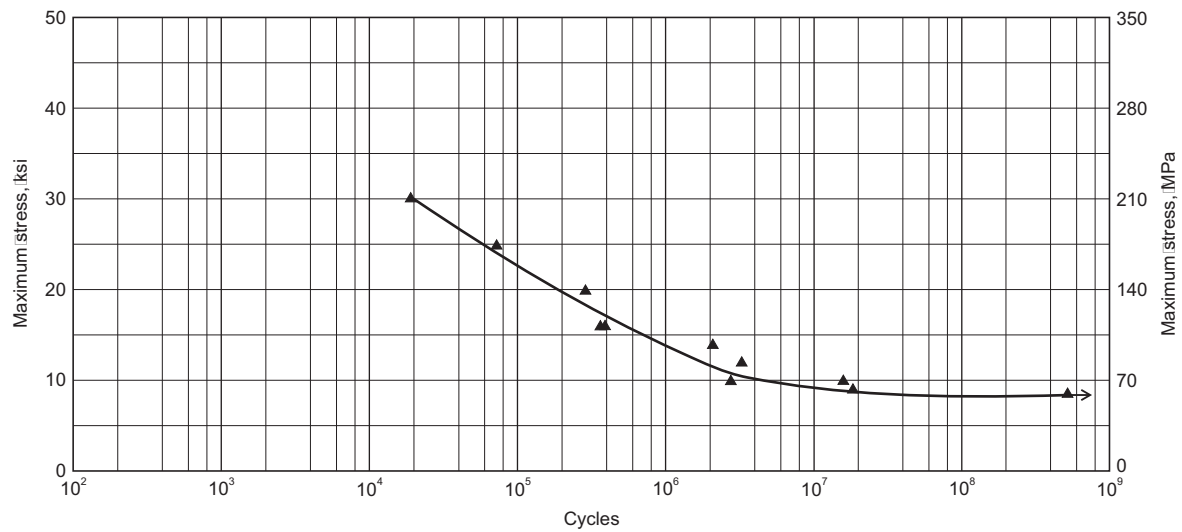


**Fig. D6.60** B355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

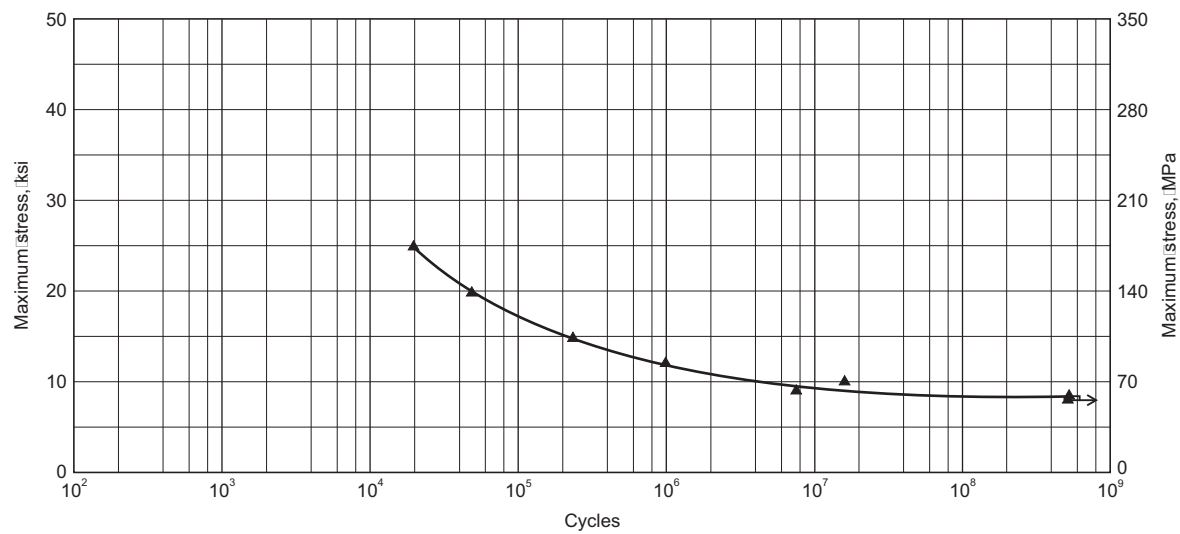


Fig. D6.61 B355.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

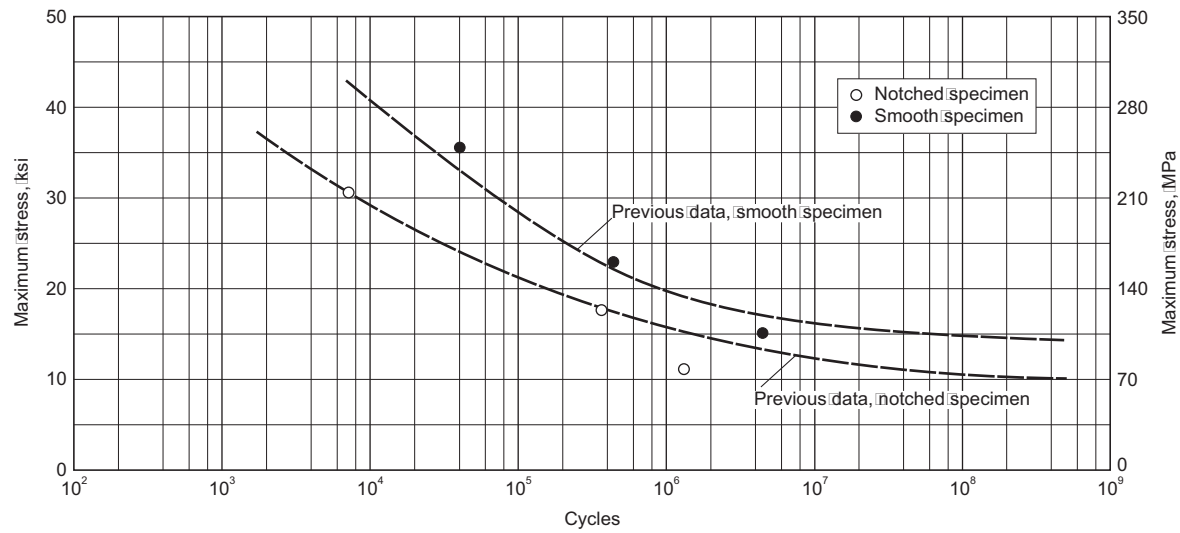


Fig. D6.62 C355.0-T61, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Data from smooth and notched specimens of one lot compared to prior curves of C355.0-T61 permanent mold specimens

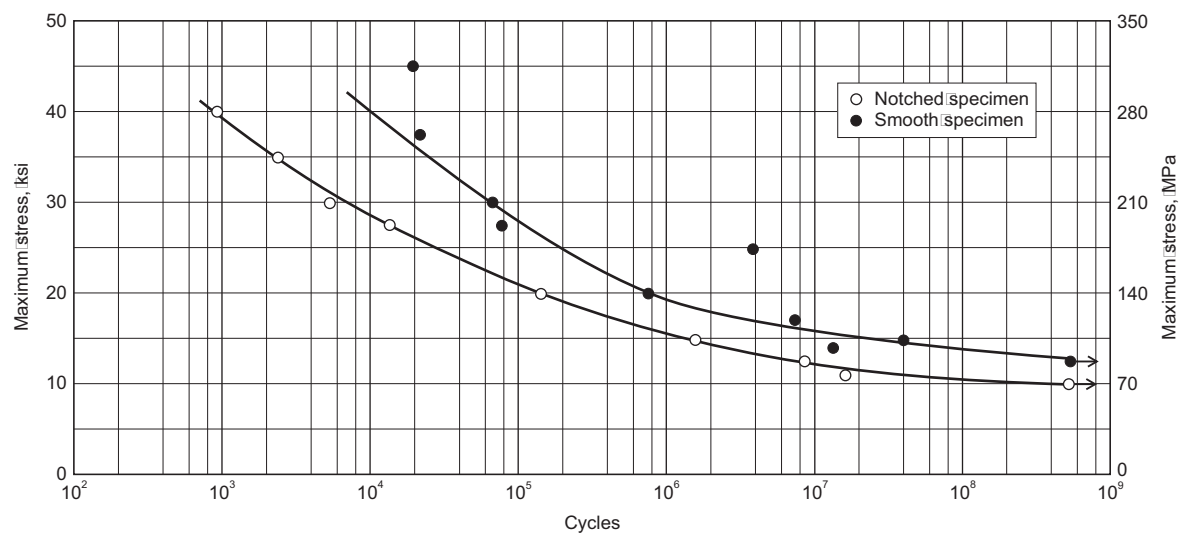


Fig. D6.63 C355.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. These data used for comparison in Fig. D6.62.

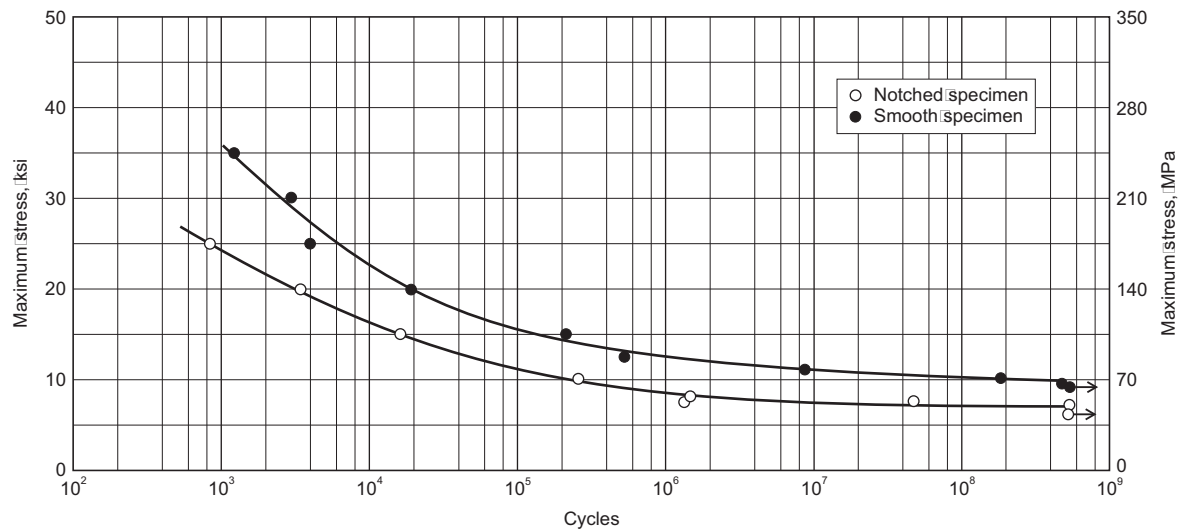


**Fig. D6.64** 356.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

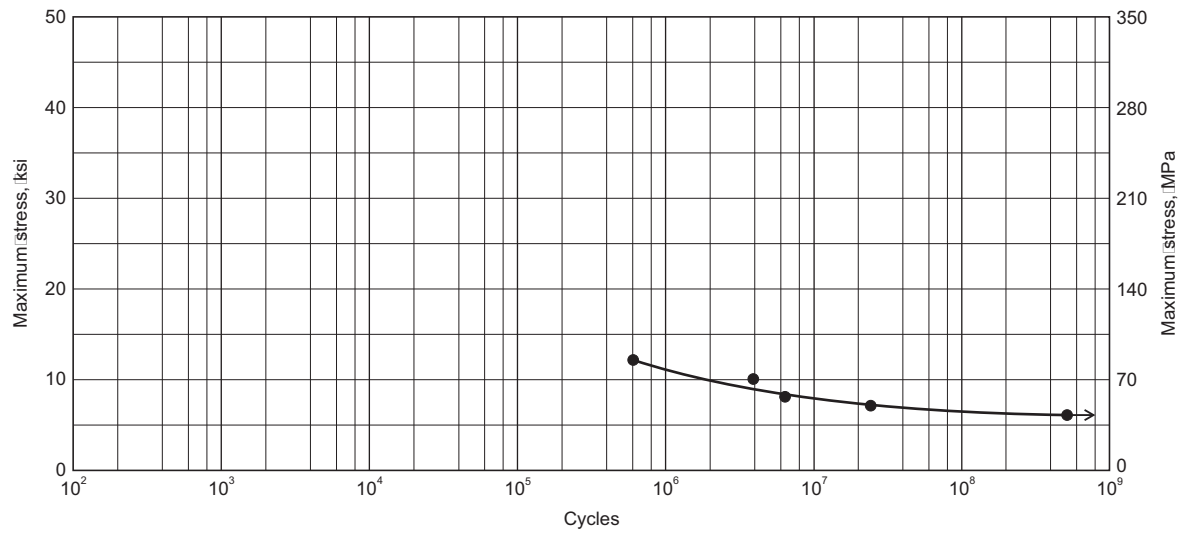


**Fig. D6.65** 356.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Smooth larger than standard specimens per Fig. A3.4, Appendix 3, from a single lot

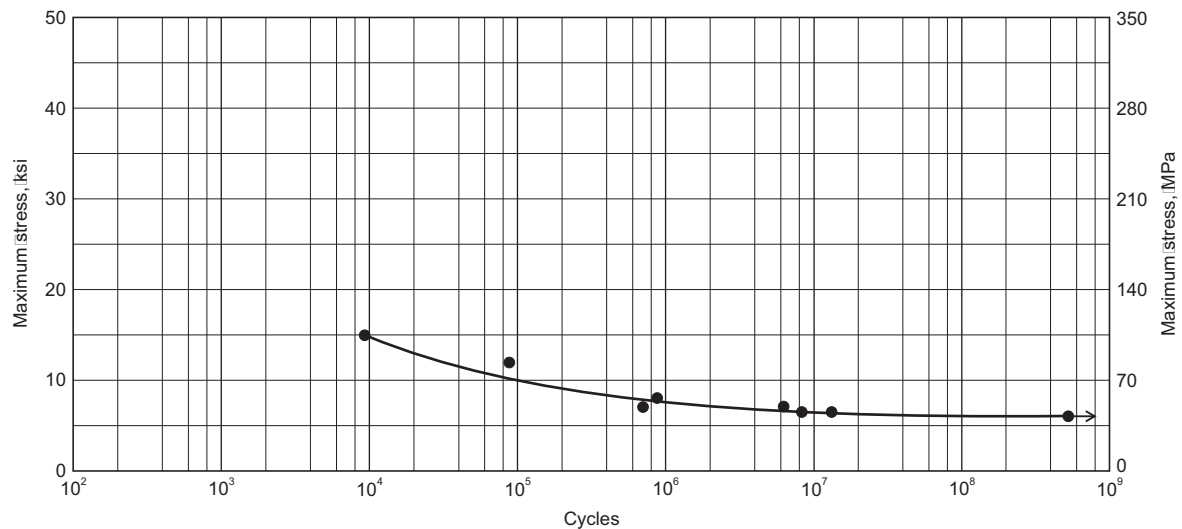


**Fig. D6.66** 356.0-T51, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot

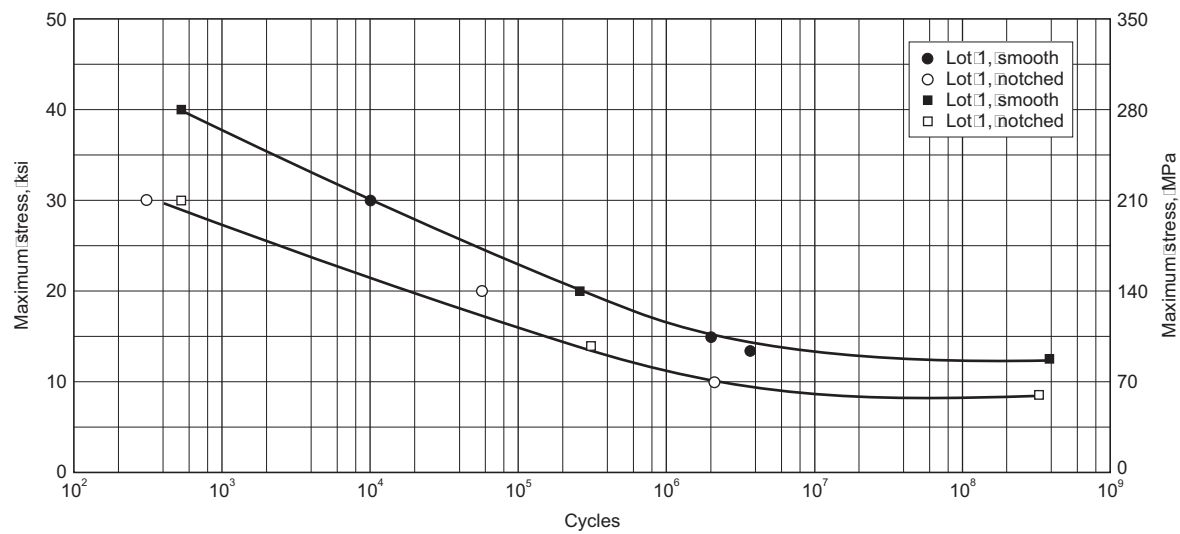


Fig. D6.67 356.0-T6, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots

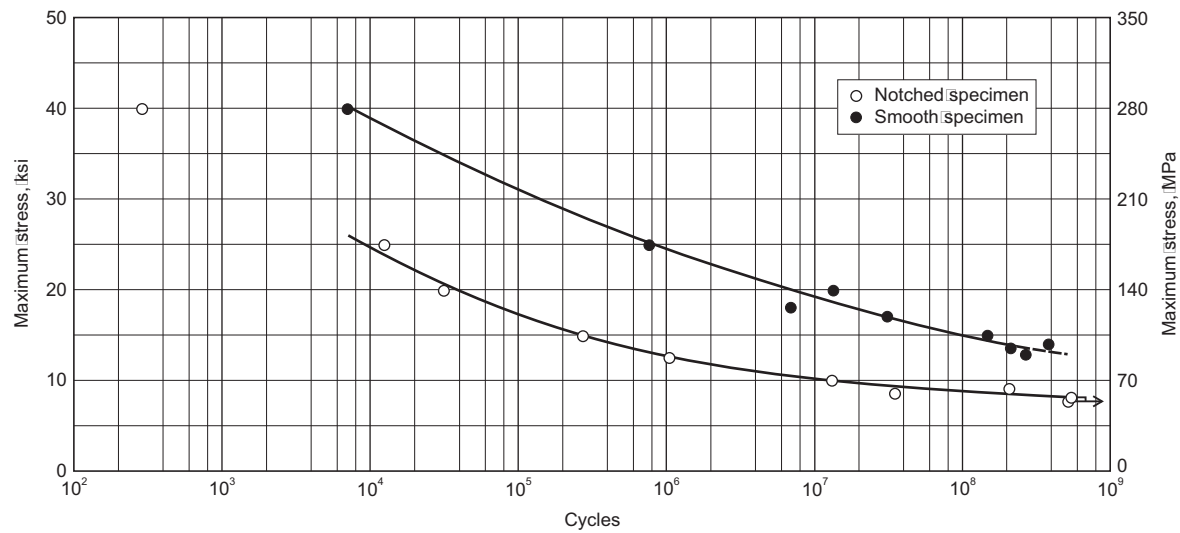


Fig. D6.68 356.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

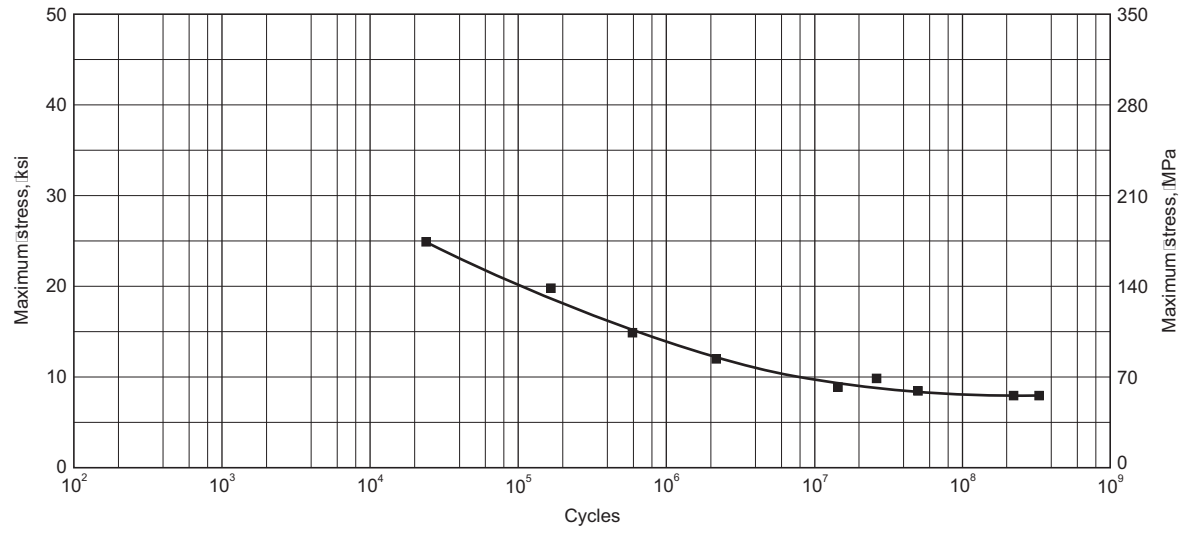


Fig. D6.69 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

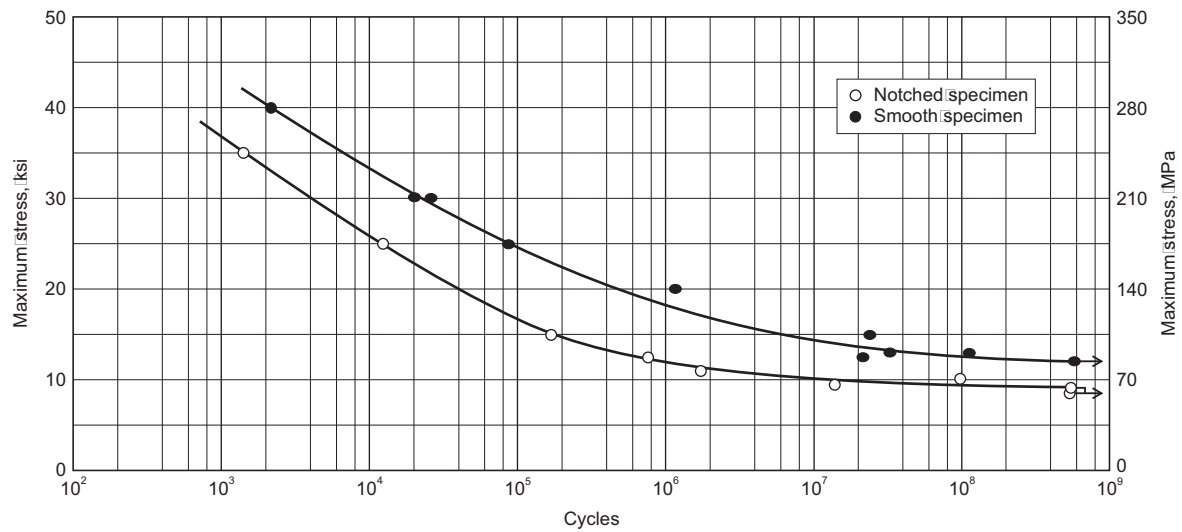


**Fig. D6.70** 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

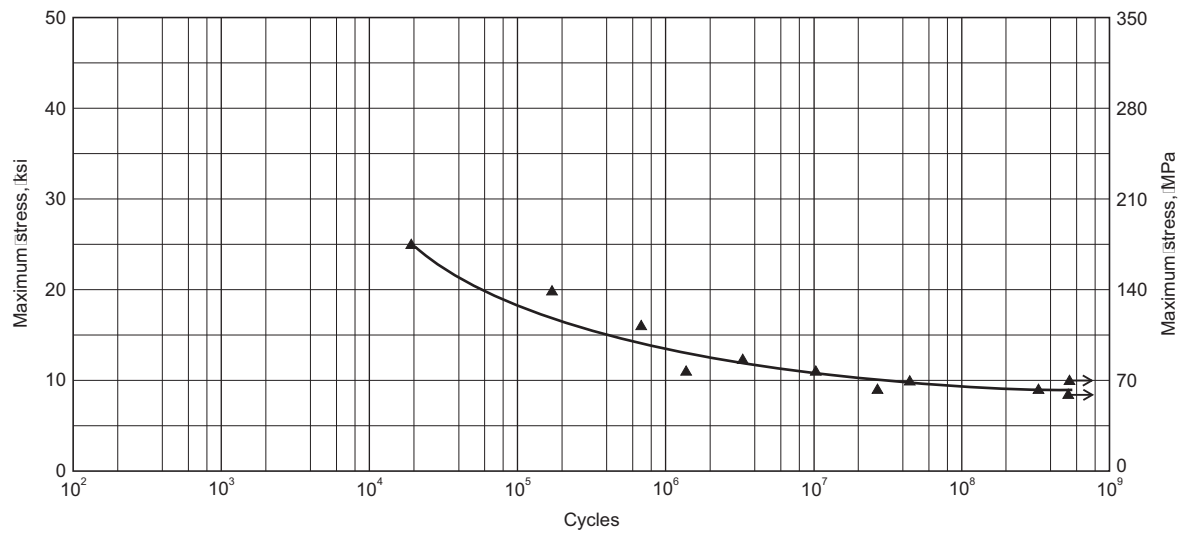


**Fig. D6.71** 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

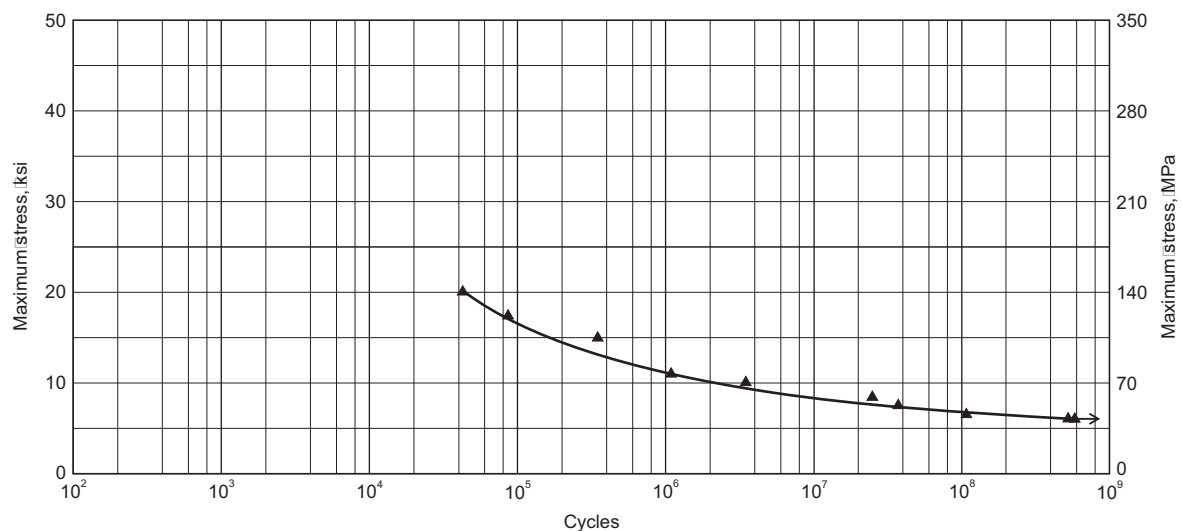


**Fig. D6.72** 356.0-T6, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens from one lot



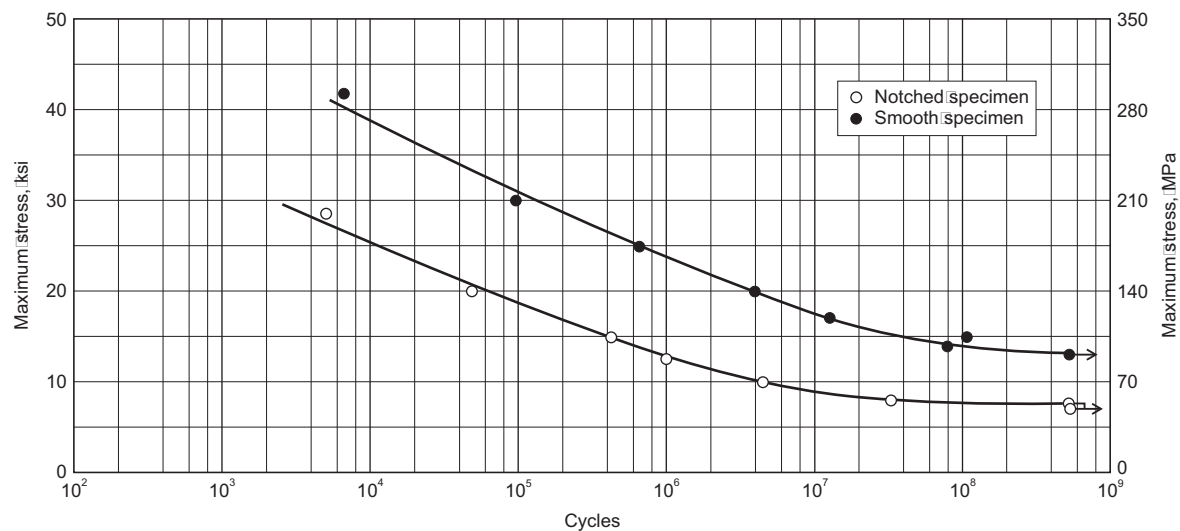


Fig. D6.73 356.0-T61, high-strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

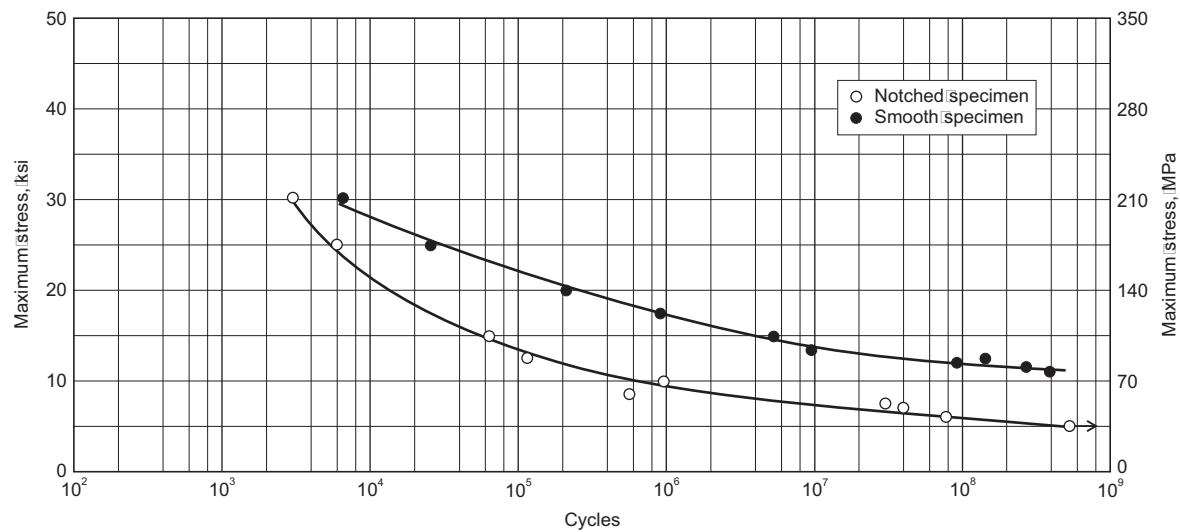


Fig. D6.74 356.0-T7, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

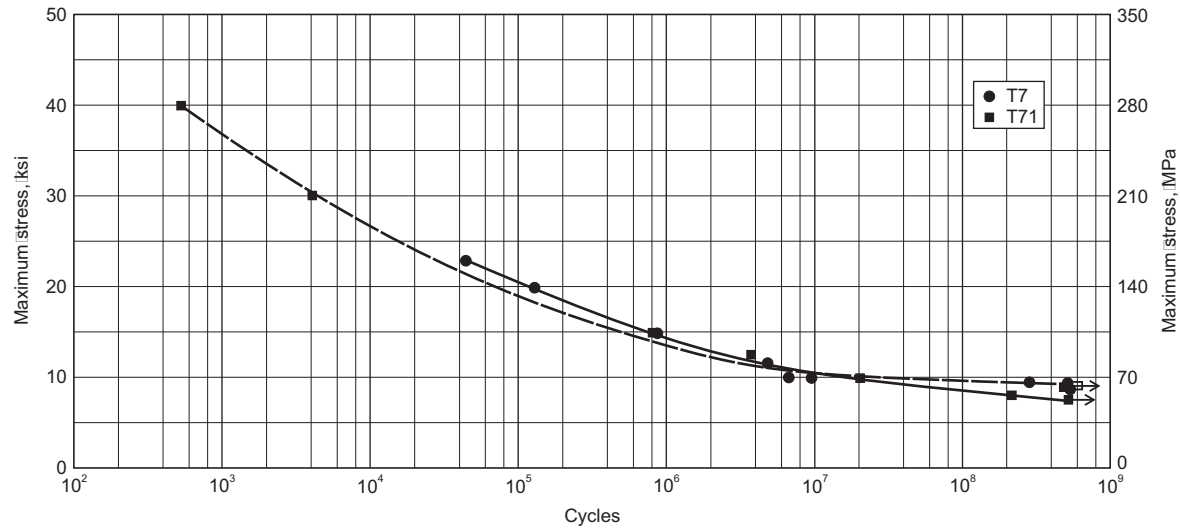


Fig. D6.75 356.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Smooth specimens with two heat treatments, each from its own lot

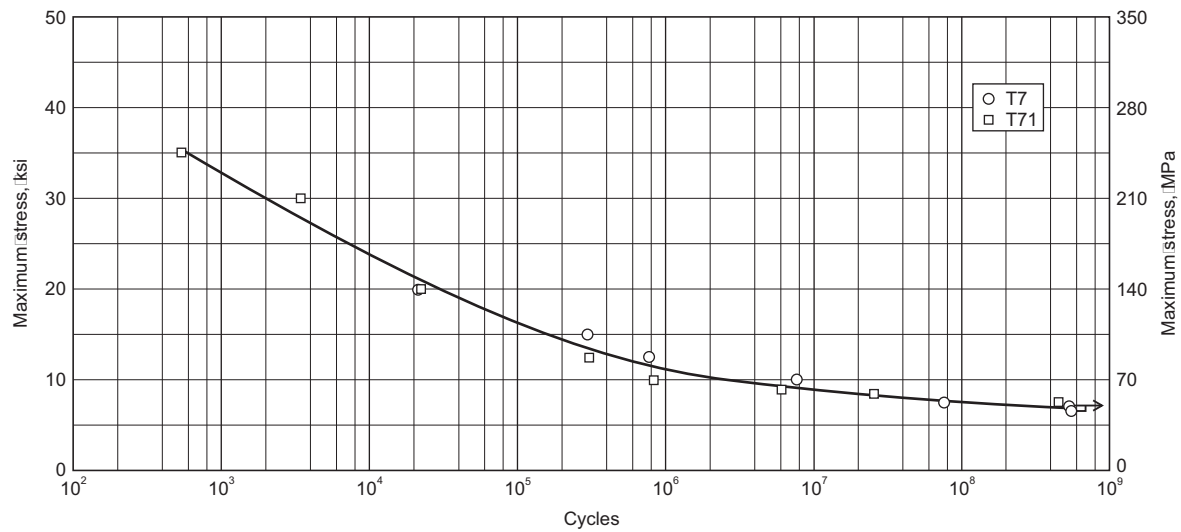


**Fig. D6.76** 356.0-T7, -T71, sand cast aluminum casting rotating-beam fatigue curve. Notched specimens with two heat treatments, each from its own lot

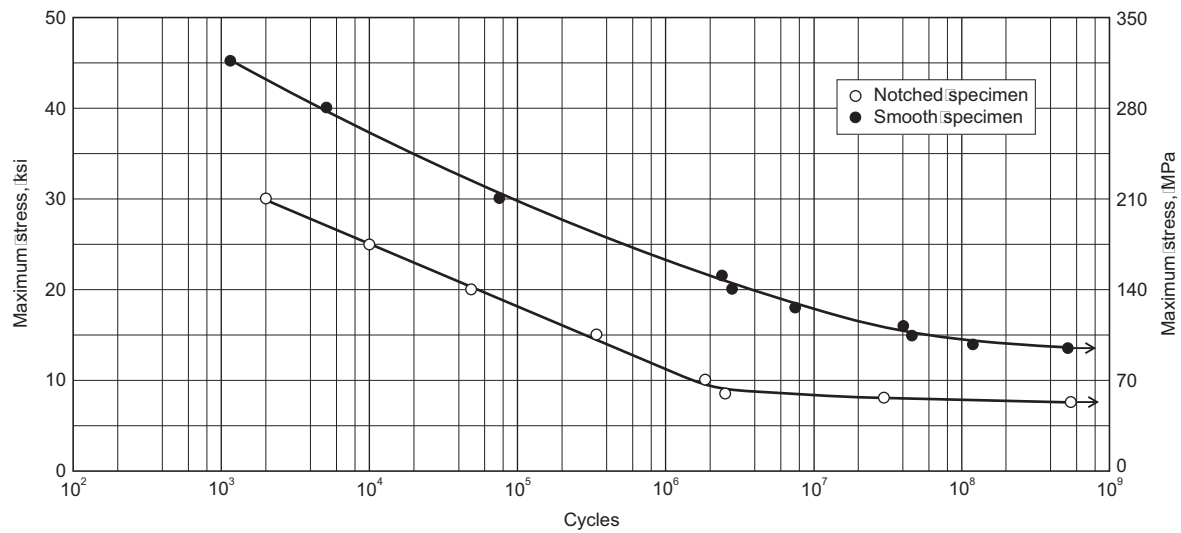


**Fig. D6.77** A356.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

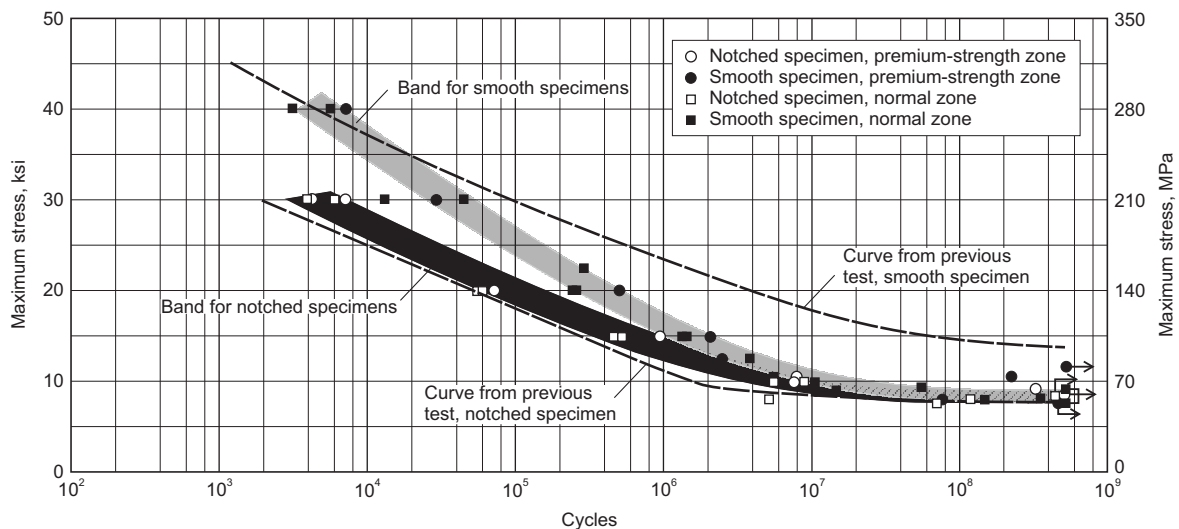


**Fig. D6.78** A356.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from premium strength and normal zones. Confidence bands envelope this data. Broken lines are the results from previous tests.

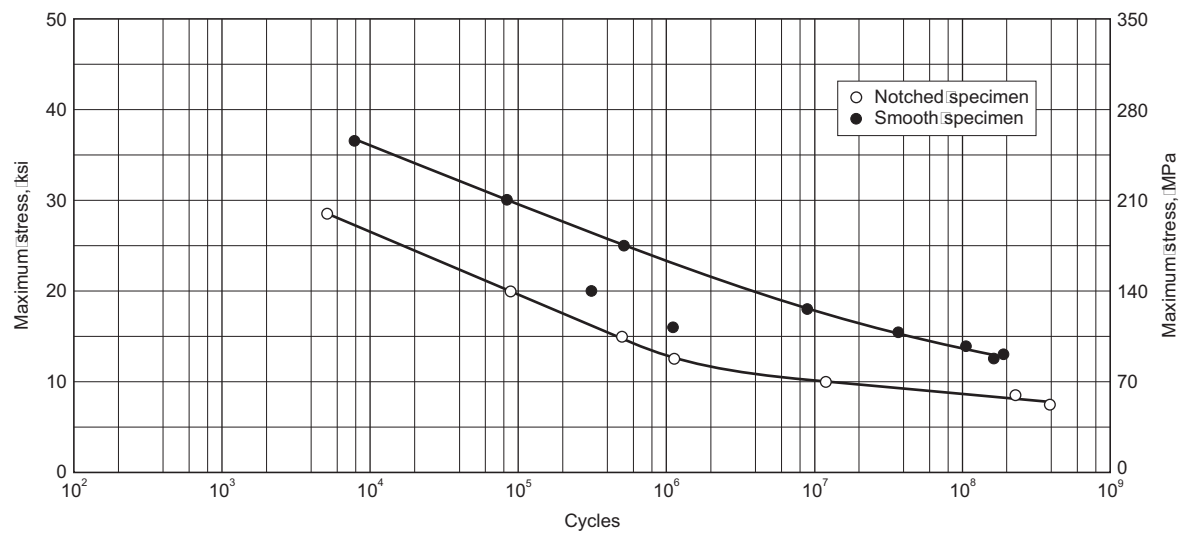


Fig. D6.79 A356.0-T61, high strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

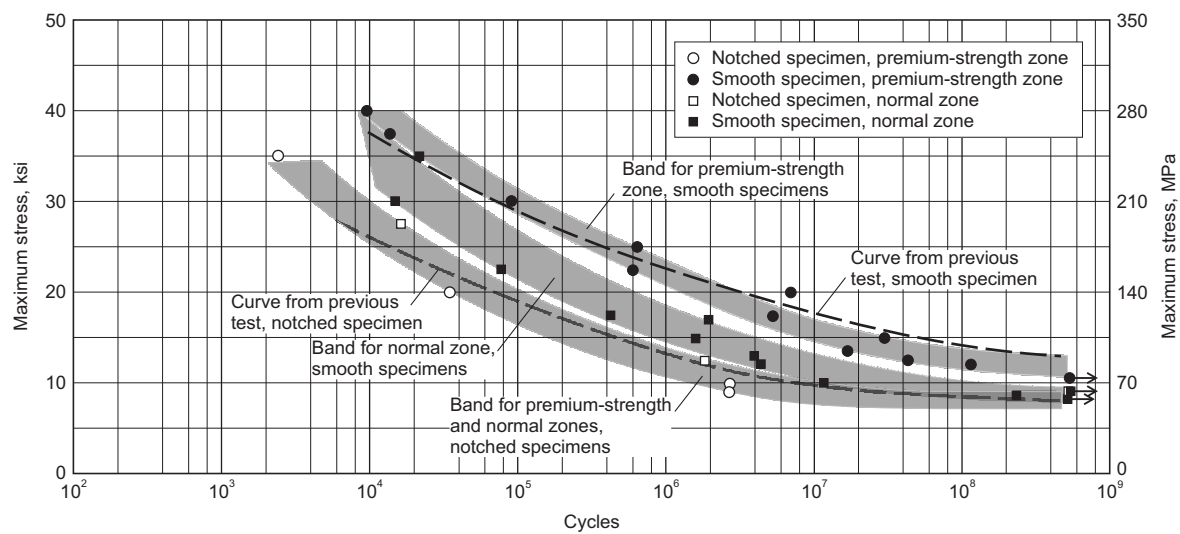


Fig. D6.80 A356.0-T61, high strength plaster cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from premium strength and normal strength zones within the same casting with differing chill practices. Bands envelope this data. Broken lines are the results from previous test, Fig. D6.79.

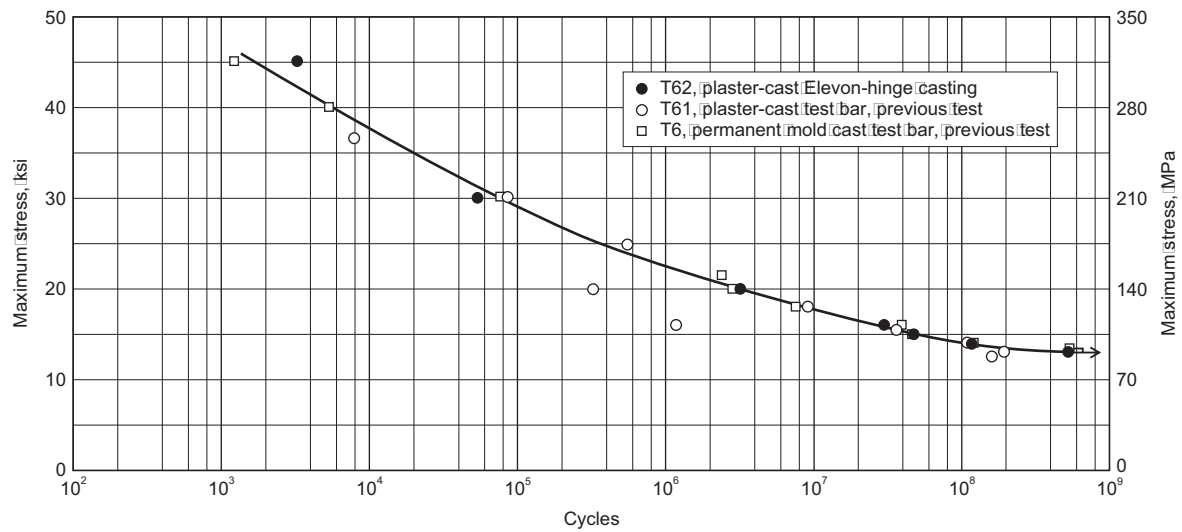


**Fig. D6.81** A356.0-T62, high strength plaster cast aluminum casting rotating-beam fatigue curve. Test data for the T62 temper plaster cast Elevon hinge casting is compared to previous T61 plaster cast and T6 permanent mold test data. The T62 temper was 10 h at 340 °F.

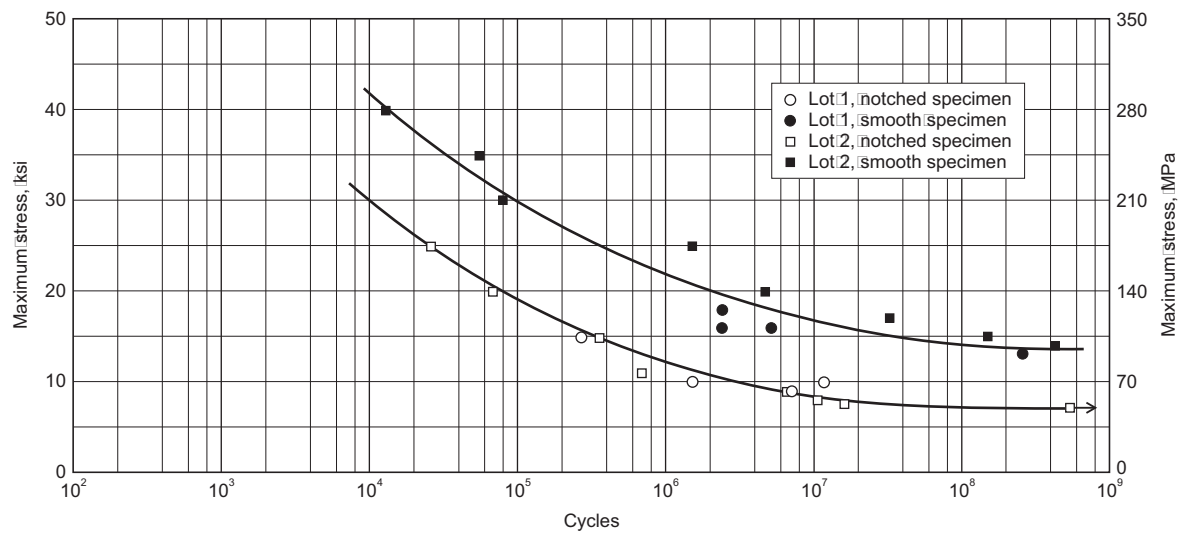


**Fig. D6.82** A357.0-T61, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots. Specimens were machined from cantilever-beam cast test bars.

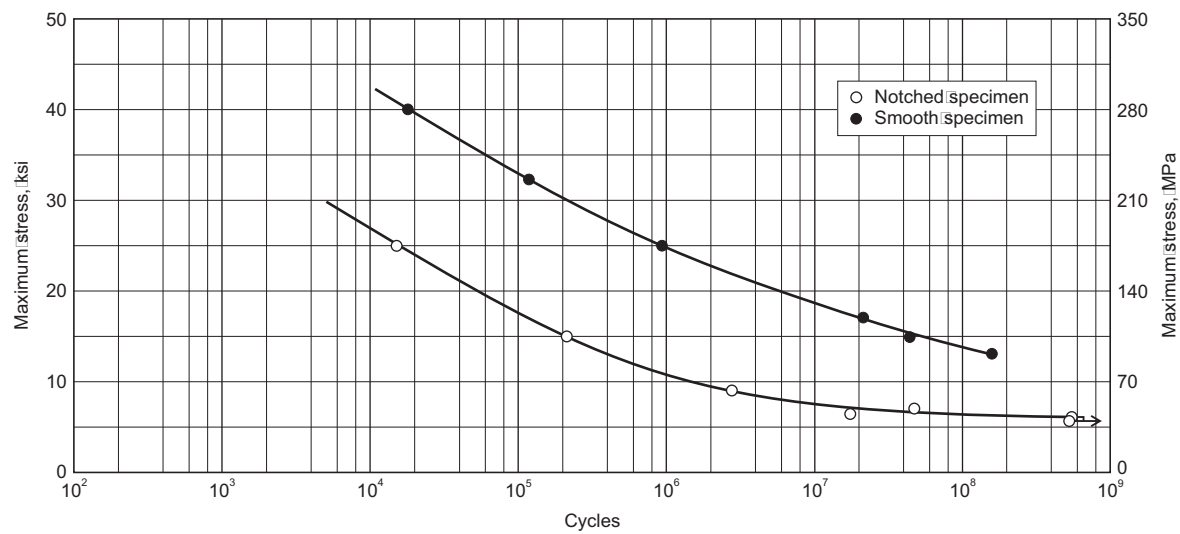


Fig. D6.83 A357.0-T62, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

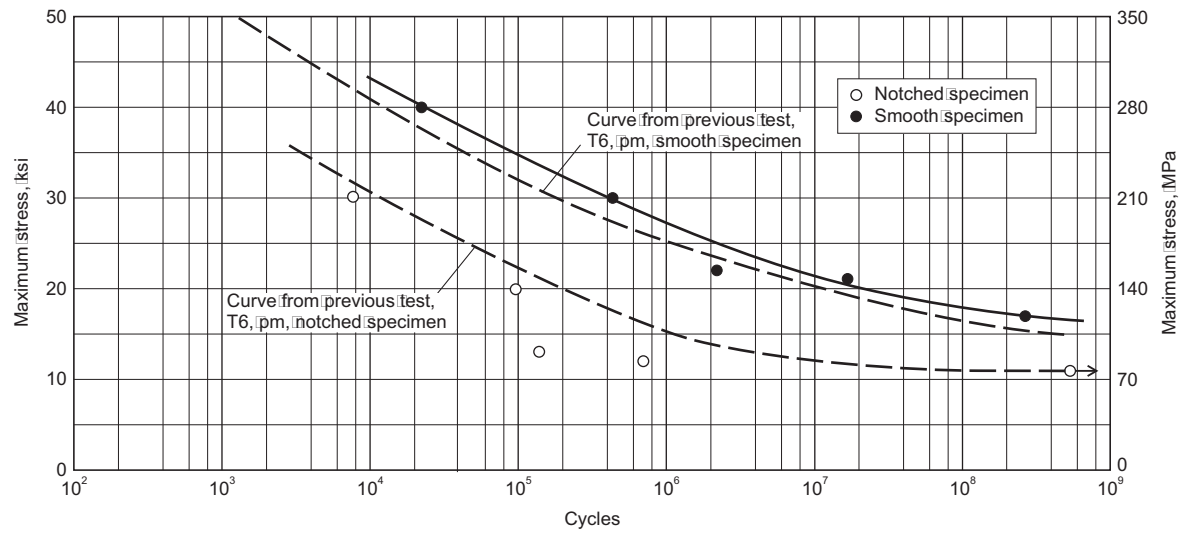


Fig. D6.84 359.0-T61, permanent mold (PM) aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot with T61 temper are compared to prior curves for PM specimens with T6 temper

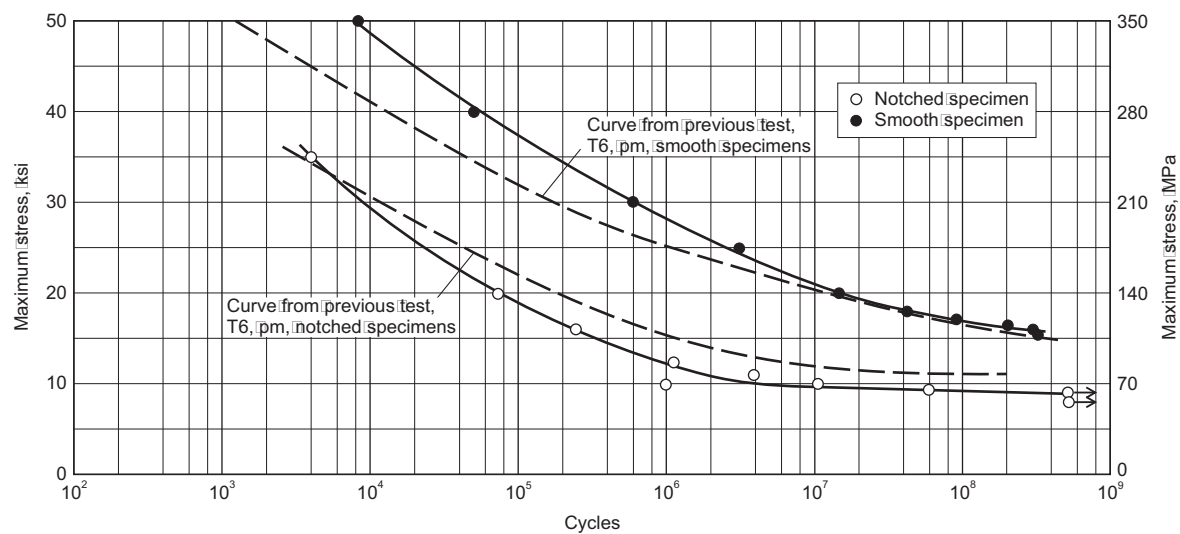


Fig. D6.85 359.0-T62, permanent mold (PM) aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot with T62 temper are compared to prior curves for PM specimens with T6 temper

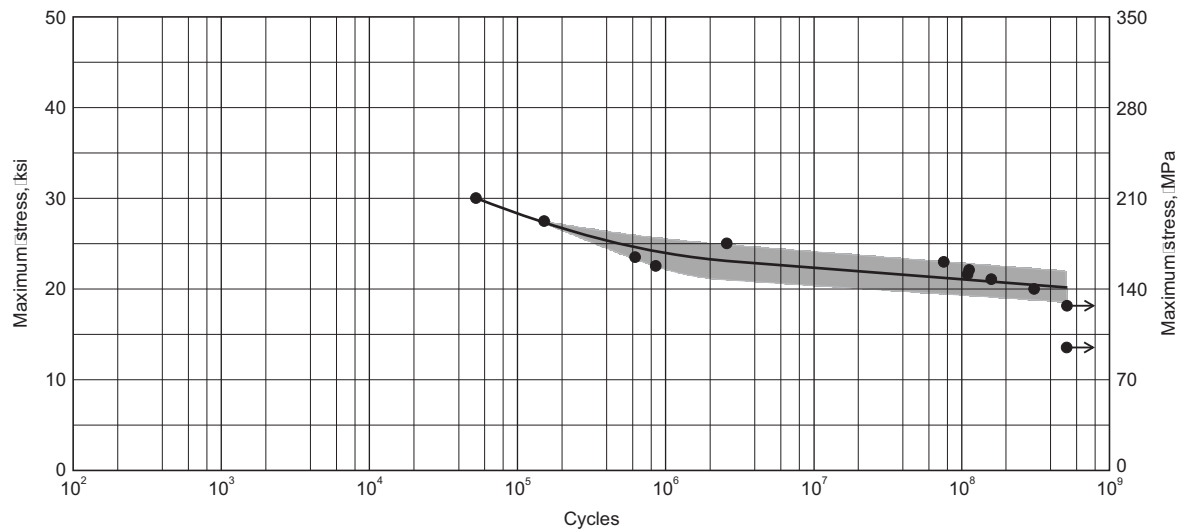


**Fig. D6.86** 360.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

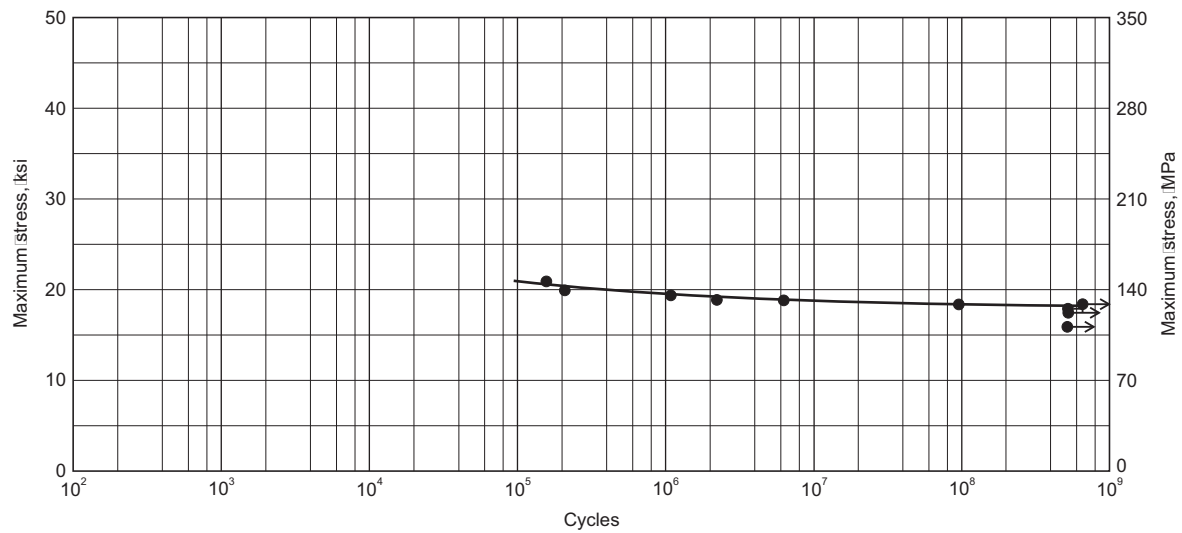


**Fig. D6.87** A360.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

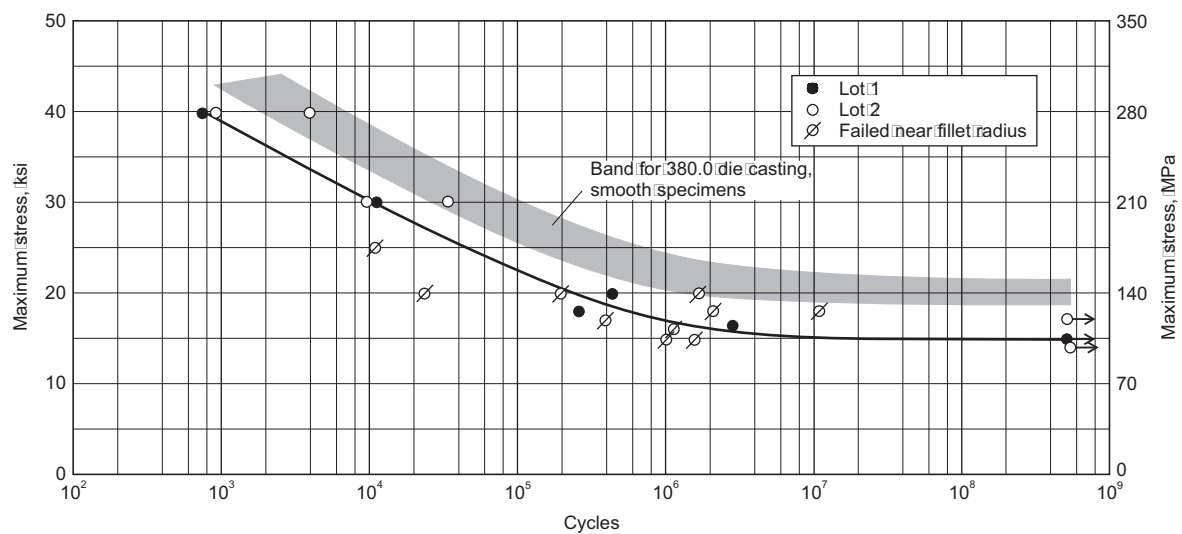


**Fig. D6.88** 364.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from two lots. Specimen per Fig. A3.4, Appendix 3. Data points with lines indicate failures near fillet radius.

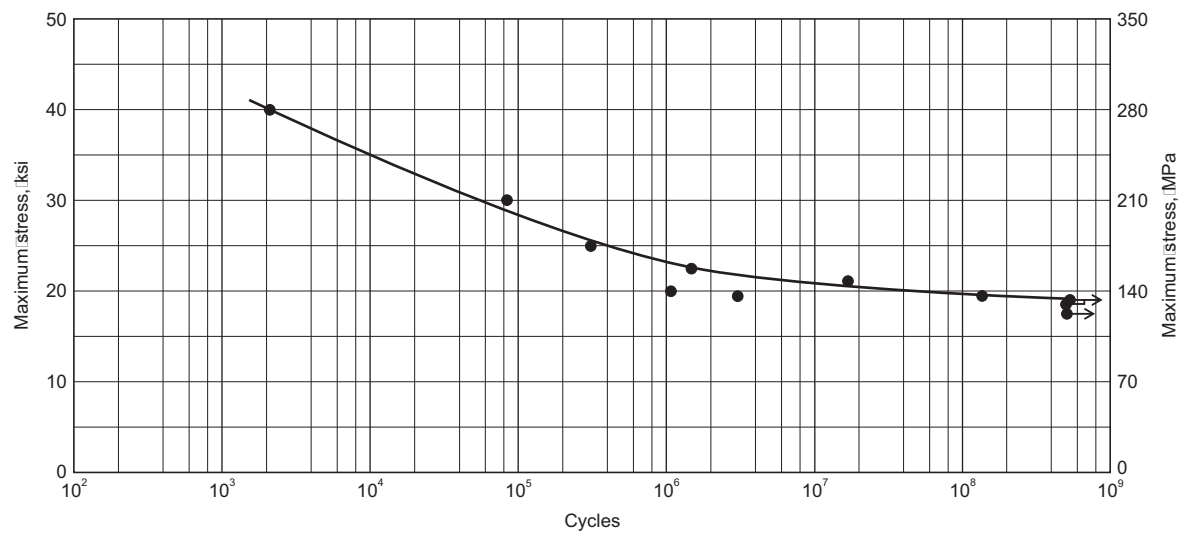


**Fig. D6.89** 380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot. Specimen per Fig. A3.4, Appendix 3.

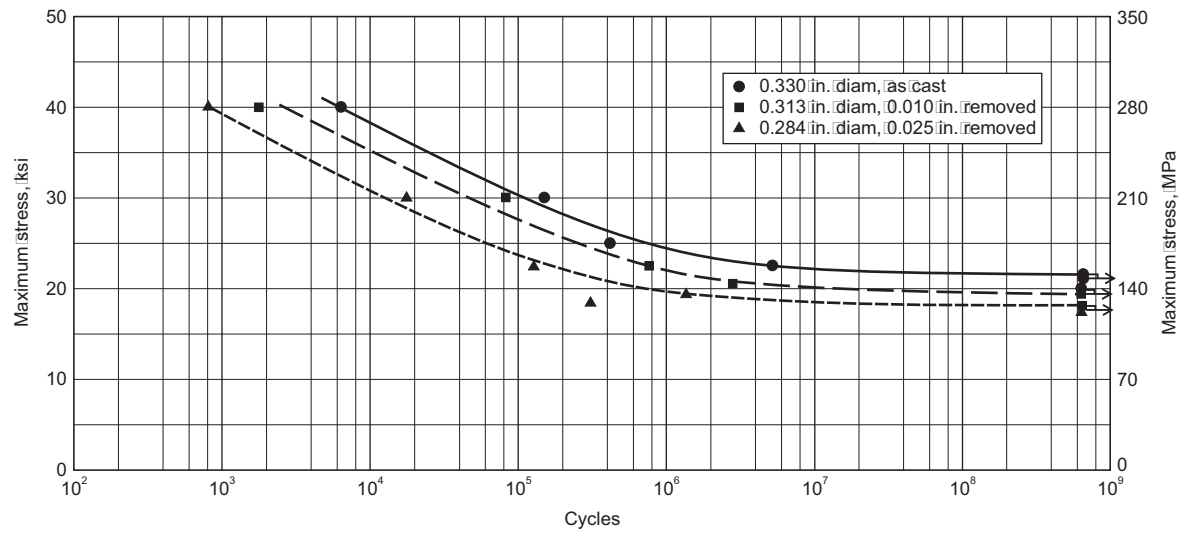


**Fig. D6.90** 380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot. Specimen per Fig. A3.4, Appendix 3, as cast. Machined to nominal diameters as noted

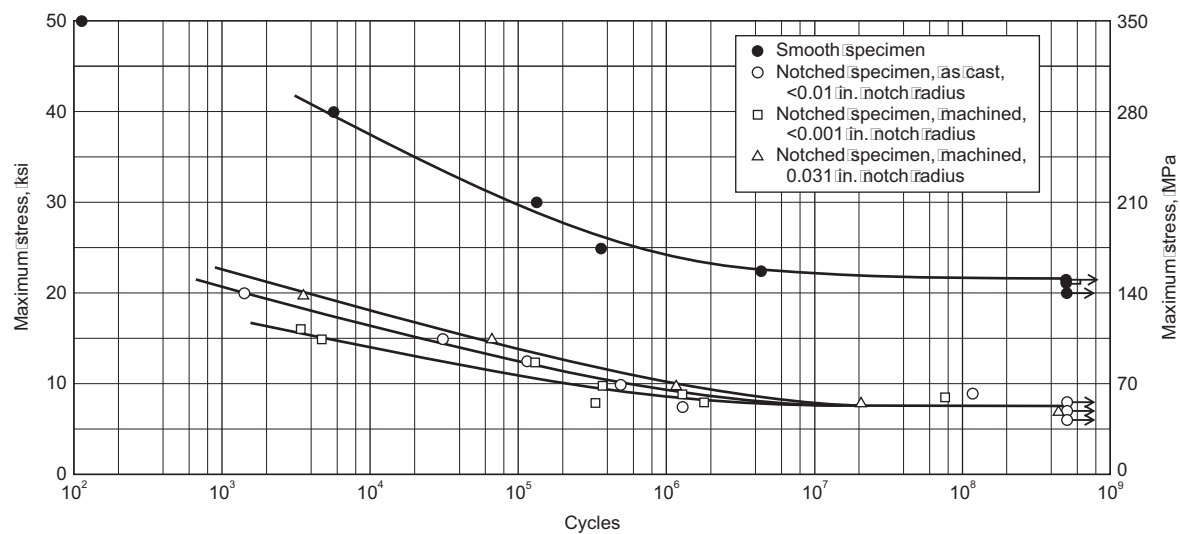


**Fig. D6.91** 380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Notched specimens similar to Fig. A3.2(b), Appendix 3, except notch radius is as noted



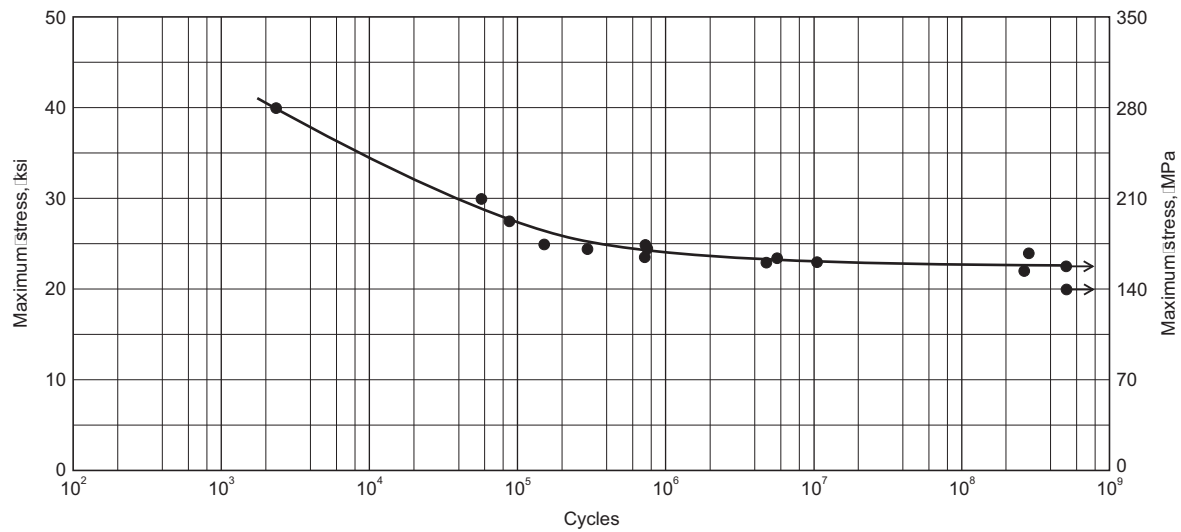


**Fig. D6.92** A380.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

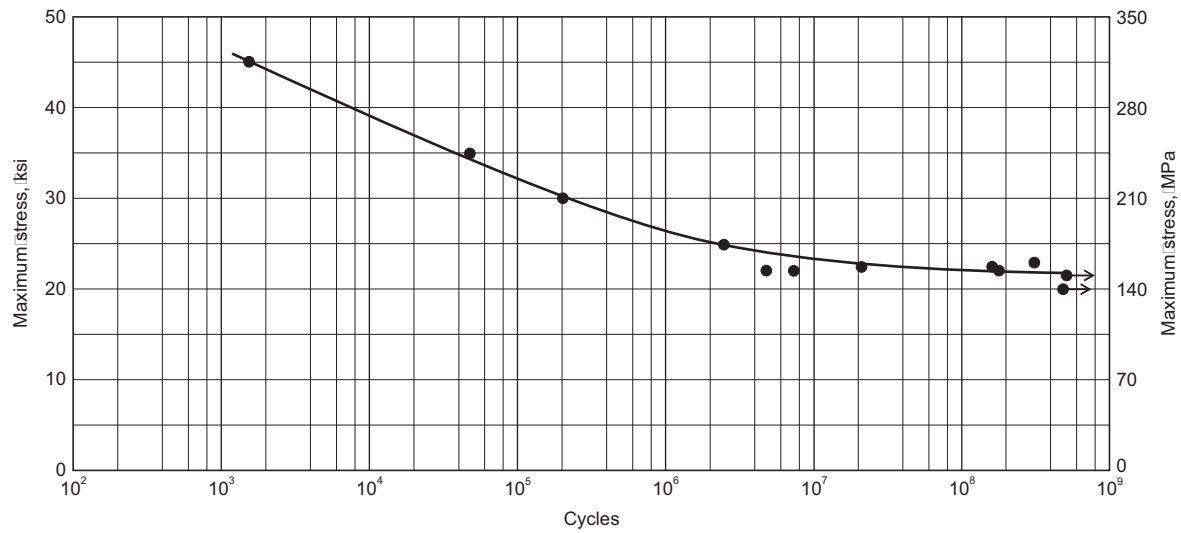


**Fig. D6.93** 384.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

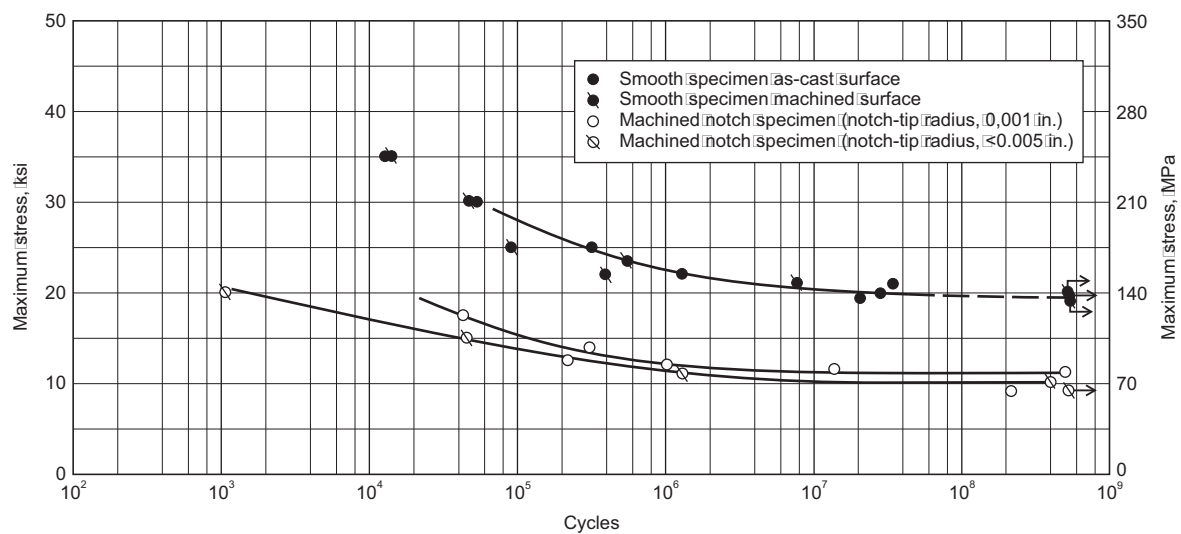


**Fig. D6.94** 390.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Smooth specimens per Fig. A3.7, Appendix 3. Notched specimens similar to Fig. A3.2(b), Appendix 3, except notch radius is as noted

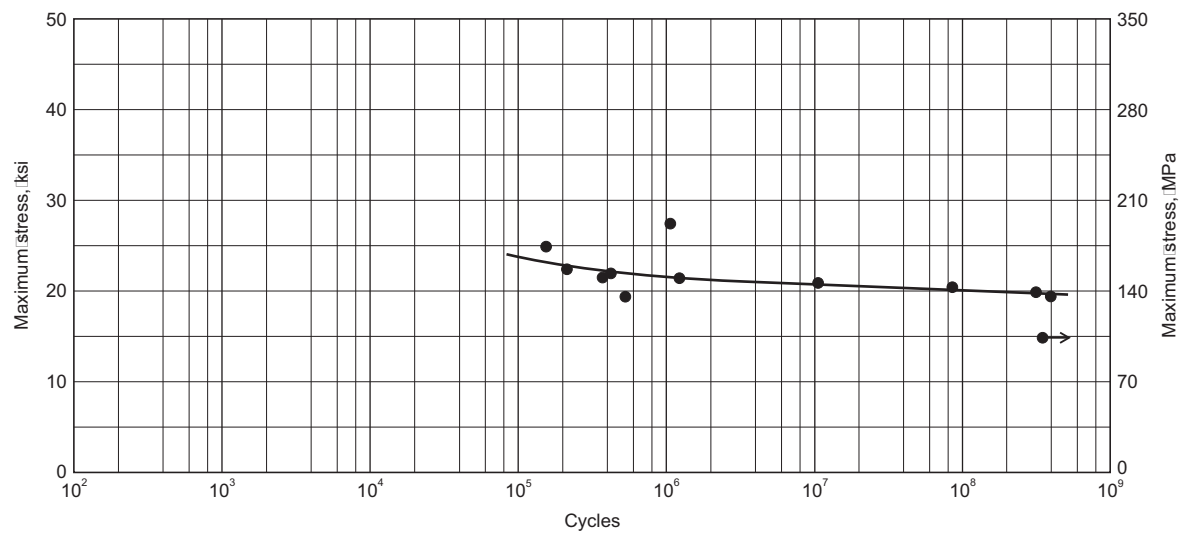


Fig. D6.95 413.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

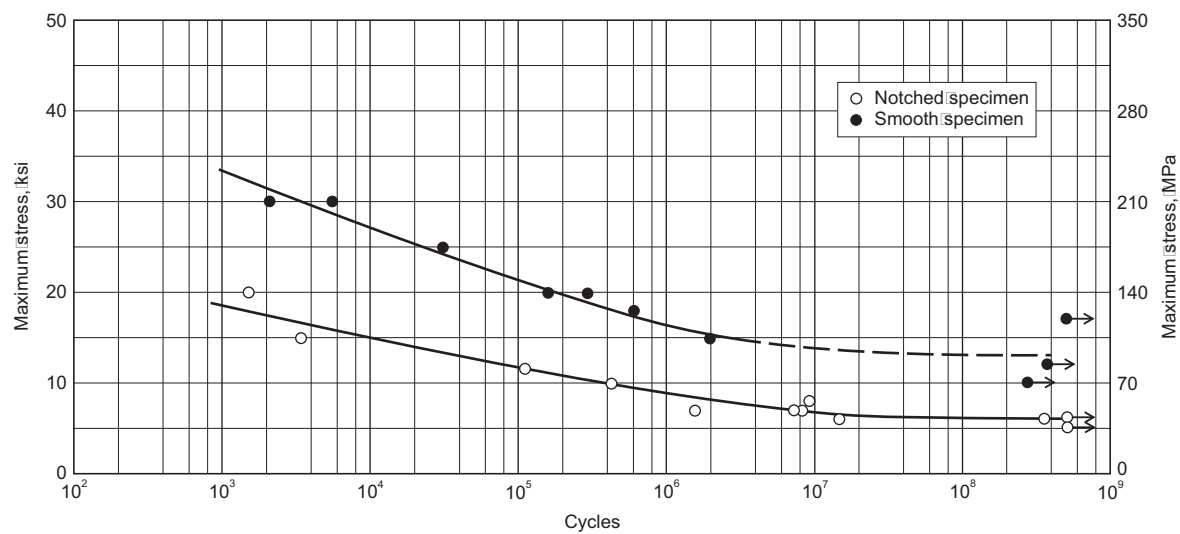


Fig. D6.96 413.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

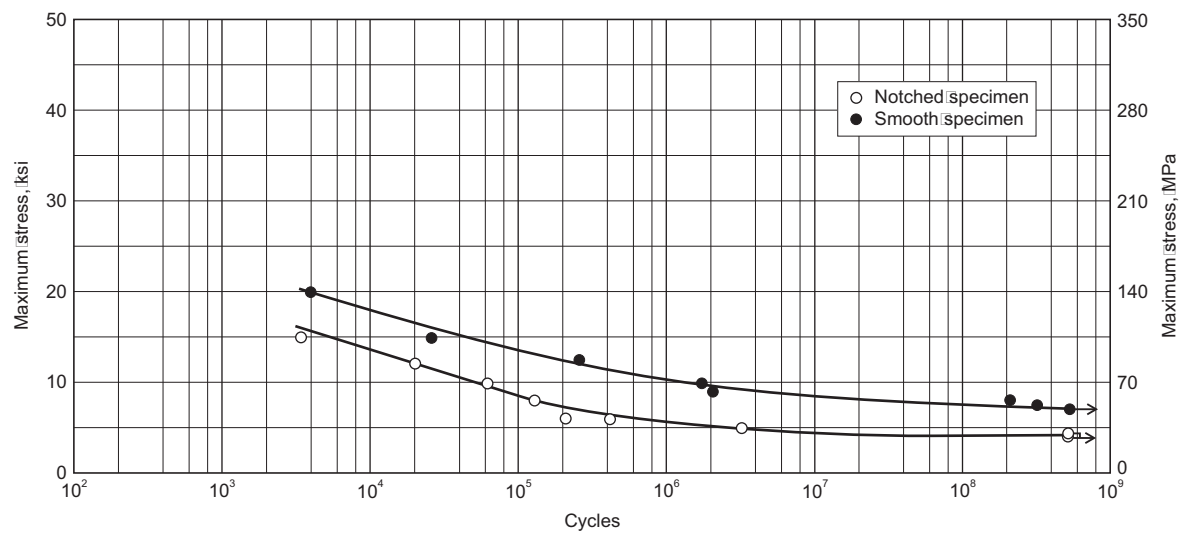


Fig. D6.97 B443.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

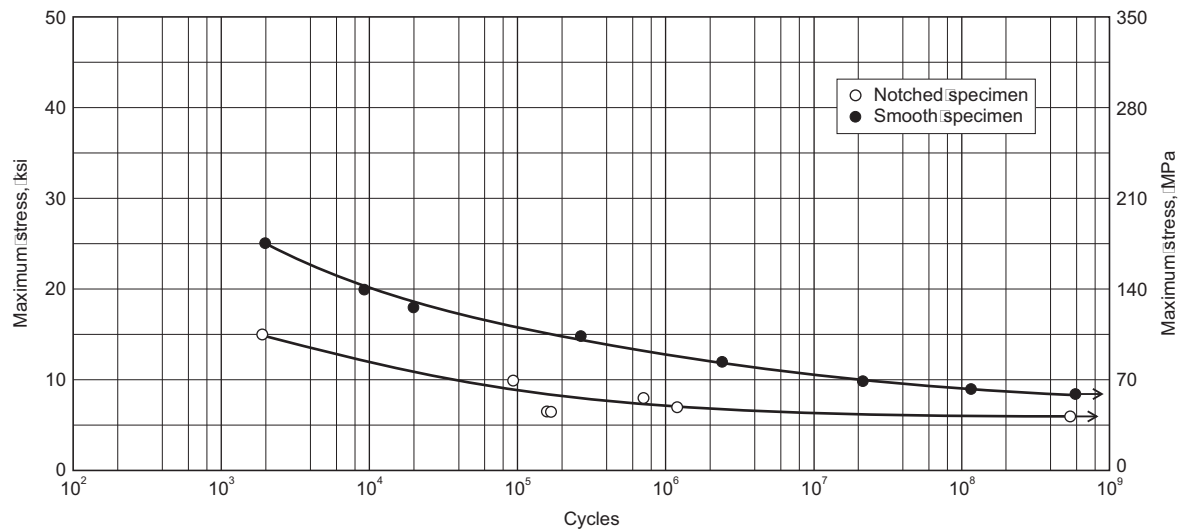


**Fig. D6.98** B443.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

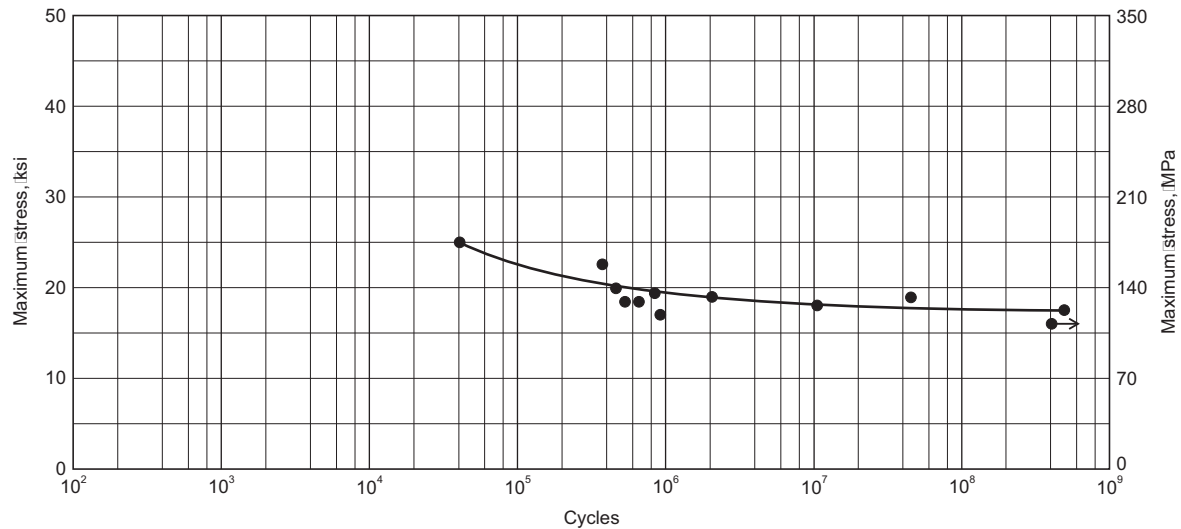


**Fig. D6.99** B443.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth specimens per Fig. A3.4, Appendix 3, from one lot

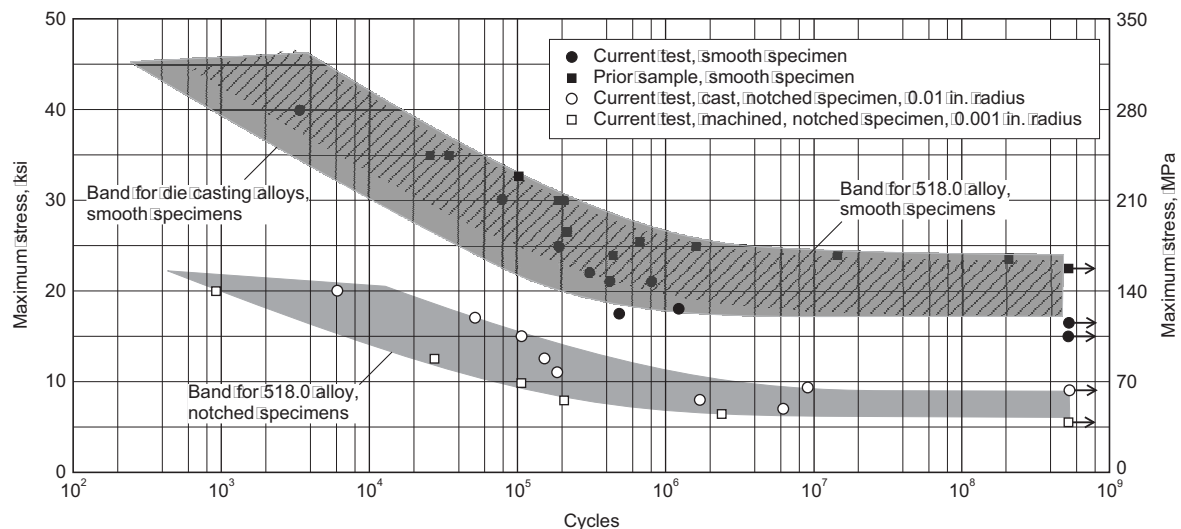


**Fig. D6.100** 518.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot, with comparison to prior test. Smooth specimens per Fig. A3.4, Appendix 3. Notched specimens similar to Fig. A3.2(b), Appendix 3, except notch radius is as noted

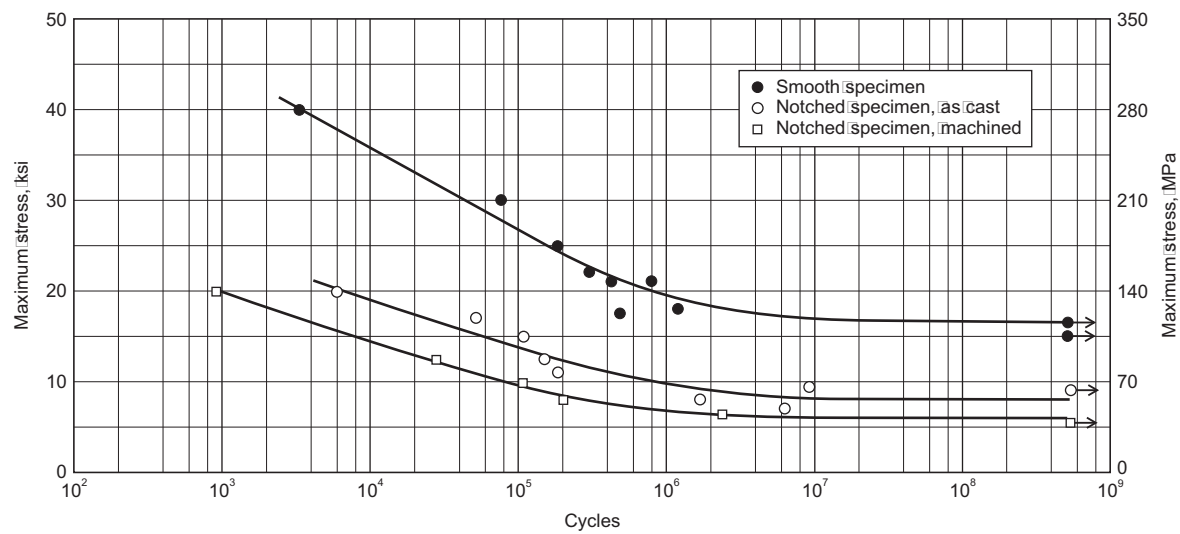


**Fig. D6.101** 518.0-F, die cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot. Smooth specimens per Fig. A3.4, Appendix 3. Machined notched specimens per Fig. A3.2(b), Appendix 3. As-cast notched specimen has radius <0.01 in.

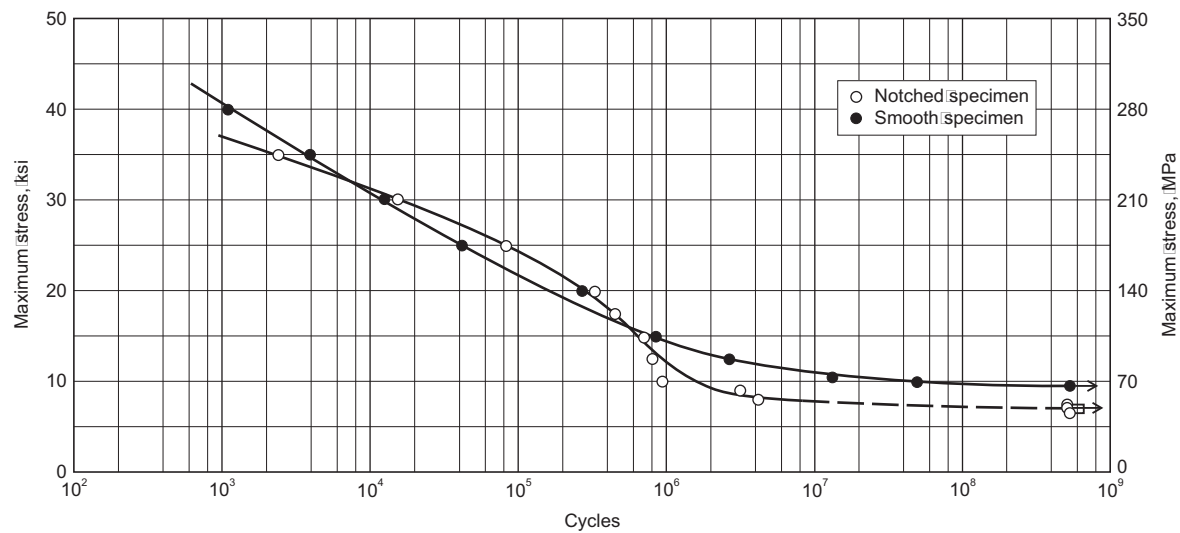


**Fig. D6.102** 712.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

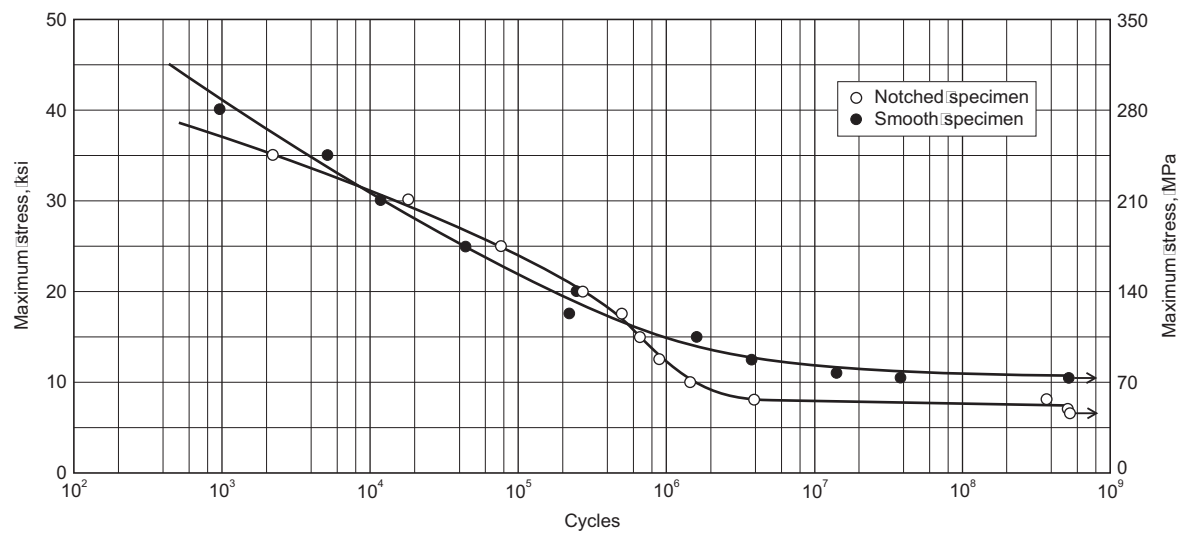


**Fig. D6.103** A712.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

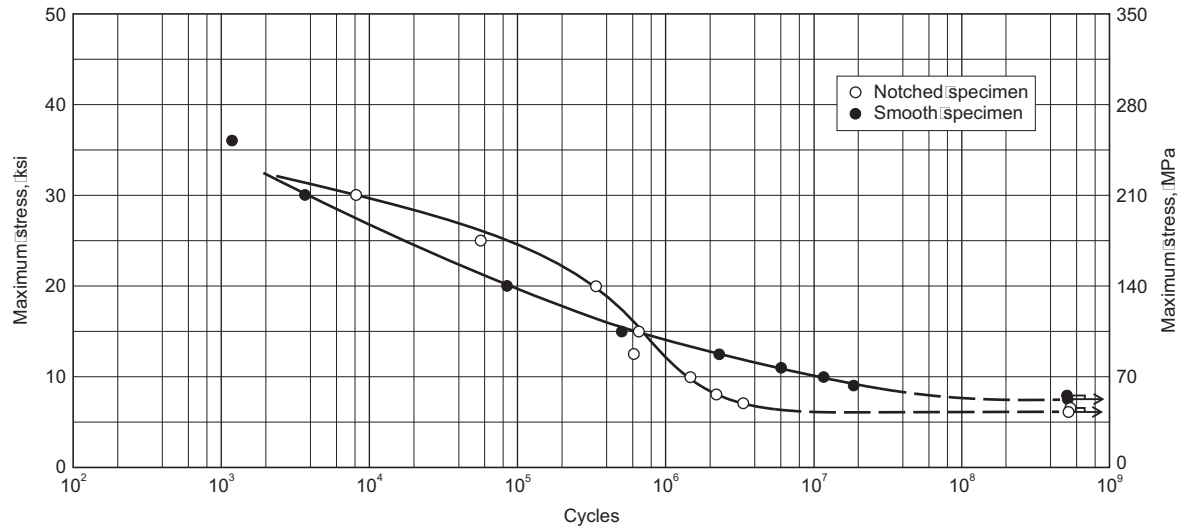


**Fig. D6.104** A712.0-F, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

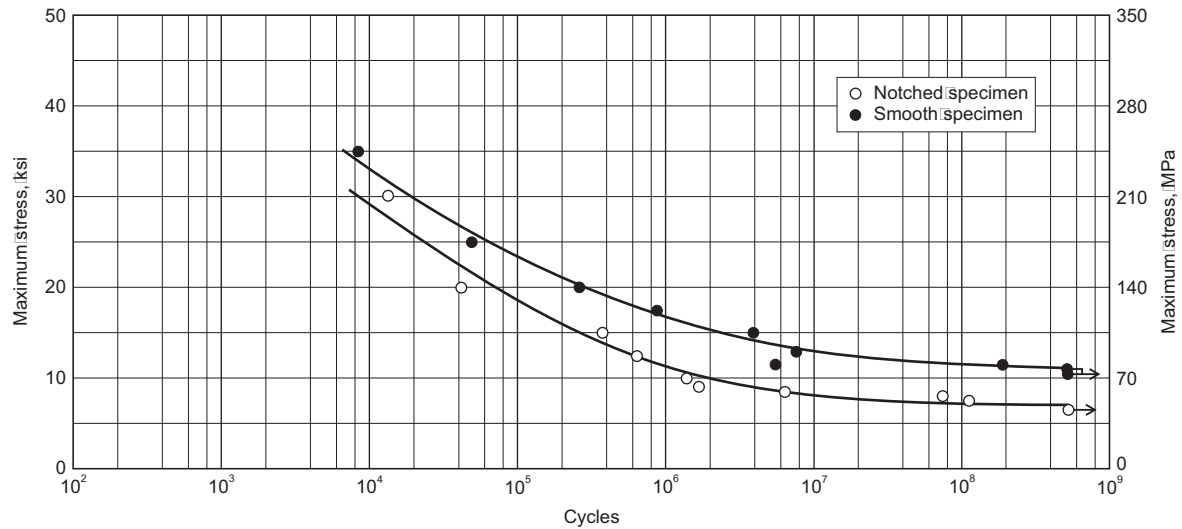


**Fig. D6.105** C712.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot

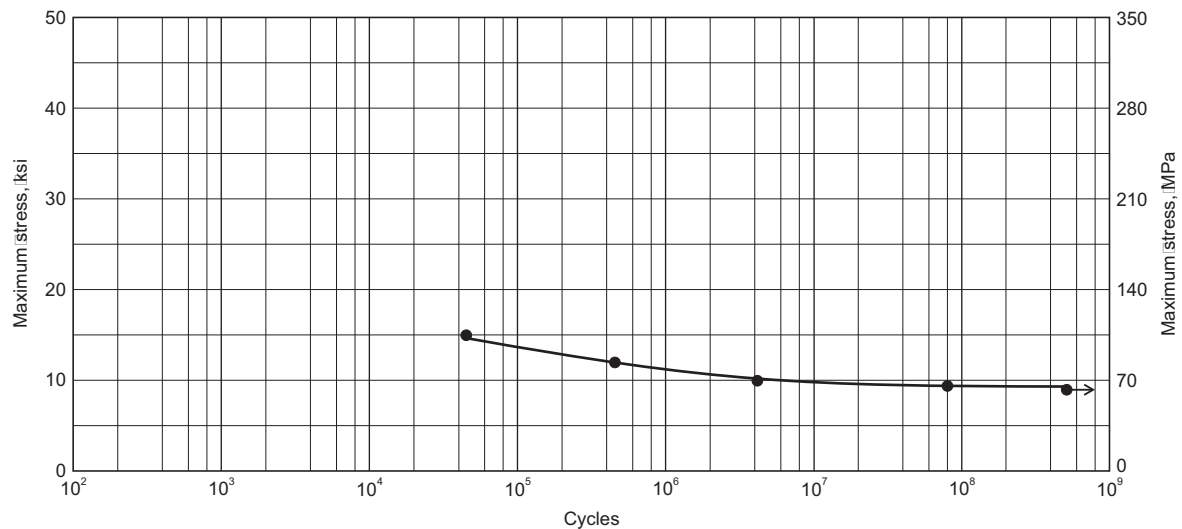


**Fig. D6.106** 850.0-F, permanent mold aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot

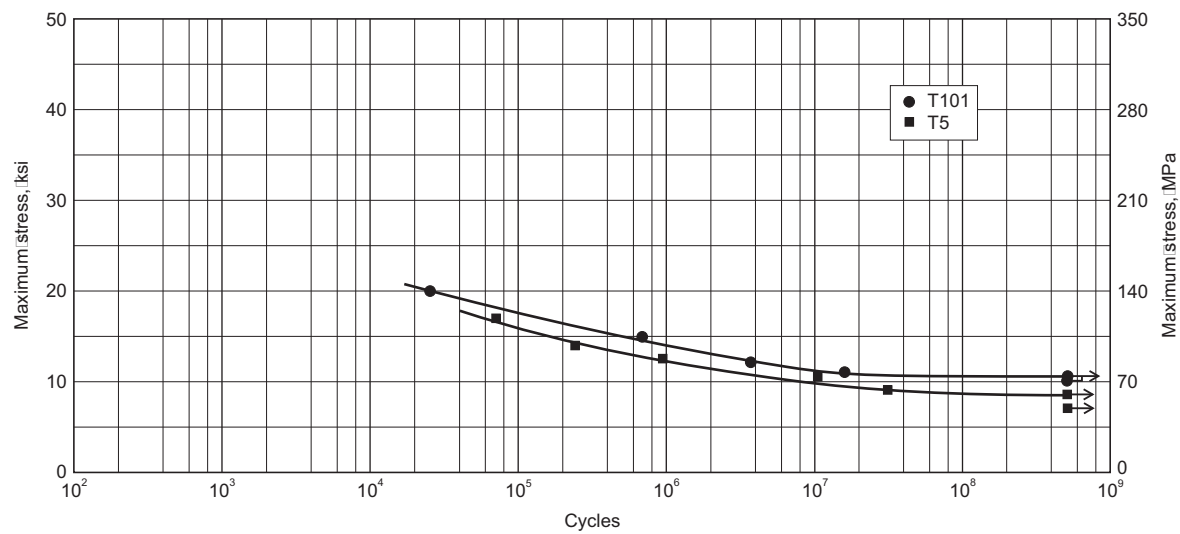


**Fig. D6.107** 850.0-T101, -T5, permanent mold aluminum casting rotating-beam fatigue curve. Comparison of smooth specimens from two lots, T5 and T101 temper

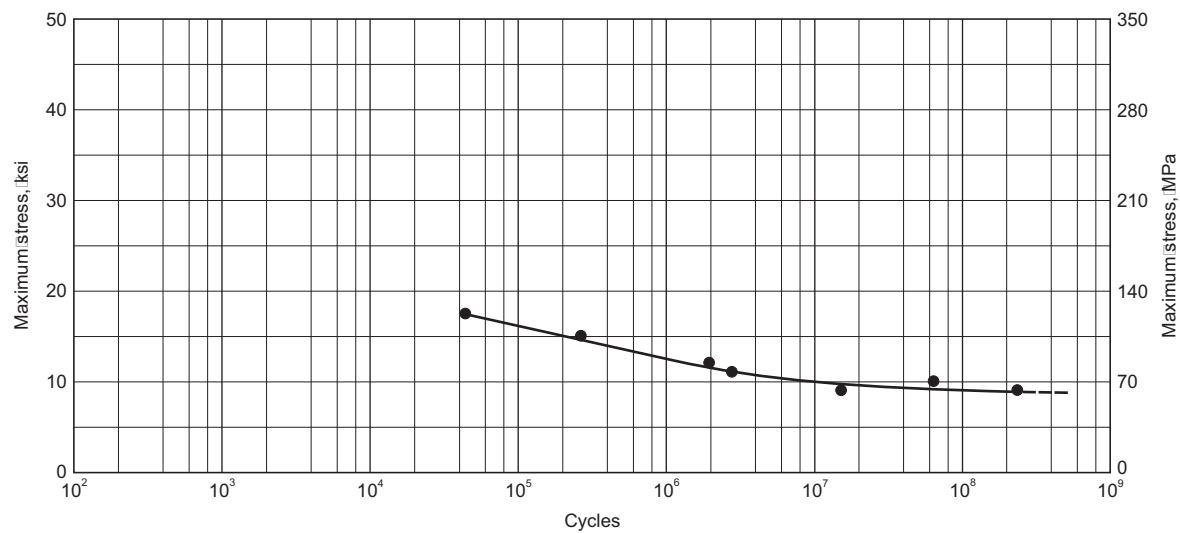


**Fig. D6.108** 851.0-T6, permanent mold aluminum casting rotating-beam fatigue curve. Smooth specimens from one lot. Heat treatment: 4 h at 900 °F, boiling water quench, 4 h at 430 °F

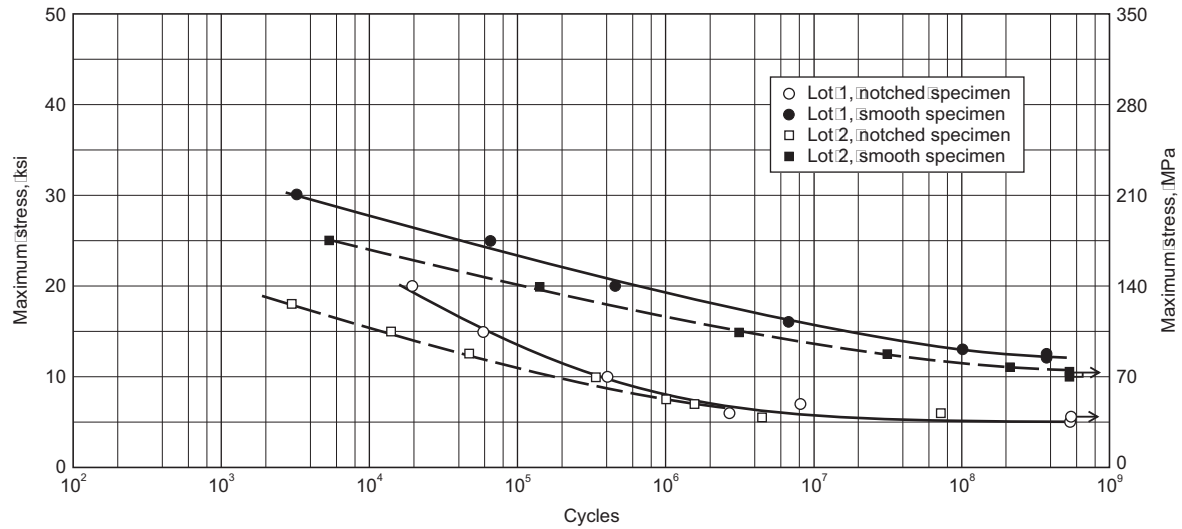


**Fig. D6.109** 852.0-T5, permanent mold aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from two lots

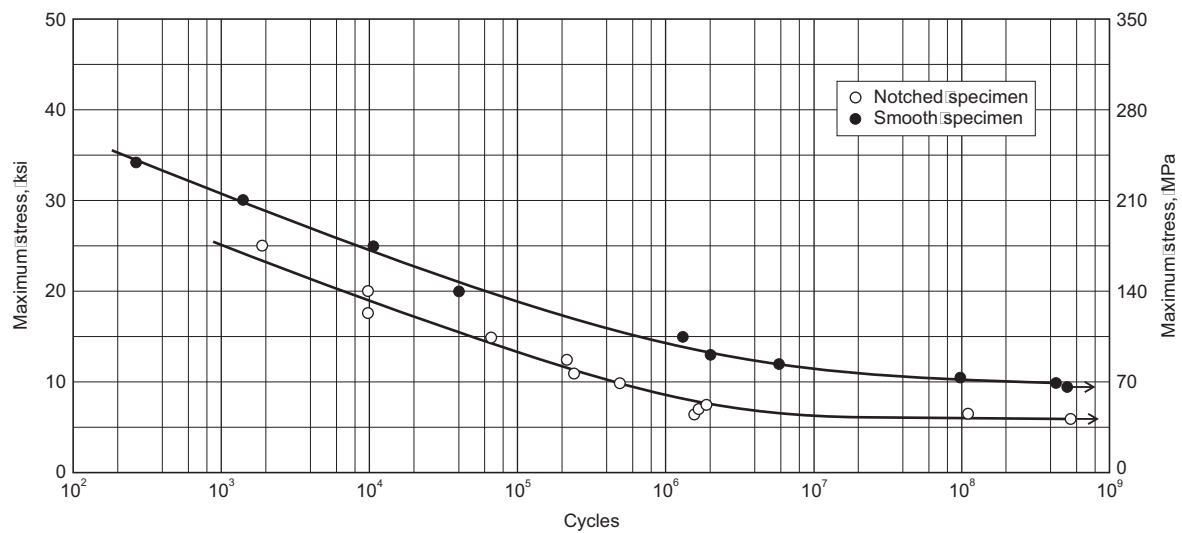


**Fig. D6.110** 852.0-T5, sand cast aluminum casting rotating-beam fatigue curve. Smooth and notched specimens from one lot





## APPENDIX 1

# Glossary of Terms

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The following list of terms is associated primarily with cast aluminum products, their production, and their properties. The list is not intended to be exhaustive, including every term likely to be used within the aluminum casting industry, but rather as a resource for readers of this book.

Many of these terms come from the Aluminum Association publication *Aluminum Standards and Data* and casting industry publications of the American Foundry Society (AFS), the North American Die Casting Association (NADCA), and the Non-Ferrous Founders' Society (NFFS). The reader is referred to those societies' publications for more complete terminology for casting and casting processes.

### A

**age hardening.** A process that results in increased strength and hardness as a result of precipitation of hardening phase(s) from solid solution.

**aging.** Precipitation from solid solution resulting in a change in properties of an alloy, usually occurring slowly at room temperature (natural aging) and more rapidly at elevated temperatures (artificial aging).

**alloy.** A substance having metallic properties composed of two or more elements.

**annealing.** Thermal treatment to soften metal by depleting solid solution, coalescing precipitates, and for relieving residual stresses.

**anodizing.** Forming a controlled oxide coating on a metal surface by electrochemical treatment.

**artificial aging.** See aging.

**as-cast condition.** Newly produced or unfinished castings. Also describing castings that have not been thermally treated.

### B

**binder.** A material used to bond grains of foundry sand to form a mold or core. It can be cereal, oil, clay, or natural/synthetic resin.

**blast cleaning.** A process to clean or finish castings by use of an air blast or airless centrifugal wheel that accelerates abrasive particles or metal shot against the surface of castings.

**blow hole.** A blister that has ruptured and may produce a void. A defect caused by entrapped gases often associated with excessive moisture or volatile reactions with mold or core components.

**brazing.** Joining metals by fusion of nonferrous alloys that have melting points above 425 °C (800 °F) but lower than those of the metals being joined. This may be accomplished by means of a torch (torch brazing), in a furnace (furnace brazing), or by dipping in a molten flux bath (dip or flux brazing).

**brazing rod.** A rolled, extruded, or cast round filler metal for use in joining by brazing.

**brazing wire.** Wire for use as a filler metal in joining by brazing.

**buffing.** A mechanical finishing operation in which fine abrasives are applied to a metal surface by rotating fabric wheels for the purpose of developing a lustrous finish.

### C

**casting** (noun). An object formed by solidification of molten metal introduced to a mold or dies.

**casting** (verb). Introducing molten metal into a mold or dies.

**casting strains.** Strains in a cast metal component resulting from internal stresses created during cooling from solidification temperature.

**casting yield.** The weight of casting or castings divided by the total weight of metal poured into the mold, expressed as a percent.

**centrifugal casting.** In the centrifugal casting process, commonly applied to cylindrical castings, a permanent mold is rotated rapidly about the axis of the casting, while a measured amount of molten metal is poured into the mold cavity. Centrifugal force is used to hold the metal against the outer walls of the mold with the volume of metal poured determining the wall thickness of the casting. Conventional permanent mold castings are produced by spinning molds during and after mold filling to enhance filling and to induce internal soundness by centrifugal force.

**chill.** Metal insert placed in a sand mold to increase localized heat flux. In permanent mold, air, mist, and water are used to selectively cool mold segments.

**cleaning.** Removal of sand and excess metal from a sand casting, ceramic and excess metal from an investment casting, or excess metal from a die casting.

**CO<sub>2</sub> process.** Molds and cores, made with sand coated with sodium silicate, which are hardened by permeating the sand with carbon dioxide gas to form a silica gel.

**cold shut.** A linear discontinuity in a cast surface caused when meeting streams of metal fail to merge prior to solidification.

**cold working.** Plastic deformation of metal at such temperature and rate that strain hardening occurs.

**coloring.** A finishing process, or combination of processes, that alters the appearance of an aluminum surface via coating, chemical, and/or mechanical operations.

**combination die** (multiple-cavity die). A die with two or more different cavities for different castings.

**condensation stain.** *See* corrosion, water stain.

**controlled cooling.** Process by which a metal object is cooled from an elevated temperature in a manner that avoids hardening, cracking, or internal damage.

**conversion coating.** An inorganic pretreatment sometimes applied to a metal surface to enhance coating adhesion and retard corrosion.

**core.** Separable part of a mold made of sand and a binder to create openings and various specially shaped cavities in sand and semi-permanent mold castings. Also drawable metallic mold components in permanent mold and die casting dies.

**coring.** Chemical segregation across grains that occurs during solidification.

**corrosion.** The deterioration of a metal by chemical or electrochemical reaction with its environment.

**corrosion, galvanic.** Corrosion associated with galvanic action between dissimilar conductors in an electrolyte or similar conductors in dissimilar electrolytes. Aluminum will sacrificially corrode if it is anodic (electronegative) to the dissimilar metal. Galvanic corrosion may also occur between dissimilar microstructural features when exposed to an electrolyte.

**corrosion, intergranular.** Corrosion occurring preferentially at grain boundaries (also termed intercrystalline corrosion).

**corrosion, pitting.** Localized corrosion resulting in small pits or craters in a metal surface.

**corrosion, stress.** Failure, usually intergranular, resulting from the simultaneous interaction of sustained tensile stresses below the yield point and exposure to a corrosive environment. The term is often abbreviated SCC (stress-corrosion cracking).

**coupon.** A casting prolongation from which a test specimen may be prepared without damaging the casting.

**cutoff.** Removal of gates, risers, and other excess metal from a casting.

## D

**defect.** Any structural discontinuity that affects acceptability or performance capabilities.

**die (in casting).** Metal form(s) used to produce a die casting, permanent mold casting, a lost foam, wax, or core pattern.

**die casting** (noun). A casting produced by the pressure die casting process.

**die casting** (verb). Injecting molten metal under pressure into a mold, which is formed by metal dies. In Europe, any casting produced in a metal mold.

**die casting, cold chamber.** Die casting process in which the metal injection mechanism is not submerged in molten metal.

**die casting, gravity.** Term used in Europe for producing a casting by pouring molten metal (gravity pouring) into a metal mold, with no application of pressure. In the United States, this is the permanent mold casting process.

**die casting, high pressure.** A die casting process in which the metal is injected under high pressure in either cold or hot chamber die casting machines. In the United States, this is simply die casting. High-pressure die casting and low-pressure die casting are terms commonly used in Europe to differentiate between what in the United States would be called, respectively, pressure die casting and gravity permanent molding.

**die casting, hot chamber.** Die casting process in which the metal injection mechanism is submerged in molten metal.

**die number.** The number assigned to a die for identification and cataloging purposes and which usually is assigned for the same purpose to the product produced from that die.

**dimensional stability.** Ability of a casting to remain unchanged in size and shape.

**double shear notch.** *See* notch, double shear.

**draft.** Taper on the sides of a die or mold impression to facilitate removal of castings, or patterns from dies or molds.

**dry sand molding.** Dry sand molds are made by many different processes. Sand mixed with binders that cure by baking is one form of dry sand mold; other more common dry sand molding techniques use sand with binders that can be cured by chemical or catalytic reaction induced by mixing with the sand or by blowing gases through the mold after it is formed.

**ductility.** The property measuring permanent deformation before fracture by stress in tension.

## E

**elastic limit.** The highest stress that a material can withstand without permanent deformation. For most practical application purposes, the elastic limit is the yield strength.

**electrical conductivity.** The capacity of a material to conduct electrical current. For aluminum, this capacity is expressed as a percentage of the International Annealed Copper Standard (IACS), which has a resistivity of  $\frac{1}{58}$  ohm-mm<sup>2</sup>/m at 20 °C (68 °F) and an arbitrarily designated conductivity of one.

**electrical resistivity.** The reciprocal of electrical conductivity. The electrical resistance of a body of unit length and unit cross-sectional area or unit weight. The value of  $\frac{1}{58}$  ohm-mm<sup>2</sup>/m at 20 °C (68 °F) is the resistivity equivalent to the IACS for 100% conductivity.

**elongation.** The property measuring permanent deformation before failure. The percentage increase in length between gage marks that results from stressing a specimen in tension to failure.

**endurance limit.** The limiting stress below which a material will withstand a specified number of cycles of stress.

**expendable pattern casting.** Casting process that employs a foam polystyrene or other plastic pattern-and-sprue assembly in a loose sand mold. Molten metal, poured into the sprue, vaporizes the pattern and replaces it to become the casting when it so-

lifies. This process is also widely referred to as lost-foam casting.

## F

**fatigue.** The tendency for a metal to break under conditions of repeated cyclic stressing below the ultimate tensile strength.

**feeder.** *See* riser.

**fillet.** A concave junction between two surfaces.

**finish.** The characteristics or relative smoothness or roughness of an as-cast or machined surface.

**flash.** A protrusion that forms when metal, in excess of that required to fill the mold impression, penetrates the parting plane.

**flash line.** A line left on a casting where flash has been removed.

**flow line.** Visible pattern on the surface of a casting corresponding to the pattern of metal flow in the mold.

**fracture toughness.** A generic term for measuring the resistance to low-ductility extension of a crack; alternatively, the energy-absorbing capability of a metallurgical structure under stress leading to failure. The term is sometimes restricted to results of a fracture mechanics test, such as ASTM E 399 for plane-strain fracture toughness,  $K_{Ic}$ , which may be directly applicable in design. Fracture toughness may also be measured in relative terms by notch tensile or tear testing.

## G

**gas porosity.** Casting defects caused by entrapped gases or by hydrogen precipitated during solidification.

**gate.** Passage(s) in the runner system through which molten metal enters the mold cavity. Sometimes used as a general term to indicate the entire assembly of connected columns and channels carrying molten metal to the casting cavity.

**gated patterns.** Patterns with integral gating.

**gating system.** The complete assembly of sprues, runners, gates, and risers in a mold through which metal flows to the casting cavity.

**grain refiner.** An alloy or salt mixture comprising components that form nuclei for the heterogeneous nucleation of aluminum grains during solidification.

**grain size.** A measure of crystal size usually reported in terms of average diameter in millimeters, grains per square millimeter, or grains per cubic millimeter.

**green sand.** Clay-bonded molding sand containing water.

**green sand molding.** The mold is composed of a prepared mixture of sand, clay, and water, usually with other additives to suppress mold reactions, aid in sand separation after casting, or alter surface quality. The mold is not cured or dried and therefore is known as a green (uncured) sand mold.

**gross to net weight ratio.** The ratio of total weight contained by the casting and gating system and casting weight.

## H

**hardener.** An alloy of aluminum and one or more added elements for use in making alloying additions. Also referred to as master alloy.

**hardness.** Resistance to plastic deformation, usually by indentation. The term also may refer to stiffness or temper, or to resistance to scratching, abrasion, or cutting. Brinell hardness of aluminum alloys is obtained by measuring the permanent impression in the material made by a ball indenter 10 mm in diameter after loading at 500 kgf (4.903 kN) for 15 s and dividing the applied load by the area of the impression. Rockwell and other hardness tests with smaller indenters provide less accurate measurements in aluminum.

**heat treatable alloy.** An alloy that may be strengthened by dissolving and reprecipitating soluble phases.

**heat treating.** Heating and cooling castings to controllably alter material properties.

**heat treat stain.** A discoloration due to nonuniform oxidation of the metal surface during solution heat treatment.

**high-pressure molding.** A term applied to certain types of sand molding machines in which high-pressure air is used to produce extremely hard, high-density molds from green sand.

**holding temperature.** The temperature at which the liquid casting alloy is held in the furnace before and during casting. Usually set as the lowest temperature consistent with mold filling.

**hot cracking.** A crack in a casting that occurs at elevated temperature caused by thermal contraction of the part during or immediately after solidification.

**hot isostatic pressing (HIP).** A process that uses high pressures at elevated temperatures to close interior voids in castings or consolidate P/M products.

**hot shortness.** The tendency of an alloy to crack during or immediately after solidification.

## I

**impregnation.** A process for making castings pressure tight by treatment with liquid synthetic resins or other sealers.

**inclusion.** Nonmetallic contamination of the metal structure.

**in-gate.** The portion of the gating system that connects runners to the mold cavity.

**ingot, remelt.** A cast form of known composition intended and suitable for remelting.

**injection.** The process of forcing molten metal or plastic into a die cavity.

**inoculant.** Material which, when added to molten metal, modifies the structure, and thereby changes the physical and mechanical properties to a degree not explained on the basis of the change in composition resulting from its use. The term is normally applied to ferrous alloys, but is sometimes used to describe grain refinement and other additions in aluminum casting alloys.

**insert.** A metal component that is placed in the mold allowing molten metal to be cast around it. The component becomes an integral part of the casting.

**inspection lot.** *See* lot, inspection.

**investment casting.** *See* investment molding.

**investment molding.** The process also is known as the lost wax process. Molds are produced by dipping wax or thermoplastic patterns in a fine slurry to produce as smooth a surface as possible. The slurry is air dried and redipped several times using less

expensive and coarser, more permeable refractory until the shell is of sufficient thickness for the strength required to contain molten metal. Investment molds also are produced as solid molds by placing the pattern assembly in a flask, which is then filled with a refractory slurry and air dried. The molds then are put into a furnace where the wax or plastic is removed by melting or volatilization. Molten metal is poured into the molds while the molds are still superheated, thus making it possible to pour very thin wall sections. A metal pattern die is used to produce the wax or plastic expendable patterns. Investment molding produces casting of superior surface finish, dimensional accuracy, and without parting fins or seams.

## L

**layout sample.** A prototype or production casting used to determine conformance to dimensional requirements.

**lost foam casting.** The casting process, also known as full-mold, polycast, cavity molding, evaporative pattern, or expendable pattern casting, is one in which a polystyrene pattern is vaporized by molten metal during the metal pour (*see also* expendable pattern casting).

**lot, heat treat.** Material traceable to one heat treat furnace or, if heat treated in a continuous furnace, charged consecutively during a finite period.

**lot, inspection.** (1) For non-heat-treated tempers, an identifiable quantity of castings of the same part submitted for inspection at one time. (2) For heat treated tempers, an identifiable quantity of castings of the same part traceable to a heat treat lot or lots and submitted for inspection at one time. In each case, the inspection lot is usually defined by a molten metal batch or continuous furnace operation of common chemistry and fixed maximum quantity.

**low-pressure casting.** A casting process in which air or gas pressure is applied to a sealed holding furnace from which molten metal is forced through a feed tube into the mold cavity.

## M

**master alloy.** *See* hardener.

**mechanical properties.** Those properties of a material that are associated with elastic and inelastic deformation when force is applied, or that involve the relationship between stress and strain. They include modulus of elasticity, tensile strength, yield strength, and ductility.

**microporosity.** Microscopic interdendritic porosity in castings caused by shrinkage and/or gas evolution.

**misrun.** Failure to completely fill the mold cavity.

**modification.** Promotion of a fibrous or lamellar structure in hypoeutectic aluminum-silicon alloys by modifying additions or solidification rate.

**modulus of elasticity.** The ratio of stress to corresponding strain throughout the range of proportionality.

**mold.** A shaped cavity into which molten metal is poured to produce a solidified casting.

**mold cavity.** The space in a mold that is filled with liquid metal to form the casting. Metal external to the mold cavity such as gates and risers are not considered part of the mold cavity.

**multiple cavity mold.** A mold in which more than one part of the same design is produced.

## N

**natural aging.** *See* aging.

**nondestructive testing.** Testing or inspection procedure that does not destroy or damage the product being inspected.

**nonfill.** Failure of metal to completely fill the mold cavity.

**non-heat-treatable alloy.** An alloy that cannot be significantly strengthened through postsolidification thermal treatment.

**notch toughness.** A general term describing the ability of a material to deform plastically locally in the presence of stress-raisers (either cracks, flaws, or design discontinuities) without cracking, and thus to redistribute loads to adjacent material or components.

**notch-yield ratio, NYR.** The ratio of the tensile strength of a notched specimen (the notch-tensile strength) to the tensile yield strength of a material. This provides a measure of notch toughness, the ability of a material to plastically deform locally in the presence of a stress-raiser, and thus to redistribute the stress. For aluminum alloys, it is measured in accordance with ASTM E 338 and E 602.

## O

**offset.** Yield strength by the offset method is computed from a load-strain curve obtained by means of an extensometer or manual plotting. A straight line is drawn parallel to the elastic portion of the load-strain curve. The most common method offsets +0.2 (0.002 mm/mm, or 0.002 in./in., of gage length). The load at the point where this line intersects the curve is used in the yield strength calculation.

**oxide discoloration.** As-cast surface coloration caused by elemental effects or differences in the composition and form of the oxide.

## P

**pattern.** A wood, metal, plastic, wax, or other replica of a casting that is used to form the cavity in a mold into which molten metal is poured to form a cast part. A pattern has the same basic features as the part to be cast, except that it is made proportionately larger to compensate for shrinkage due to the contraction of the metal during cooling after solidification.

**permanent mold casting.** A gravity or countergravity casting process that uses a metal or graphite mold that can be used repeatedly to produce cast parts of the same design.

**physical properties.** Intrinsic properties that pertain to the physical behavior of a material. Physical properties include specific gravity, electrical and thermal conductivity, and thermal expansion characteristics.

**plane strain.** The condition in which the stresses in all three directions may be significant (i.e., a triaxial stress condition may prevail), and the strains in one principal direction are essentially uniform or zero, usually through the thickness. This condition is approximated at the tip of a crack, where the strain through the thickness of a component along the crack front is zero.



**porosity.** Voids in a casting usually caused by shrinkage or hydrogen.

**precipitation hardening.** *See* aging.

**precipitation heat treating.** *See* aging.

**prolongation.** A physical extension of a casting that provides the source of test coupons without affecting the integrity of the part.

## Q

**quality.** An indefinite measurement of structural integrity.

**quench crack.** Failure caused by stresses induced during rapid cooling or quenching.

**quenching.** Rapid cooling of a metal from elevated temperature.

## R

**radiographic inspection.** Examination of soundness by radiography.

**radiography.** The use of radiant energy in the form of x-rays or gamma rays for nondestructive examination of opaque objects, such as castings, to produce graphic records that indicate the comparative soundness of the object being tested.

**refinement.** Phosphide nucleation of primary silicon in hypereutectic aluminum-silicon alloys.

**riser.** Sometimes referred to as a head or feeder. A strategically located volume of thermally and/or pressure differentiated molten metal that forms a reservoir from which volumetric losses caused by shrinkage as the casting solidifies can be compensated.

**runner.** That portion of the gating assembly that conveys molten metal from the sprue to in-gates.

**runner system.** Also called gating; the set of channels in a mold through which molten metal travels to the mold cavity; includes sprues, runners, gates, and risers.

## S

**sample.** A part, portion, or piece taken for purposes of inspection or test as representative of the whole.

**sand castings.** Castings produced in sand molds.

**sand mold.** A mold formed from chemically or naturally bonded sand.

**semisolid casting.** Also referred to as semisolid forging, thixocast, or forge casting, it is a process in which metal at a temperature between the liquidus and the solidus is pressed into closed dies. Billet for this process are produced by solidification with inductive or mechanical stirring. Versions include simplified techniques for final solidification from partially solidified structures.

**shear strength.** The maximum stress that a material is capable of sustaining in shear. In practice, shear strength is considered to be the maximum average stress computed by dividing the ultimate load in the plane of shear by the original area subject to shear.

**shell cores.** Cores produced from thermosetting sand blends with thicknesses controlled by the thermal cycle.

**shell molding.** Shell molds are made from a mixture of sand and thermosetting resin binder. Shell molds are backed by loose sand.

**shell mold process.** A process in which resin-coated sand is deposited on a heated pattern, bonding it to form a hardened shell about 10 to 20 mm (0.40 to 0.80 in.) thick. Two mating shells are glued together to make a precision mold to produce a casting with excellent dimensional accuracy and a smooth surface texture.

**shrinkage.** Contraction that occurs when metal cools from liquid to solid and in the solid state from solidification to room temperature.

**solution heat treating.** Heating an alloy at a suitable temperature for sufficient time to allow soluble constituents to enter into solid solution where they are retained in a supersaturated state after quenching.

**specimen.** A sample taken for evaluation of some specific characteristic or property.

**sprue.** The vertical portion of the gating system through which molten metal first enters the mold.

**squeeze casting.** Also known as liquid metal forging or forge casting, it is a casting process by which molten metal solidifies under hydraulic pressure. Other squeeze casting process variations include the insertion of cores under pressure during solidification, cast-forge, and a hinged/displacement technique for casting large thin-walled parts.

**stabilizing.** Overaging to achieve dimensional stability.

**stress.** Force per unit of area. Stress is normally calculated on the basis of the original cross-sectional dimensions. The three kinds of stresses are tensile, compressive, and shear.

**stress-corrosion cracking (SCC).** *See* corrosion, stress.

## T

**tear resistance.** A general term describing the resistance of a material to crack propagation under static loading, in either an elastic stress field (brittle fracture) or a plastic stress field (tearing). Like fracture toughness, it is generally used in connection with crack growth, not crack initiation. Tear resistance measured by unit propagation energy from a tear test made in accordance with ASTM B 871.

**temper.** For castings, the material condition produced by thermal treatment or a statement of the as-cast condition.

**tensile strength.** In tensile testing, the ratio of maximum load to original cross-sectional area. Also termed ultimate tensile strength or ultimate strength.

**tolerance.** Allowable deviation from a nominal or specified dimension.

## U

**ultimate tensile strength.** *See* tensile strength.

**unit propagation energy, UPE.** A measurement of energy required to propagate a crack under stress, expressed in in.-lb/in.<sup>2</sup> It is measured in a tear test (ASTM E 871) as amount of energy required to propagate a crack across a unit area in a tear specimen, in terms of the total energy to propagate the crack divided by the nominal crack area (i.e. the original net area of the specimen). Unit propagation energy provides a relative measure of fracture toughness.

## V

**vacuum casting process.** A process in which metal is drawn into the casting cavity by vacuum pressure applied to the mold cavity. Alternatively, the application of vacuum to the die cavity in pressure die casting and placing the mold under vacuum before pouring in investment and other casting processes.

## W

**welding.** Joining two or more pieces of aluminum by applying heat or pressure, or both, with or without filler metal, to produce a localized union through fusion across the interface. Cold weld-

ing is a solid-state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld.

**welding rod.** A rolled, extruded, or cast round filler metal for use in joining or repairing by welding.

**welding wire.** Wire for use as filler metal in welding.

**wrought product.** A product formed by mechanical working by such processes as rolling, extruding, and forging.

## Y

**yield strength.** The stress at which a material exhibits transition from elastic to plastic deformation.

# Subject Index

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## A

- AA. *See* Aluminum Association.
- Abbreviations, 299
- Acurad die casting process, 31
- Aerospace industry, 29(F)
  - alloys used, 1
  - applications, 18, 19, 20, 34, 35, 36-37(F)
  - investment castings, 26
  - semisolid formed applications, 29
- Age hardening
  - definition, 293
- Aging, 64-66, 122, 184(F)
  - artificial, 17, 20, 64, 194-198(F), 202(F), 203(F), 205-208(F)
  - artificial, aluminum-zinc-magnesium alloys, 14
  - artificial, corrosion resistance, 120
  - artificial, heat treatment designation T, 9
  - definition, 293
  - natural, 17, 19
  - natural, aluminum-zinc-magnesium alloys, 14
  - room-temperature, 15, 194-198(F), 205-208(F)
  - silver content effect, 13
- Aging. *See also* Precipitation aging.
- Aging response, 65
- Aging response curves, 133, 134-173(F), 175
  - artificial, 146-173(F)
  - high-temperature, 146-173(F)
  - natural, 133, 134-146(F)
  - room-temperature, 133, 134-146(F)
- Air blast quenching
  - casting alloys, 149(F)
- Air cooling, 194-198(F), 205-208(F)
- Aircraft industry
  - alloys used, 1, 2(F)
  - applications, 18, 19, 20, 34, 35, 36-37(F)
  - design fatigue strengths, 103, 104(F)
  - premium engineered castings, 33(F), 34(F)
- Alcoa A359 process, 56, 57(T), 58(T), 59(F)
- Al-fin process, 35
- Allcast. *See* Alloy Index, 319.0.
- Alloy
  - definition, 293
- Alloy designations, 8-13(T)
- Alloying composition
  - altering of properties, 1
- Alloying elements, 13, 14-17
- Almag 35. *See* Alloy Index, 535.0.
- AlMMCs. *See* Aluminum metal-matrix composites.
- Alternating bending stress
  - fatigue curves, 101(F)
- Alumina
  - aluminum metal-matrix composites, vibration damping performance, 130(F)
- Aluminum
  - as alloying element, 10(T), 11(T), 13-14
  - castability, 21
  - mechanical properties, 80(T)
  - melting point, 21
  - physical properties, 80(T)
  - recyclability, 7
  - unalloyed, 31
- Aluminum Association (AA), 7, 9
- Aluminum Association (AA) casting alloy designation system, 8-9, 10(T), 11(T)
  - digit significance, 8
  - revisions, 9
  - variations, 9, 12(T)
- Aluminum Association (AA) casting temper designation system, 9
- Aluminum carbides, 51
- Aluminum-containing peritectic elements, 15
- Aluminum-copper alloys, 13
  - aging, 65
  - composition, 13
  - corrosion resistance, 116, 120
  - mechanical properties, 13
  - permanent mold castings, 27
  - porosity, 50
- Aluminum-copper-magnesium alloys
  - aging, artificial, 65
- Aluminum-iron-chromium-manganese segregate found in die castings, 30
- Aluminum-iron-manganese phases, 16
- Aluminum-magnesium alloys, 14, 15, 16
  - anodized, 14
  - applications, 14, 20
  - castability, 14
  - corrosion resistance, 14, 120
  - die castings, 30
  - machinability, 14
  - mechanical properties, 14
  - physical properties, 14, 15
  - porosity, 49, 50
  - weldability, 14
- Aluminum metal-matrix composites (AlMMCs), 122-130(F, T)
  - anodizing, 129(T)
  - applications, 36-37, 36-37(F)
  - casting characteristics, 129(T)
  - corrosion resistance, 129(T)
  - electroplatability, 129(T)
  - elevated-temperature strength, 129(T)
  - hot cracking resistance, 129(T)
  - machinability, 129(T)
  - mechanical properties, 36, 124, 128(T)
  - nomenclature system, 9-13
  - physical properties, 124, 127(T)
  - polishability, 129(T)
  - processing, 36-37(F)
  - semisolid forming, 29
  - vibration damping performance, 125, 130(F)
  - wear resistance, 129(T)
- Aluminum nitrides, 51
- Aluminum oxides, 14, 51
- Aluminum phosphide, 16
- Aluminum-silicon alloys, 13, 15, 16, 19
  - applications, 17-19(F)
  - castability, 13
  - corrosion resistance, 13, 120
  - die castings, 30
  - fluidity, 13
  - impurities, 13
  - machinability, 13
  - mechanical properties, 13
  - permanent mold castings, 27
  - physical properties, 13
  - porosity, 50
- Aluminum-silicon-copper alloys, 13
  - applications, 17
  - castability, 13, 17
  - corrosion resistance, 17
  - machinability, 13
  - mechanical properties, 13, 17



## 326 / Aluminum Alloy Castings: Properties, Processes, and Applications

- Aluminum-silicon-copper alloys (continued)
    - porosity, 50
  - Aluminum-silicon-copper-magnesium alloys, 18-19(F)
    - applications, 18-19(F)
    - castability, 18
    - corrosion resistance, 18, 120
    - mechanical properties, 18-19
    - permanent mold castings, 27
  - Aluminum-silicon eutectic, 16
  - Aluminum-silicon eutectic modification, 34, 40-45(F, T)
  - Aluminum-silicon hypereutectic refinement, 45(F)
  - Aluminum-silicon-magnesium alloys, 14
    - aging, 65
    - castability, 14
    - coefficient of linear thermal expansion, 14
    - corrosion resistance, 14, 120
    - die castings, 18(F)
    - mechanical properties, 14
    - permanent mold castings, 27
    - premium engineered castings, 32-33
  - Aluminum spinels, 14
  - Aluminum-tin alloys, 14, 20, 34-35
    - castability, 14
    - cold working, 14
    - corrosion resistance, 14, 122
    - fatigue strength, 14
    - free-machining properties, 14
    - friction, 14
    - heat dissipation, 14
    - immiscibility, 14
    - mechanical properties, 14
    - physical properties, 14
  - Aluminum-titanium-boron refiners, 40
  - Aluminum-titanium refiners, 40
  - Aluminum-zinc alloys, 15
    - corrosion resistance, 120, 122
  - Aluminum-zinc-magnesium alloys, 14
    - aging, 64, 65-66
    - aging, artificial, 14
    - aging, natural, 14
    - annealing, 14
    - applications, 20
    - brazing, 14
    - castability, 14
    - corrosion resistance, 14
    - defects, 14
    - heat treatments, 14
    - machinability, 14
    - mechanical properties, 14
    - melting temperatures, 14
  - Aluminum-zinc-magnesium-copper alloys
    - applications, 20
  - American National Standards Institute (ANSI), 8
    - H35.5, 9
  - Anisotropy
    - absence of, 3
  - Annealed (heat treatment designation O), 9
  - Annealing, 1, 66
    - aluminum-zinc-magnesium alloys, 14
    - definition, 293
    - temperature range, 61(F)
  - Anodized coatings, 19
  - Anodizing, 16, 19, 70(T)
    - aluminum-magnesium alloys, 14
    - definition, 293
  - ANSI. *See* American National Standards Institute.
  - Antifriction, 16
  - Antimony
    - as alloying element, 13, 14
    - chemical modifier, 40, 45
  - Anti-soldering to die, 70(T)
  - Appliance industry
    - applications, 17
  - Applications
    - aluminum-magnesium alloys, 14, 20
    - aluminum metal-matrix composites, 36-37, 36-37(F)
    - aluminum-silicon-copper alloys, 17
    - aluminum-silicon-copper-magnesium alloys, 18-19(F)
    - aluminum-zinc-magnesium alloys, 20
    - aluminum-zinc-magnesium-copper alloys, 20
    - casting alloys, 1, 2-3(F)
    - premium engineered castings, 33(F), 35
    - wrought alloys, 1
  - Applied stress-intensity factor, 116
  - Architectural products industry, 14
    - applications, 17
  - Artificial aging. *See* Aging.
  - Artificially aged (heat treatment designation T), 9
  - As-cast condition, 2, 20
    - alloying element effects, 15
    - aluminum-magnesium alloys, 14
    - aluminum-silicon-copper-magnesium alloys, 18
    - aluminum-zinc-magnesium alloys, 14
    - definition, 293
    - general-purpose alloys, 17
    - mechanical properties, 13
    - residual stresses, 94, 97
  - As-fabricated (heat treatment designation F), 9
  - Aspiration, 23
  - ASTM standards, 7
    - specification designations, 12(T)
  - Atomic absorption, 67
  - A-U5GT. *See* Alloy Index, 204.0.
  - Automated molding processes, 22
  - Automation, 21
    - casting alloys, 3
  - Automotive industry
    - alloys used, 1, 2(F), 3
    - applications, 17, 18(F), 19, 20, 27, 29(F), 32, 34, 35, 36-37(F), 55(F)
    - engine emissions, 3
    - fuel efficiency, 3, 5
    - light-weighting, 3, 4(F)
    - light-weighting due to aluminum content, 4-5(F)
    - semisolid formed applications, 29
  - Averages
    - rule of, 69
  - Axial compression
    - for stress relief, 14
- ## B
- Bars
    - mechanical properties, 97
    - squeeze castings, 88
    - uniaxial tensile testing, 211, 212-242(T)
  - Bearings, 14, 16, 20, 34-35
    - aluminum-tin alloys, 14
    - heat treatment, 61
    - mechanical properties, premium engineered castings, 93(T)
  - Beryllium
    - as alloying element, 14, 15
    - content effect on premium engineered castings, 33
  - Beta phase, 65
  - Beverage processing industry, 14
    - applications, 17, 20
  - Billet, 29
  - Binder
    - definition, 293
  - Bismuth, 67
    - as alloying element, 14, 15
  - Blast cleaning
    - definition, 293
  - Blow hole, 47
    - definition, 293
  - Boiling water quenching, 149-151(F), 153(F), 161(F), 167(F), 176-178(F), 180-185(F), 187-189(F), 192(F)
    - permanent mold castings, 290(F)
  - Borides, 15

- Boron
  - as alloying element, 15, 16
- Boron treatments, 15
- Brass
  - cast using extractive metallurgy, 21
- Brazeability, 21
- Brazed parts, 20
- Brazing, 20
  - aluminum-zinc-magnesium alloys, 14
  - definition, 293
- Brazing rod
  - definition, 293
- Brazing wire
  - definition, 293
- Brinell hardness (HB), 67
  - aging response curves, 133, 134-146(F), 148-173(F)
  - casting alloys, 175, 177-180(F), 182(F), 184-190(F)
- Brittle fracture, 113
- Bronze
  - cast using extractive metallurgy, 21
- Bubble formation, 47, 48, 49, 52
- Buffing
  - definition, 293
- Bushings, 20
- C**
- Cadmium
  - as alloying element, 14, 15
  - volatilization, 15
- Calcium, 67
  - as alloying element, 13, 15
  - chemical modifier, 40, 45
- Cantilever beam cast test bars
  - for fatigue rotating beam testing, 266(F), 281(F)
- Cantilever-beam vibration tests, 69, 80(F)
- Carbides
  - grain refiners, 40
- Carcinogens
  - beryllium-containing compounds, 15
- Castability, 3, 7-8, 15, 20
  - alloying composition, 1
  - alloying element effect, 14
  - aluminum, 21
  - aluminum-magnesium alloys, 14
  - aluminum-silicon alloys, 13
  - aluminum-silicon-copper alloys, 13, 17
  - aluminum-silicon-copper-magnesium alloys, 18
  - aluminum-silicon-magnesium alloys, 14
  - aluminum-tin alloys, 14
  - aluminum-zinc-magnesium alloys, 14
  - definition, 7
  - silicon alloying effects, 16
- Castability ratings, 7
- Cast gray iron
  - aluminum metal-matrix composites, vibration damping performance, 130(F)
- Casting
  - aging response curves, 133, 134-173(F)
  - definition, 293
  - industry of the future, 4
- Casting alloys
  - advantages, 2-3(F)
  - aging response curves, 133, 134-173(F)
  - air blast quenching, 149(F)
  - anodizing, 70(T)
  - anti-soldering to die, 70(T)
  - applications, 1, 2-3(F)
  - automation, 3
  - automotive industry, 3
  - bimetal parts, 2
  - castability, 2
  - casting characteristics, 70(T)
  - composition, 5-6
  - compositions registered, 2
  - cooling in still air, 148(F)
  - corrosion resistance, 70(T)
  - cost, 1, 2, 3
  - economy of, 3
  - electroplatability, 70(T)
  - elevated-temperature strength, 70(T)
  - finishes, 2
  - finishing characteristics, 70(T)
  - fluidity, 3
  - fluidity/die filling capacity, 70(T)
  - growth curves, 175, 176-192(F)
  - hot cracking resistance, 70(T)
  - limitations, 2-3(F)
  - machinability, 2, 70(T)
  - mechanical properties, 2, 3
  - melting point, 3
  - multicomponent assemblies, 2
  - performance characteristics, 70(T)
  - physical properties, 2, 72-79(T)
  - polishability, 70(T)
  - pressure tightness, 70(T)
  - process selection, 5-6
  - quality, 2, 3
  - quenched in boiling water, 149(F)
  - quenching, 148(F)
  - selection of composition, 5-6
  - shipments (annual) in the U.S., 3
  - shrinkage, 70(T)
  - solidification characteristics, 2
  - tooling, 2
  - wear resistance, 70(T)
  - weldability, 70(T)
- Casting cavity, 26
- Casting characteristics, 70(T)
- Casting design, 21
- Casting (noun)
  - definition, 293
- Casting processes, 21-37(F)
  - altering of properties, 1
  - selection criteria, 21-22
  - technology, 22-23(F)
- Casting quality, 97, 101
- Casting strains
  - definition, 293
- Casting yield
  - definition, 293
- Cast pistons
  - fatigue, 257(F)
- Cast-to-shape fatigue specimens, 97
- Cathodic protection systems, 16
- Centrifugal casting, 28
  - applications, 28
  - definition, 293
- Ceramic shell investment casting, 25
- Characteristic process solidification rate, 16
- Chemical aggression, 50
- Chemical finishing, 15, 16, 21
- Chemically bonded sand casting, 21
- Chemical processing industry
  - applications, 120
- Chill, 24, 25-26, 32, 62
  - aluminum-copper alloys, 13
  - definition, 293
  - die casting, 27
  - rates, 106
  - vacuum riserless casting, 28
- Chill cast aluminum, 204(F)
- Chip breakers, 17
- Chopped fibers
  - designation, 13
- Chopped filaments
  - designation, 13
- Chopped monofilaments
  - designation, 13

328 / Aluminum Alloy Castings: Properties, Processes, and Applications

- Chromium
  - as alloying element, 10(T), 11(T), 15
  - effect in/out of solution on resistivity, 80(T)
  - mechanical properties, 80(T)
  - physical properties, 80(T)
- Chromium aluminide (CrAl<sub>3</sub>), 15
- Clay/water bonded sand casting, 21
- Cleaning
  - definition, 293
- Closed-loop recycling, 5
- Coating
  - insulated, 26-27
- Coefficient of thermal expansion, 16
  - alloy constants for calculation, 80(T)
  - aluminum metal-matrix composites, 124, 127(T)
  - aluminum-silicon alloys, 13
  - aluminum-silicon-magnesium alloys, 14
  - casting alloys, 2
  - die castings, 78(T)
  - elevated-temperature alloys, 19
  - permanent mold castings, 74(T), 76(T), 78(T)
  - sand castings, 72(T), 74(T)
- Cold chamber process, 21
- Cold shut
  - definition, 294
- Cold water quenching, 182-184(F), 192(F)
- Cold welding. *See* Welding, definition.
- Cold working
  - aluminum-tin alloys, 14
  - definition, 294
- Coloring
  - definition, 294
- Combination die
  - definition, 294
- Complex insoluble phases, 16
- Composite die materials, 22
- Composition, 9, 10-11(T), 10(T), 11(T), 67, 206(F), 209(F)
  - altering of properties, 1
  - beryllium addition effect, 15
- Composition biasing, 8
- Composition groupings, 13-14
- Composition limits, 8, 10-11(T), 10(T), 11(T)
- Compression yield strength
  - die castings, 91(T)
  - permanent mold castings, 90-91(T)
  - premium engineered castings, 93(T)
  - sand castings, 89-90(T)
- Compressive strength
  - aluminum-tin alloys, 14
  - sand molding parameter, 23-24
- Compressive stress-strain curves, 205(F), 209(F)
- Compressive tangent modulus
  - insulated mold castings, 195(F), 196(F), 198(F), 206(F), 208(F)
  - permanent mold castings, 195(F), 196(F), 198(F), 206(F), 208(F)
  - sand castings, 195(F), 196(F), 198(F), 206(F), 208(F)
- Compressive tangent modulus curves, 193, 195(F), 196(F), 198(F), 206(F), 208(F)
- Compressive yield strength, 20, 198(F), 207(F), 209(F)
  - aluminum-tin alloys, 14
  - insulated mold castings, 194(F), 196(F), 197(F), 205(F), 208(F)
  - permanent mold castings, 194(F), 196(F), 197(F), 205(F), 208(F)
  - sand castings, 194(F), 196(F), 197(F), 205(F), 208(F)
- Concentration limits, 8
- Condensation stain. *See* Corrosion, water stain.
- Conductivity, 15
- Confidence bands
  - rotating-beam fatigue curve, 279(F)
- Construction industry
  - applications, 17, 18
- Consumer products industry
  - alloys used, 2(F)
  - applications, 37
  - semisolid formed applications, 29
- Continuous fibers
  - designation, 13
- Continuous filaments
  - designation, 13
- Continuous monofilaments
  - designation, 13
- Controlled cooling
  - definition, 294
- Conversion coating
  - definition, 294
- Cooling curve
  - modified vs. unmodified eutectic alloy, 44-45(F)
- Cooling in still air
  - casting alloys, 148(F)
- Cooling rate, 16, 21-22, 63, 64(F)
  - during and after solidification, 1
  - altering of properties, 1
  - annealing, 66
  - tensile stress-strain curves, 204(F)
- Cope, 23, 25
- Copper
  - as alloying element, 10(T), 11(T), 13, 14, 15, 20
  - cast using shaped cavities, 21
  - content effect for high-temperature resistance, 80
  - content effect on corrosion resistance, 116, 120
  - content effect on heat treatment, 61(F)
  - effect in/out of solution on resistivity, 80(T)
  - mechanical properties, 80(T)
  - physical properties, 80(T)
  - shrinkage porosity in alloys, 50
- Copper aluminide, 65
- Copper-free aluminum-silicon alloys, 18
- CO<sub>2</sub> process
  - definition, 294
- Core
  - definition, 294
- Coring, 67
  - definition, 294
- Corrosion
  - aluminum-copper alloys, 13
  - definition, 294
  - elevated temperatures, 66
  - galvanic, definition, 294
  - intergranular, definition, 294
  - pitting, definition, 294
  - stress, definition, 294
- Corrosion. *See also* Corrosion resistance.
- Corrosion resistance, 5, 21, 70(T), 116-122, 126(T)
  - aluminum-copper alloys, 116, 120
  - aluminum-magnesium alloys, 14, 120
  - aluminum-silicon alloys, 13, 17, 120
  - aluminum-silicon-copper alloys, 17
  - aluminum-silicon-copper-magnesium alloys, 18, 120
  - aluminum-silicon-magnesium alloys, 14, 120
  - aluminum-tin alloys, 14, 122
  - aluminum-zinc alloys, 120, 122
  - aluminum-zinc-magnesium alloys, 14
  - chromium addition effect, 15
  - copper addition effects, 15
  - magnesium alloying effects, 15
  - permanent mold castings, 126(T)
  - sand castings, 126(T)
- Corrosion resistance. *See also* Corrosion.
- Cost, 22
  - aluminum-zinc-magnesium alloys, 14
  - casting alloys, 1, 3
  - heat treatment, 21
  - machining, 21
  - unit, 22
  - welding, 21
- Cost-effectiveness, 21
- Countergravity mold filling, 25
- Countergravity processes, 22
- Coupon
  - definition, 294
- Cracking, 1, 7, 17, 27, 31, 55, 67, 113-114, 116, 117(T), 122(F), 125(F)

- elevated-temperature, 44
  - stress raiser, 104
- Crack size, 114, 121(T)
- Creep, 115
  - die castings, 251(T)
  - permanent mold castings, 246-248(T), 250(T)
  - sand castings, 244-246(T), 248-250(T), 252(T)
- Creep crack growth, 116, 125(F)
- Creep crack growth rate, 116, 125(F)
- Creep rupture stress
  - die castings, 251(T)
  - permanent mold castings, 246-248(T), 250(T)
  - sand castings, 244-246(T), 248-250(T), 252(T)
- Creep rupture tests, 243-252(T)
- Critical crack-size index, 121(T), 123(T)
- Critical nucleation size, 64-65
- Critical stress-intensity factor, 113, 114, 121(T)
- Cryogenic tensile properties
  - sand castings, 224(T)
- Cure depth, 25
- Cut fibers
  - designation, 13
- Cutoff
  - definition, 294
- Cutting fluids, 17
- Cyclic hardening, 193
- Cyclic loading, 193
- Cyclic stress-strain curves, 193, 199(F), 200(F), 201(F)

## D

- Dairy industry
  - applications, 17
- Damping, 69, 80(F)
- Damping capacity, 69, 80(F)
- DC. *See* Direct chill casting.
- Decorative products industry, 14
- Defect(s), 47, 50, 55, 67, 113-115
  - aluminum-zinc-magnesium alloys, 14
  - definition, 294
  - prevention, 52
  - rotor castings, 31
  - solidification, 1
  - surface, and solidification, 1
  - wormhole, 52
  - wormhole or sponge, 50
- Deformation
  - aging for resistance to, 64
  - aluminum-tin alloys, 14
  - notch-yield ratio, 104
  - plastic, 55, 56, 66
  - postquench plastic, through compression, 61
- Degassing, 16, 49, 51
- Degree of nonequilibrium cooling, 16
- Degree of solution, 62
- Degree of superheat, 7
- Dendrite-arm regions, 52
- Dendrite arm spacing, 31, 39-40(F), 41(F)
- Dendrite cell interval, 39-40(F)
- Dendrite cell size, 39-40(F), 41(F)
- Densal II process, 56, 57(T), 59(F), 60(F)
- Dense discontinuity-free parts
  - solidification, 1
- Densification process, 55, 56
- Density, 69
  - aluminum alloying elements, 80(T)
  - aluminum metal-matrix composites, 127(T)
  - aluminum-silicon alloys, 17
  - die castings, 78(T)
  - permanent mold castings, 74(T), 76(T), 78(T)
  - sand castings, 72(T), 74(T)
- Dental equipment
  - applications, 17
- Deposition of hard, wear-resistant die surfaces, 22

- Design
  - considerations affecting process selection, 21
- Designations, 8-13(T)
- Design fatigue strength, 103, 104(F)
- Design life, 114
- Design mechanical properties, 71
  - premium engineered castings, 93(T)
- Die casting, 16, 17, 21, 22, 29-31
  - aging response curves, 143(F), 144(F), 171(F)
  - aluminum-silicon-copper alloys, 13
  - aluminum-silicon-magnesium alloys, 18(F)
  - characteristic process solidification rate, 16
  - cold chamber, definition, 294
  - cold chamber process, 30
  - cooling rate, 40
  - definition, 294
  - dendrite arm spacing, 40
  - gravity, definition, 294
  - high pressure, definition, 294
  - hot chamber, definition, 294
  - hot chamber process, 30
  - iron alloying effects, 15
  - sludge, 15
- Die casting(s)
  - aluminum metal-matrix composites, 127(T), 128(T)
  - AV, 95(T)
  - castability, 30
  - casting, finishing and performance characteristics, 70(T)
  - cracking, 30
  - definition, 294
  - density, 78(T)
  - fatigue, 283-288(F)
  - growth curves, 185-188(F)
  - HP, 95(T)
  - light vehicle change in aluminum content, 1999-2002, 4(F)
  - mechanical properties, 85(T), 88(T), 97(T), 99(T), 101, 236-240(T), 251(T)
  - minimum mechanical properties, 91(T)
  - minimum mechanical properties, published, 71
  - physical properties, 78-79(T)
  - residual stresses, 97
  - weldability, 30
- Die (in casting)
  - definition, 294
- Die number
  - definition, 294
- Dies, 30
- Die soldering, 7
- Die sticking, 15
- Dimensional stability, 19-20, 21
  - definition, 294
- Dimensional verification, 35
- Direct chill (DC) casting, 34-35, 52
  - aluminum-tin alloys, 14
- Directional solidification, 26, 27, 30, 32, 50
- Discontinuities, 116
  - design, 113, 114-115
  - limitations, 3
  - radiographic inspection for, 53-54
- Discontinuity-free parts
  - solidification, 1
- Dislocations, 64
- Dislocation tangles, 64
- Dissolved hydrogen, 31, 32, 51(T), 52
- Distortion, 19-20, 63, 64
- Double shear notch. *See* Notch, double shear.
- Downsprue, 22, 26, 34
- Draft
  - definition, 294
- Drag, 23, 25
- Drawn products
  - light vehicle change in aluminum content, 1999-2002, 4(F)
- Dry sand
  - definition, 23

### 330 / Aluminum Alloy Castings: Properties, Processes, and Applications

- Dry sand molding
  - definition, 294
- Ductility, 1, 8, 15, 17, 21, 64
  - aluminum-copper alloys, 13
  - aluminum-silicon alloys, 13
  - aluminum-silicon-copper alloys, 17
  - aluminum-silicon-copper-magnesium alloys, 18
  - aluminum-silicon-magnesium alloys, 14
  - definition, 294
  - die castings, 30
  - iron alloying effects, 15
  - permanent mold castings, 26
  - solidification, 1
  - wrought alloys, 3
- E**
- Elastic limit
  - definition, 294
- Elastic modulus. *See* Modulus of elasticity.
- Electrical conductivity, 21, 67
  - aluminum metal-matrix composites, 127(T)
  - casting alloys, 2
  - definition, 294
  - die castings, 79(T)
  - permanent mold castings, 75(T), 77(T), 79(T)
  - rotor casting alloys, 31
  - sand castings, 73(T), 75(T)
- Electrical resistivity
  - definition, 294
  - die castings, 79(T)
  - permanent mold castings, 75(T), 77(T), 79(T)
  - sand castings, 73(T), 75(T)
- Electrification industry, 1
  - alloys used, 2(F)
  - applications, 20
  - boron addition effects, 15
- Electronegative alloys, 16
- Electronics industry
  - applications, 17, 18, 25, 37
- Elements
  - effects in/out of solution on resistivity, 80(T)
- Elevated-temperature alloys, 19
  - mechanical properties, 19
- Elevated-temperature cracking, 44
- Elevated temperatures
  - aluminum-copper alloys, 13
  - aluminum-silicon-copper alloys, 13
  - casting alloys, 211
  - corrosion, 66
  - effect on mechanical properties, 71, 80
  - hot isostatic processing, 55
  - iron alloying effects, 15
  - nickel alloying effects, 16
  - rotating-beam fatigue strength, 100-101(T)
  - stability, 66
- Elevated-temperature strength, 21, 70(T)
- Eleven hinge plaster casting
  - fatigue, 281(F)
- Elongation, 17(F), 66-67, 80
  - aging response curves, 133, 134-146(F), 148-173(F)
  - aluminum metal-matrix composites, 128(T)
  - aluminum-silicon-magnesium alloys, 14
  - casting alloys, 2, 211-233(T), 234-242(T)
  - definition, 294
  - die castings, 84(T), 88(T), 91(T), 236-240(T)
  - high-integrity die castings, 92(F)
  - hot isostatic processing effect, 56, 57(T)
  - modified vs. unmodified eutectic alloys, 44(T)
  - permanent mold castings, 82-84(T), 86-88(T), 90-91(T), 94(T), 105(T), 109-110(T), 117(T), 123(T), 214(T), 218-221(T), 222(T), 229(T), 231(T), 233(T), 234-236(T)
  - premium engineered castings, 88, 92(T), 93(T), 105-106(T), 110(T), 117(T), 121(T), 123(T)
  - sand castings, 81(T), 82(T), 85-86(T), 89-90(T), 94(T), 105(T), 109(T), 113(T), 117(T), 121(T), 123(T), 212(T), 213(T), 215-218(T), 223-226(T), 228(T), 230(T), 232(T), 241(T), 242(T)
  - semisolid castings, 94(T)
  - squeeze castings, 94(T)
  - USCAR program castings, 95(T)
  - weldments, 106(T)
- Embrittlement
  - aluminum-magnesium alloys, 16
  - iron alloying effects, 15
- Endurance limit, 94
  - aluminum metal-matrix composites, 124-125, 128(T)
  - definition, 294
  - die castings, 97(T), 99(T), 101(T)
  - hot isostatic processing effect, 56, 60(F)
  - permanent mold castings, 96-97(T), 98-99(T), 100-101(T)
  - plaster mold castings, 98(T)
  - sand castings, 96(T), 98(T), 100(T)
- Energy-absorbing thin-wall cast space frames, 3
- Energy absorption, 17(F)
- Energy efficiency, 5
- Engine emissions, 3
- EPC. *See* Evaporative (lost-foam) pattern casting.
- Equilibrium phase, 65
- Euronorm designation system, 9, 12(T)
- Eutectic melting, 67
- Eutectic melting point, 62
- Eutectic modification, 16
- Eutectic modifiers, 16
- Eutectic temperature, 7
- Evaporative (lost-foam) pattern casting (EPC), 21, 24-25(F)
- Expansion, 21
- Expendable mold gravity-feed casting processes, 23-26(F)
- Expendable molds, 22
- Expendable pattern casting
  - definition, 294-295
- Extensometers
  - autographic, 211
  - with strain-transfer devices, 211
- Extractive metallurgy, 21
- Extruded products
  - light vehicle change in aluminum content, 1999-2002, 4(F)
- F**
- Families
  - of aluminum casting alloys, 13-14
- Fatigue, 115
  - casting alloys, 92-103(F, 104(F), T)
  - definition, 295
  - die castings, 283-288(F)
  - high-strength plaster castings, 269(F), 274(F), 276(F), 278(F), 280-281(F)
  - permanent mold castings, 254(F), 256-257(F), 260-261(F), 263-271(F), 274(F), 276(F), 278-279(F), 281-282(F), 286(F), 289-291(F)
  - rotating-beam fatigue curves, 253, 254-291(F)
  - sand castings, 254-256(F), 258-262(F), 267(F), 268(F), 269-279(F), 287-289(F), 291(F)
- Fatigue crack growth rate (FCGR), 115, 116, 124(F), 125(F)
- Fatigue crack growth rate (FCGR) tests, 115, 124(F)
- Fatigue endurance limit, 94, 96-97(T)
  - aluminum metal-matrix composites, 128(T)
  - premium engineered castings, 92(T)
- Fatigue life, 100-101(T)
  - hot isostatic processing effect, 56, 58(T), 59-60(F, T)
- Fatigue limit
  - casting alloys, 2
- Fatigue performance, 1
  - hot isostatic processing effect, 56, 58(T), 59-60(F, T)
- Fatigue strength, 21
  - aluminum-tin alloys, 14
  - die castings, 97(T), 101(T)
  - permanent mold castings, 96-97(T), 100-101(T)



sand castings, 96(T), 100(T)  
solidification, 1  
weldments, 102-103, 104(F)  
wrought alloys, 97, 101  
Fatigue testing, 104, 199(F), 200(F), 201(F)  
Fatigue ultimate limit  
  die castings, 84(T), 88(T)  
  permanent mold castings, 82-84(T), 86-88(T)  
  sand castings, 81(T), 82(T), 85-86(T)  
FCGR. *See* Fatigue crack growth rate.  
Federal specification designations, 12(T)  
Feeder. *See* Riser.  
Feeding, 7, 16, 34  
  iron alloying effects, 15  
Fibers  
  designation, 13  
Filaments  
  designation, 13  
Fillet  
  definition, 295  
Filtration, 28, 32, 34, 51(T)  
Finish  
  definition, 295  
Finite-element modeling, 32, 52  
Flash  
  definition, 295  
Flash line  
  definition, 295  
Flat rolled products  
  light vehicle change in aluminum content, 1999-2002, 4(F)  
Flaws, 113-115  
Flexural fatigue tests, 101  
Flow line  
  definition, 295  
Flow-measuring devices, 17, 18  
Fluid dynamics  
  solidification, 1  
Fluidity, 7, 16, 17, 70(T)  
  aluminum-silicon alloys, 13  
  casting alloys, 3  
  process selection criteria, 21  
Fluorescent penetrant inspection, 35  
Fluoroscopy  
  inclusions, 53-54  
  porosity, 53-54  
Fluxing, 32, 51  
  countercurrent, 32  
  postaddition, 41, 45  
Folds, 1  
Food processing industry, 14  
  applications, 17, 20, 120  
Forge casting. *See also* Squeeze casting; Semisolid casting.  
Forgings  
  light vehicle change in aluminum content, 1999-2002, 4(F)  
Form, 8  
Foundry product  
  designation for casting alloys, 9  
Fracture resistance, 103-114(F, 115(F), 116(F), 117(T), 118(F),  
  119-120(F, 121(T), 122(F), T)  
Fracture toughness, 112-114, 121(T), 122(F)  
  aluminum-copper alloys, 13  
  aluminum-magnesium alloys, 14  
  aluminum metal-matrix composites, 128(T)  
  definition, 295  
Fracture toughness tests, 103, 115, 116  
Free-machining  
  aluminum-tin alloys, 14  
Friction, 16  
  aluminum-tin alloys, 14  
Frontier 40E. *See* Alloy Index, 712.0.  
F temper  
  aging response curves, 133, 134-173(F)  
  designation, 62  
Fuel consumption, 3  
Fuel efficiency, 3, 4(F), 5

Fuel regulation industry  
  applications, 17, 18, 19

## G

Gas fluxing, 32, 41, 45, 49, 51  
Gas porosity  
  definition, 295  
Gate  
  definition, 295  
Gated patterns  
  definition, 295  
Gating system, 22-23(F), 34, 50-53  
  aluminum-magnesium alloys, 14  
  aluminum metal-matrix composites, 36  
Christmas-tree systems, 25  
  definition, 295  
  die castings, 27  
  gravity-based, 30  
  investment casting, 25-26  
  permanent mold castings, 22(F), 26  
  sand mold castings, 22(F), 24  
Gating system. *See also* Runner system.  
General-purpose alloys, 17-19(F)  
Germination, 15  
Gold  
  cast using shaped cavities, 21  
GP  
  theta transition phase, 65  
GP. *See* Guinier-Preston zone.  
Grain growth, 15  
Grain refinement, 16-17, 31, 34, 40, 41(F), 50  
  aluminum-copper alloys, 13  
  boron-containing compounds, 15  
Grain refiner  
  definition, 295  
Grain size  
  definition, 295  
Grain structure  
  wrought alloys, 3  
Gravimetric separation, 50  
Gravity-based gating, 30  
Gravity casting, 7, 15, 16, 17, 34  
  aluminum metal-matrix composites, 36  
  castability components, 7  
  grain refinement, 40  
  sludge, 15  
Gravity feed casting processes, 26-29(F)  
Gravity segregation  
  aluminum-tin alloys, 14  
Green sand  
  definition, 23, 295  
Green sand, shell casting  
  cooling rate, 40  
  dendrite arm spacing, 40  
Green sand molding  
  definition, 295  
Groove welds, 119-120(T)  
Gross to net weight ratio  
  definition, 295  
Growth  
  definition, 69  
Growth curves, 175, 176-192(F)  
Growth factor, 175, 176-192(F)  
Guinier-Preston (GP) zone, 64, 65

## H

Hall-Heroult electrolytic reduction process, 1  
Hardener  
  definition, 295

### 332 / Aluminum Alloy Castings: Properties, Processes, and Applications

- Hardening
    - room-temperature, 20
  - Hardness, 20, 21
    - aging response curves, 135-136(F), 138(F), 140-143(F), 145-146(F), 148-158(F), 161-173(F)
    - alloying element effects, 15
    - aluminum-copper alloys, 13
    - aluminum metal-matrix composites, 128(T)
    - aluminum-silicon-copper alloys, 17
    - aluminum-silicon-copper-magnesium alloys, 18
    - aluminum-tin alloys, 14
    - aluminum-zinc-magnesium alloys, 14
    - beryllium addition effect, 15
    - casting alloys, 2
    - definition, 295
    - die castings, 84(T), 88(T)
    - elevated-temperature alloys, 19
    - permanent mold castings, 82-84(T), 86-88(T)
    - sand castings, 81(T), 82(T), 85-86(T)
    - tensile stress-strain curves, 204(F)
  - Hardness testing, 175, 177-180(F), 182(F), 184-190(F)
  - HB. *See* Brinell hardness.
  - Head. *See also* Riser.
  - Heat checking
    - mold, 22
  - Heat-flow equilibrium, 52
  - Heat flux, 7
  - Heat treatable alloy
    - definition, 295
  - Heat treating, 9, 15, 17, 19-20, 61-68(F), 202(F), 203(F)
    - altering properties, 1
    - aluminum-copper alloys, 13
    - aluminum-magnesium alloys, 14
    - aluminum-silicon-copper alloys, 13
    - aluminum-silicon-copper-magnesium alloys, 18
    - aluminum-silicon-magnesium alloys, 18
    - aluminum-tin alloys, 14
    - aluminum-zinc-magnesium alloys, 14
    - copper alloying effects, 15
    - corrosion resistance, 120
    - cost, 21
    - definition, 295
    - high-integrity die castings, 92
    - insulated mold castings, 194-198(F), 205-208(F)
    - permanent mold castings, 194-198(F), 205-208(F)
    - problem diagnosis and acceptance criteria, 66-67
    - sand castings, 194-198(F), 205-208(F)
    - stepped, 62
    - temperature ranges, 61(F)
  - Heat treat stain
    - definition, 295
  - Heat-up times, 150(F)
  - Heavy metals, 14
  - Hiduminium. *See* Alloy Index, 203.0.
  - Hiduminium 350. *See* Alloy Index, 203.0.
  - High-definition detailing, 17
  - High-integrity die casting, 91-92(F)
  - High-integrity pressure die casting, 31
  - High-intensity infrared light
    - bonding, 22
  - High-pressure molding
    - definition, 295
  - High-silicon casting alloys
    - weldments, 112
  - High-speed molding machines, 22
  - High-strength alloys, 20
    - applications, 20
  - High-strength aluminum alloy castings
    - requirements, 84
  - High-strength plaster casting(s)
    - fatigue, 269(F), 274(F), 276(F), 278(F), 280-281(F)
  - High-temperature aging response curves, 146-173(F)
  - High-temperature oxidation, 47, 67
  - Highway construction industry, 17(F)
  - HIP. *See* Hot isostatic pressing; Hot isostatic processing.
  - History of aluminum castings, 1-2
  - Holding temperature
    - definition, 295
  - Holes, 101
  - Hot cracking
    - definition, 295
    - resistance to, 7, 70(T)
  - Hot isostatic pressing (Hot isostatic processing) (HIP), 1, 37, 55
  - Hot isostatic processing (Hot isostatic pressing) (HIP), 55-60(F, T)
    - fatigue performance affected, 56, 58(T), 59-60(F, T)
    - permanent mold castings, 55, 56, 57(T)
    - radiographic inspection, 56, 58, 60(F)
    - sand castings, 55
  - Hot shortness, 17, 24, 27
    - aluminum-silicon-copper alloys, 13
    - aluminum-tin alloys, 14
    - definition, 295
  - Hot tearing, 16
    - aluminum-zinc-magnesium alloys, 14
    - copper alloying effects, 15
    - iron alloying effect, 15
    - process selection criteria, 21
  - Humidity
    - hydrogen porosity, 49
  - Hydraulic injection systems, 21
  - Hydrogen
    - content in aluminum alloys, 16
    - solubility, 34, 51
    - solubility in aluminum alloys, 47(F), 48
  - Hydrogen contamination sources, 49
  - Hydrogen pore formation, 1
  - Hydrogen porosity, 1, 41, 44, 47-49(F), 51-52, 53(F), 67
  - Hydrogen precipitation, 29, 47-49, 51, 52, 55
  - Hydrogen threshold, 48
  - Hygroscopic salts, 41
  - Hypereutectic alloys, 16
  - Hypereutectic silicon alloys, 13
  - Hypoeutectic alloys, 16
  - Hypoeutectic aluminum-silicon alloys, 13
  - Hypoeutectic aluminum-silicon-copper alloys, 13
  - Hysteresis loops, 193
- ## I
- Immiscibility
    - aluminum-tin alloys, 14
  - Impact resistance, 17(F)
  - Impacts
    - light vehicle change in aluminum content, 1999-2002, 4(F)
  - Impact strength, 21
  - Impellers, 17-19, 25, 26(F), 32, 34
    - requirements, 84-85
  - Impregnation, 21
    - aluminum metal-matrix composites, 36
    - definition, 295
    - die castings, 30
  - Impurities, 7-8, 8, 67
    - aluminum-copper alloys, 13
    - aluminum-silicon alloys, 13
    - limits, 8
    - premium engineered castings, 33
  - Inclusions, 50-51(T), 52(F), 67
    - aluminum-magnesium alloys, 14
    - beryllium additions, 15
    - boron additions, 15
    - definition, 295
    - die castings, 27
    - homogeneous halide salts, 51(T)
    - nonmetallic, 47, 50, 51(T)
    - particle/salt, 51(T)
    - sources and types, 51(T)
  - Inclusions. *See also* Nonmetallic inclusions.
  - Induction melting, 51
  - Inert gas fluxing, 41, 45, 49
  - In-feeds, 26



Infrared light  
  bonding, 22  
In-gate, 23, 24  
  definition, 295  
Ingot, remelt  
  definition, 295  
Injection  
  definition, 295  
Injection under pressure, 22  
Inoculant  
  definition, 295  
Insert  
  definition, 295  
In situ bonding of dissimilar materials, 22  
Insoluble phases, 62  
Inspection lot. *See* Lot, inspection.  
Instability, 15  
Insulated mold casting(s), 194-198(F), 205-208(F)  
Intercrystalline corrosion. *See also* Corrosion, intergranular.  
Interdendritic feeding, 50  
Interdendritic shrinkage  
  aluminum-copper alloys, 13  
Intermetallic phases, 15, 39  
Intermetallics  
  boride contribution, 15  
  coarse, formation of, 14  
  constituents, 8  
  insoluble, 62  
  iron-containing, 15  
Internal soundness, 1  
Internal voids, 1  
International Casting Alloy Designations, 9, 12(T)  
Investment casting, 16, 21, 24-26  
  characteristic process solidification rate, 16  
  cooling rate, 40  
  dendrite arm spacing, 40  
  hot isostatic processing, 59(T)  
  low-volume, 22  
  molds used, 22  
  solution heat treatment, 62  
Investment casting. *See also* Investment molding.  
Investment casting(s)  
  aluminum metal-matrix composites, 127(T), 128(T)  
  applications, 26  
  minimum mechanical properties, 93(T)  
Investment molding, 204(F)  
  definition, 295-296  
Iron  
  as alloying element, 10(T), 11(T), 14-15, 18  
  cast using extractive metallurgy, 21  
  content effect on notch toughness, 106  
  content effect on premium engineered castings, 33  
  content effect on rotor casting, 31  
  content in casting alloys, 8  
  content in die castings, 30  
  deposition in metallurgical bonding, 36  
  dies, 21  
  effect in/out of solution on resistivity, 80(T)  
  isomorphous with manganese, 16  
  mechanical properties, 80(T)  
  molds, 21  
  physical properties, 80(T)  
  shrinkage porosity in alloys, 50  
Isomorphous elements, 16  
ISO specification designations, 12(T)

## J

Jobbing die casters, 21  
Joint strength efficiency  
  weldments, 106(T)

## K

K01. *See* Alloy Index, 201.0.

## L

Lamellar eutectic, 14  
Lamellar structure, 41-42(F)  
Lasers  
  bonding, 22  
Layered feeding, 52  
Layout sample  
  definition, 296  
Lead, 67  
  as alloying element, 15  
Lead-base alloys, 21  
Level pour process, 34, 35  
Life-cycle analysis  
  recycling, 5  
Light emission spectroscopy, 67  
Light-weighting, 3, 4  
  vehicle change, North America, 1973-2002, 4-5(F)  
Linear elastic fracture mechanics, 113  
Liquid metal forging. *See also* Squeeze casting.  
Liquid-solid mushy zones, 52  
Liquidus, 7  
Lithium  
  effect in/out of solution on resistivity, 80(T)  
Locking pressure, 30  
Log decrement of decay, 69  
Loose patterns, 22  
Lost foam (evaporative pattern) casting, 21, 24-25(F), 95(T)  
  definition, 296  
Lost foam (evaporative pattern) casting(s)  
  light vehicle change in aluminum content, 1999-2002, 4(F)  
Lot, heat treat  
  definition, 296  
Lot, inspection  
  definition, 296  
Low-expansion alloys, 19  
Low-pressure (LP) casting  
  definition, 296  
  die casting, 27-28(F)  
  permanent mold, 21  
LP. *See* Low-pressure casting.  
Lubrication, 20, 30, 31

## M

Machinability, 2, 16, 19-21, 64, 70(T)  
  aluminum-magnesium alloys, 14  
  aluminum-silicon alloys, 13, 17  
  aluminum-silicon-copper alloys, 13, 17  
  aluminum-tin alloys, 14  
  aluminum-zinc-magnesium alloys, 14  
  annealed condition, 66  
  bismuth-containing compounds, 15  
  cadmium addition effect, 15  
  lead alloying effects, 15  
Machinery parts, 18-20  
Machining  
  cost, 21  
  finish, 2  
Magnesium  
  as alloying element, 10-11(T), 13-15  
  content in casting alloys, 8  
  content restriction in die castings, 30  
  die casting, 30  
  effect in/out of solution on resistivity, 80(T)  
  mechanical properties, 80(T)  
  modulus of elasticity, 69  
  oxidation, 50

### 334 / Aluminum Alloy Castings: Properties, Processes, and Applications

- Magnesium (continued)
    - physical properties, 80(T)
  - Magnesium oxides, 14, 51
  - Magnesium oxide spinels, 14
  - Magnesium silicides, 15, 16, 65
  - Major alloying elements, 8
  - Manganese
    - as alloying element, 10-11(T), 15-16
    - effect in/out of solution on resistivity, 80(T)
    - isomorphous with iron, 16
    - mechanical properties, 80(T)
    - physical properties, 80(T)
  - Manganese aluminide, 16
  - Marine exposure, 16
    - aluminum-magnesium alloys, 14
  - Markets for aluminum applications, 1-2
  - Mass feeding, 50
  - Master alloy. *See* Hardener.
  - Material costs, 21
  - Matrix-hardening alloys, 19
    - aluminum-silicon-copper alloys, 13
  - Matrix softening, 15
  - Mechanical agitation
    - aluminum-tin alloys, 14
  - Mechanical densification, 55
  - Mechanical performance, 1
  - Mechanical properties, 85-88(T)
    - altering of, 1
    - definition, 296
    - die castings, 85(T)
    - minimum values, 71, 81-88(T)
    - permanent mold castings, 82-84(T)
    - process selection criteria, 21
    - sand castings, 81-82(T)
  - Medical equipment, 17
  - Melting point
    - aluminum, 21
    - aluminum-zinc-magnesium alloys, 14
    - casting alloys, 3
  - Melting range
    - aluminum metal-matrix composites, 127(T)
    - die castings, 78(T)
    - permanent mold castings, 74(T), 76(T), 78(T)
    - sand castings, 72(T), 74(T)
  - Melt refinement practices, 45
  - Mercosil. *See* Alloy Index, 391.0; A391.0; B391.0.
  - Mercury
    - as alloying element, 16
  - Metal casting
    - history, 21
  - Metallic borides, 15
  - Metallography, 53
  - Metallurgical bonding, 35-36
  - Metal-matrix composites (MMCs)
    - mechanical properties, 20
    - nomenclature system, 9-13
  - Metal-matrix composites (MMCs). *See also* Aluminum metal-matrix composites.
  - Microporosity, 52, 55
    - definition, 296
  - Microradiography, 53
  - Microsegregation, 62, 67
    - magnesium-zinc phases, 14
  - Microshrinkage, 31, 50
  - Microstructure, 19, 39-46(F, T)
    - alloying element effect, 14
    - aluminum-silicon alloys, 13
    - embrittlement, 15
    - internal features, 3
    - phases, alloying composition, 1
  - Military parts industry, 18
    - semisolid formed applications, 29
  - Military specification designations, 12(T)
  - Minor alloying elements, 8
  - Misrun(s), 1, 41
    - definition, 296
    - tendencies, 16
  - Mixed scrap, 5
  - MMC. *See* Metal-matrix composites.
  - Moderate-strength alloys with low residual stresses, 19-20
  - Modification
    - definition, 296
    - levels, 16
  - Modulus of elasticity, 69
    - aluminum alloying elements, 80(T)
    - aluminum metal-matrix composites, 124, 128(T)
    - casting alloys, 2, 212-218(T), 222-223(T), 225(T), 227-236(T), 240-242(T)
    - definition, 296
    - die castings, 84(T), 88(T), 236(T), 240(T)
    - permanent mold castings, 82-84(T), 86-88(T), 214(T), 218(T), 222(T), 225(T), 229(T), 231(T), 233-236(T)
    - sand castings, 81-82(T), 85-86(T), 212-213(T), 215-218(T), 223(T), 225(T), 228(T), 230(T), 232(T), 241-242(T)
  - Moisture reactions, 1
  - Mold cavity, 29
    - definition, 296
  - Mold(s)
    - definition, 296
    - expendable, 22
    - nonexpendable, 22
  - Monocoque assemblies, 3
  - Monofilaments
    - designation, 13
  - Monotonic stress-strain curves, 199-201(F), 204(F)
  - Moore type rotating-beam fatigue machine, 253
  - Multicomponent welded or joined assemblies, 2, 3(F)
  - Multiple cavity mold
    - definition, 296
- ## N
- Natural aging. *See* Aging.
  - Natural aging response curves, 133-146(F)
  - Near-net-shape forming, 29, 204(F)
    - aluminum metal-matrix composites, 36
    - dies, 22
    - premium engineered castings, 88
  - Near-net-shape parts
    - casting alloys, 2
  - New scrap, 5
  - Nickel
    - as alloying element, 10-11(T), 13-16
    - effect in/out of solution on resistivity, 80(T)
    - mechanical properties, 80(T)
    - physical properties, 80(T)
    - shrinkage porosity in alloys, 50
  - Nomenclature, 8
  - Nondestructive testing, 35, 53-54, 115
    - definition, 296
  - Nonexpendable casting processes, 26-29(F)
  - Nonexpendable molds, 22
  - Nonfill
    - definition, 296
  - Non-heat-treatable alloy
    - definition, 296
  - Notches, 101
  - Notch sensitivity, 103-115(F, T)
  - Notch-strength ratio, 104
    - permanent mold castings, 105(T), 109-110(T)
    - premium engineered castings, 105-106(T), 110(T)
    - sand castings, 105(T), 109(T)
    - weldments, 106(T)
  - Notch tensile strength, 103, 104
    - permanent mold castings, 105(T), 109-110(T)
    - premium engineered castings, 105-106(T), 110(T)
    - sand castings, 105(T), 109(T), 113(T)
    - weldments, 106(T)
  - Notch tensile testing, 104
  - Notch toughness, 103-115(F, T)

definition, 296  
permanent mold castings, 107, 109-110(T), 111(F)  
premium engineered castings, 107, 110(T), 111(F)  
sand castings, 107, 109(T), 111(F)  
subzero temperatures, 107-114(F, T)  
Notch toughness tests, 105-106(T), 109-110(T), 113(T)  
Notch-yield ratio (NYR), 104, 106(T), 108(F), 114(F), 115(F)  
definition, 296  
permanent mold castings, 105-107(F, 109-112(F, 122-123(F, T)  
premium engineered castings, 105-107(F, 110-112(F, 123(T), T)  
sand castings, 105-107(F, 109(T), 111-112(F), 122-123(F, T)  
weldments, 106(T)  
NYR. *See* Notch-yield ratio.

## O

Offset  
definition, 296  
Old scrap, 5  
Olivine, 24  
Optical systems, 20  
O temper, 66  
designations, 62  
Outgassing, 58  
Overaging, 66, 67  
Overmodification, 16  
Oxidation, 30, 50-51  
alloying element effects, 15  
Oxidation rates  
aluminum-magnesium alloys, 14  
Oxide discoloration  
definition, 296  
Oxide removal, 51

## P

Particles  
designations, 13  
Particulates  
designations, 13  
Parting plane, 23  
Passivation, 16  
Pattern(s), 24  
definition, 296  
Penetrant inspection, 7  
Percent liquid in solidification range, 16  
Performance capabilities  
alloying composition, 1  
Performance characteristics, 70(T)  
Performance testing, 1  
Permanent mold casting, 1-2, 16, 22, 26-27(F)  
aging response curves, 134-141(F), 145-148(F), 150(F), 152-164(F),  
166-170(F)  
characteristic process solidification rate, 16  
cooling rate, 40  
definition, 296  
dendrite arm spacing, 40  
expendable or gravity, 22  
gating system, 22(F)  
modification effect on mechanical properties, 44(T)  
molds used, 22  
washes or dressings, 27  
Permanent mold casting(s), 21, 194-201(F), 205-208(F)  
aluminum-copper alloys, 13  
aluminum metal-matrix composites, 127(T), 128(T)  
aluminum-silicon-copper alloys, 13  
aluminum-silicon-copper-magnesium alloys, 18  
aluminum-tin alloys, 14  
bars, mechanical properties, 247(T)  
boiling water quenching, 290(F)  
casting characteristics, 70(T)  
corrosion resistance, 126(T)

density, 74(T), 76(T), 78(T)  
elevated-temperature alloys, 19  
fatigue, rotating-beam reversed-bending, 254(F), 256-257(F),  
260-261(F), 263-271(F), 274(F), 276(F), 278-279(F), 281-282(F),  
286(F), 289-291(F)  
finishing characteristics, 70(T)  
growth curves, 176-192(F)  
hardness curves, 176-180(F), 182(F), 184-190(F)  
hot isostatic processing, 55, 56, 57(T), 58(T), 60(F)  
light vehicle change in aluminum content, 1999-2002, 4(F)  
mechanical properties, 82-84(T), 86-88(T), 94(T), 96-99(T),  
105-110(F, 112(F), 117-118(F, 123(T), 214(T), 218-222(T),  
225(T), 229(T), 231(T), 233-236(T), 246-248(T), 250(T), T)  
minimum mechanical properties, 90-91(T), 93(T)  
performance characteristics, 70(T)  
physical properties, 74-78(T)  
radiographic inspection standards, 54  
solution heat treatment, 62  
unit propagation energy, 117(T), 118(F), 119-120(T), 123(T)  
Permeability  
sand molding parameter, 23-24  
Pewter, 21  
Phases  
beta, 65  
equilibrium, 65  
formation, 8  
insoluble, 67  
intermetallic, 39  
Phosphorus  
as alloying element, 13, 14, 16  
content effect on modification mechanism, 44, 45(F)  
Physical properties  
altering of, 1  
casting alloys, 72-79(T)  
definition, 296  
process selection criteria, 21  
Plane strain  
definition, 296  
Plane-strain fracture toughness, 103, 114, 121(T), 122(F)  
aluminum metal-matrix composites, 125  
permanent mold castings, 123(T)  
premium engineered castings, 123(T)  
sand castings, 123(T)  
Plane-strain fracture toughness tests, 121(T)  
Plaster cast Elevon hinge casting  
fatigue, rotating-beam reversed-bending, 281(F)  
Plaster casting, 16, 25, 26(F)  
characteristic process solidification rate, 16  
molds used, 22  
Plaster mold casting, 21  
Plaster mold casting(s)  
mechanical properties, 98(T)  
Plaster molding, 32  
Plate  
hot isostatic processing, 60(F)  
stress-strain curves, 206(F), 209(F)  
thick, die casting, 185-188(F)  
Pneumatic injection systems, 21  
Poisson's ratio  
aluminum metal-matrix composites, 127(T)  
die castings, 79(T)  
permanent mold castings, 75(T), 77(T), 79(T)  
sand castings, 73(T), 75(T)  
Polishability, 70(T)  
Polishing  
aluminum-magnesium alloys, 14  
Pore-free pressure die casting, 31  
Pore volume fraction, 1  
Porosity, 15, 16, 41, 44, 55, 56, 114  
definition, 297  
degrees of, 101  
hydrogen, 1  
internal, 1, 47-54(F, 56, 58, T)  
secondary (micron-size), 47  
semisolid forming, 29

### 336 / Aluminum Alloy Castings: Properties, Processes, and Applications

Porosity (continued)  
  shrinkage, 49-50(F)  
Postsolidification cooling rate, 39  
Postsolidification cracking, 7  
Postsolidification densification  
  altering properties, 1  
Postsolidification thermal treatment, 1  
Powder metallurgy composites, 36(F)  
  aluminum metal-matrix composites, 36  
PRC. *See* Pressure riserless casting.  
Precedent 71. *See* Alloy Index, 771.0; 772.0.  
Precedent 71A. *See* Alloy Index, 771.0.  
Precedent 71B. *See* Alloy Index, 772.0.  
Precipitation  
  boride addition effects, 15  
Precipitation aging, 1  
Precipitation hardened (heat treatment designation), 9  
Precipitation hardening, 16, 19, 64-66, 133  
  aluminum-tin alloys, 14  
Precipitation hardening. *See also* Aging.  
Precipitation heat treating, 64-66  
  temperature range, 61(F)  
Precipitation heat treating. *See also* Aging.  
Precipitation softening, 133  
Premium engineered casting, 101  
Premium engineered casting(s), 31-33(F)  
  aircraft applications, 84, 88  
  applications, 33(F), 35  
  definition, 31  
  impurities, 33  
  mechanical properties, 32-33, 84, 88, 92-93(T), 105-108(F, 110(T), 112(F), 114, 117-118(F, 120-121(F, 123(T), T)  
  microstructure, 31  
  molds and alloy materials, 32-33(F), 34-35  
  quality assurance, 32, 35  
  unit propagation energy, 117(T), 118(F), 123(T)  
Premium quality casting(s). *See* Premium engineered casting(s).  
Pressure die casting, 1-2, 16, 21, 29-31  
Pressure die casting(s), 22, 23  
  castability, 7  
Pressure drop, 50  
Pressure riserless casting (PRC), 27-28(F)  
Pressure tightness, 17, 21, 70(T)  
Print type, 21  
Process-optimization procedures, 5  
Process yield, 21  
Procurement specifications, 7  
Producer variation (heat treatment designation Padded), 9  
Product form, 8  
Productivity, 21  
Prolongation  
  definition, 297  
Proprietary designations, 8, 9, 12(T)  
Prototypes, 22  
Pump impellers, 17  
Purity, 15

## Q

Quality, 22, 30, 97, 101  
  assurance, sand castings, 23-24  
  casting alloys, 2, 3, 4  
  definition, 22, 297  
  premium engineered castings, 35  
Quality control, 53  
  premium engineered castings, 32, 35  
  procedures, 5  
  sand castings, 24  
Quenchant temperature, 63, 67  
Quench crack  
  definition, 297  
Quench delay, 62-63, 67  
Quench delay limit, 62  
Quenched (heat treatment designation), 9

Quenching, 62-64(F), 66  
  air blast, 149(F)  
  boiling water, 149-151(F), 153(F), 161(F), 167(F), 176-178(F), 180-185(F), 187-189(F), 192(F)  
  boiling water, permanent mold castings, 290(F)  
  casting alloys, 148-151(F), 153-155(F), 159-160(F)  
  chromium content effect, 15  
  cold water, 182-184(F), 192(F)  
  corrosion resistance, 120  
  definition, 297  
  fan or mist, 63-64  
  in 110°F water, 148(F), 154-155(F), 159-160(F), 166(F), 168(F)  
  in 150°F water, 150(F), 167-170(F)  
  in 200°F water, 163(F)  
  inadequate, 67  
  mechanical properties affected, 64  
  quenchant additions, 63  
  residual stresses, 66  
  in room-temperature water, 160(F)  
  solutions, 63  
  water, 194-198(F), 202-203(F), 205-208(F)  
  with water, 19

## R

Radiographic inspection, 7, 35  
  definition, 297  
  hot isostatically pressed castings, 56, 58, 60(F)  
  inclusions, 52-54  
  porosity, 52-54  
Radiography  
  definition, 297  
Ramberg-Osgood parameter, 198(F), 207(F), 209(F)  
Rapid solidification, 14, 16, 34  
Recovery rate, 5  
Recycling, 5, 17  
  aluminum, 7  
  market growth, 2  
Reduced section tensile strength  
  permanent mold castings, 119-120(T)  
  sand castings, 119(T)  
Reduction in area  
  casting alloys, 224(T)  
  permanent mold castings, 105(T), 109-110(T)  
  premium engineered castings, 105-106(T), 110(T)  
  sand castings, 105(T), 109(T), 113(T), 224(T)  
  USCAR program castings, 95(T)  
  weldments, 106(T)  
Red X-8. *See* Alloy Index, 328.0.  
Refinement, 50, 67  
  definition, 297  
Refiners, 40-46(F, T)  
Reheat treatment, 56, 58  
Reinforcement  
  composition designated in metal-matrix composites, 13  
  type of, designation, 13  
Reinforcement designation, 13  
Remelt, 49  
  ingot form, 8  
Remelted scrap, 7  
Representative values  
  uniaxial tensile tests, 211  
Research and development, 1-4  
Residual life, 114  
Residual stresses, 62-64, 66(F)  
  as-cast surface, 94, 97  
  die castings, 97  
Resolution heat treatment, 67-68  
Reversed-bending fatigue curves, 98-99(T)  
Rheocasting, 21  
Rheocasting/thixocasting, 21  
Riser  
  definition, 297  
Rising, 22-23(F), 49, 50, 52  
  aluminum-magnesium alloys, 14

die casting, 30  
investment casting, 25  
premium engineered castings, 34, 35  
Risers, 22-23(F), 26  
  die casting, 27  
Rocker arms, 88  
Rod  
  permanent mold casting, 176-190(F)  
  sand casting, 185(F), 188(F)  
Room temperature  
  aging response curves, 133, 134-146(F)  
  casting alloys, 211  
  water quenching, 160(F)  
Room-temperature aging response curves, 133-146(F)  
Rotary degassing, 51  
Rotating beam fatigue life, 56, 59(F)  
Rotating-beam fatigue strength, 92, 96(T)  
  die castings, 101(T)  
  permanent mold castings, 100-101(T)  
  sand castings, 100(T), 101, 103(F)  
Rotating-beam reversed-bending fatigue, 92  
Rotating-beam reversed-bending fatigue curves, 253, 254-291(F)  
Rotating bending fatigue S-N curves, 56, 60(F)  
Rotor alloys, 15  
Rotor casting, 31  
Rotors, 34, 36(F), 84-85  
  die casting application, 30  
Round-robin test program, 204(F)  
Rule of averages, 69  
Runner(s), 23, 24, 26, 30, 34  
  definition, 297  
Runner system  
  definition, 297  
Rupture stress  
  die castings, 251(T)  
  permanent mold castings, 246-248(T), 250(T)  
  sand castings, 244-246(T), 248-250(T), 252(T)

**S**

Sacrificial anodes, 16  
SAE. *See* Society of Automotive Engineers.  
Sample  
  definition, 297  
Sand casting  
  cooling rate, 40  
  dendrite arm spacing, 40  
  dry sand, 23-24  
  green sand, 23-24  
  molds used, 22  
Sand casting(s), 1-2, 16, 21, 194-198(F), 205-208(F)  
  aging response curves, 134-138(F), 140(F), 144-145(F), 148-153(F),  
    160-161(F), 163-165(F), 168(F), 170(F), 172-173(F)  
  aluminum metal-matrix composites, 127(T), 128(T)  
  aluminum-silicon alloys, 13  
  aluminum-silicon-copper-magnesium alloys, 18  
  aluminum-tin alloys, 14  
  casting characteristics, 70(T)  
  characteristic process solidification rate, 16  
  corrosion resistance, 126(T)  
  definition, 297  
  fatigue, rotating-beam reversed-bending, 254-256(F), 258-262(F),  
    267-279(F), 287-289(F), 291(F)  
  finishing characteristics, 70(T)  
  growth curves, 185(F), 188(F)  
  hardness testing, 185(F), 188(F)  
  hot isostatic processing, 55, 56, 58(T), 60(F)  
  light vehicle change in aluminum content, 1999-2002, 4(F)  
  mechanical properties, 81-82(T), 85-86(T), 94(T), 96(T), 98(T), 101,  
    105-109(F), 112-114(F), 117-118(F), 120-121(F), 123(T),  
    212-213(T), 215-218(T), 223-226(T), 228(T), 230(T), 232(T),  
    241-242(T), 244-246(T), 248-250(T), 252(T), T)  
  minimum mechanical properties, 89-90(T), 93(T)  
  modification effect on mechanical properties, 44(T)

performance characteristics, 70(T)  
physical properties, 72-75(T)  
porosity, 52  
radiographic inspection standards, 54  
solution heat treatment, 62  
unit propagation energy, 119(T)  
Sand mold  
  definition, 297  
Sand mold casting  
  gating system, 22  
Sand molding, 24  
SCC. *See* Stress-corrosion cracking.  
Scrap, 17  
  recovery rates, 5  
Seawater corrosion, 16  
  aluminum-magnesium alloys, 14  
Sectioning, 53  
Segregate precipitation, 30  
Semipermanent mold casting, 26  
Semisolid casting  
  definition, 297  
Semisolid casting. *See also* Semisolid forming.  
Semisolid casting(s), 95(T), 101  
  light vehicle change in aluminum content, 1999-2002, 4(F)  
  mechanical properties, 91, 94(T)  
Semisolid forming, 21, 29(F)  
  aluminum metal-matrix composites, 29  
Semisolid forming. *See also* Semisolid casting.  
Shaped castings  
  solidification, 1  
Shear strength  
  casting alloys, 2  
  definition, 297  
Shear ultimate strength  
  die castings, 84(T), 88(T), 91(T)  
  permanent mold castings, 82-84(T), 86-88(T), 90-91(T)  
  premium engineered castings, 93(T)  
  sand castings, 81-82(T), 85-86(T), 89-90(T)  
Shell cores  
  definition, 297  
Shell molding, 21  
  definition, 297  
Shell mold process, 25(F)  
  definition, 297  
Shot chamber, 30, 31  
Shot cycle, 23  
Shrinkage, 1, 47-48, 67, 70(T)  
  aluminum-copper alloys, 13  
  aluminum-zinc-magnesium alloys, 14  
  definition, 297  
  displacement, 50  
  interdendritic, 15  
  internal, 7, 55  
  premium engineered castings, 34  
  process selection criteria, 21  
  rotor castings, 31  
  volumetric, 22-23  
Shrinkage porosity, 16, 49-50(F), 51-52, 56  
Silafont-36. *See* Alloy Index, 365.0  
Silicon  
  as alloying element, 10(T), 11(T), 13, 14, 16, 17-19(F), 20  
  content effect in rotor casting, 31  
  content effect on aluminum metal-matrix composite plane-strain  
    fracture toughness, 125  
  content effect on castability, 7  
  content effect on corrosion resistance, 120  
  content effect on modification mechanism, 40-41, 44, 45  
  effect in/out of solution on resistivity, 80(T)  
  mechanical properties, 80(T)  
  physical properties, 80(T)  
Silicon carbide (SiC) particulate  
  aluminum metal-matrix composites, 124  
Silver  
  as alloying element, 13, 16  
  cast using shaped cavities, 21



### 338 / Aluminum Alloy Castings: Properties, Processes, and Applications

- Simple patterns, 22
  - Sintered carbide tools, 17
  - Size
    - casting alloys, 3
  - Sludging, 15, 30
  - Smelted aluminum, 7, 51
  - Society of Automotive Engineers (SAE) specification designations, 12(T)
  - Sodium, 67
    - as alloying element, 13, 14, 16
    - chemical modifier, 40-44(F, 45, T)
    - content in premium engineered castings, 34
    - as eutectic modifier, 16
  - Sodium chloride, 41
  - Sodium fluoride, 41
  - Softening, 133
  - Soldering, 15
  - Solid feeding, 50
  - Solidification, 7, 21-22, 32
    - altering properties, 1
    - cooling rate, 1
    - limitations, 3
    - mechanics, 1
  - Solidification cracking, 7, 16
    - aluminum-copper alloys, 13
  - Solidification rate, 16, 32, 39(F), 40
    - aluminum-silicon alloys, 13
    - aluminum-tin alloys, 14
  - Solid mold investment casting, 25
  - Solid-solution effects
    - alloying composition, 1
  - Solid-state coefficient of thermal contraction, 49
  - Solution heat treated (heat treatment designation), 9
  - Solution heat treating, 1, 62
    - aging response curves, 133, 134-173(F)
    - aluminum-zinc-magnesium alloys, 14
    - definition, 297
    - high-integrity die casting, 92
    - temperature range, 41(F)
    - tensile stress-strain curves, 202-203(F)
  - Solution potentials, 62, 126(T)
  - Soundness
    - internal, 16
  - Sparging, 32
  - Specifications, 7-8
    - limits, 21
    - requirements, 21-22
  - Specific gravity, 16, 21
    - aluminum metal-matrix composites, 127(T)
    - aluminum-silicon alloys, 13
    - casting alloys, 2
    - die castings, 78(T)
    - elevated-temperature alloys, 19
    - permanent mold castings, 74(T), 76(T), 78(T)
    - sand castings, 72(T), 74(T)
  - Specific heat
    - aluminum metal-matrix composites, 127(T)
    - die castings, 79(T)
    - permanent mold castings, 75(T), 77(T), 79(T)
    - sand castings, 73(T), 75(T)
  - Specimen(s)
    - definition, 297
    - semisolid castings, values, 91
    - typical and minimum values for mechanical properties, 88
  - Spinel, 14, 50, 51
  - Spinning-rotor techniques, 49
  - Sprue
    - definition, 297
  - Squeeze casting, 21, 29(F), 88, 92, 95(T)
    - aluminum metal-matrix composites, 36
    - applications, 29(F)
    - definition, 297
  - Squeeze casting(s), 101, 103(F), 115, 124(F), 125(T)
    - light vehicle change in aluminum content, 1999-2002, 4(F)
    - mechanical properties, 88, 91, 94(T)
  - Stability, 66
    - aluminum-silicon-copper alloys, 17
    - definition, 66
  - Stabilizing
    - definition, 297
  - Stainless steel
    - aluminum metal-matrix composites, vibration damping performance, 130(F)
  - Steel
    - cast using extractive metallurgy, 21
    - dies, 21
  - Stibine gas formation, 14
  - Stoichiometric ratios, 8
  - Strain
    - expanded range, 206(F)
    - full range, 206(F)
  - Strain energy release rate, 113
  - Strain hardening
    - investment mold castings, 204(F)
  - Strain rate
    - tensile stress-strain curves, 202-203(F)
  - Straube-Pfeiffer test, 32
  - Stress
    - definition, 297
  - Stress concentration factors, 98-99(T), 101-103
  - Stress-corrosion cracking (SCC), 67, 115, 122, 126(T)
    - aluminum-copper alloys, 13
    - aluminum-zinc-magnesium alloys, 14
    - copper content effect, 15
    - crack growth, 116
    - definition, 297
    - elevated temperatures, 66
    - silver content effect, 13
  - Stress-corrosion resistance, 16
  - Stress-intensity factor, 113, 115, 116, 124(F), 125(F)
  - Stress raiser, 97-99(T), 101-104(F), 116
  - Stress relief, 66
  - Stress rupture tests, 104
  - Stress-strain curves, 193-209(F)
    - hot isostatic processing effect, 60(F)
  - Stress-strain diagram, 67
  - Strontium
    - as alloying element, 13, 14, 16
    - chemical modifier, 40-44(F, 45, T)
    - content in premium engineered castings, 34
    - as eutectic modifier, 16
    - recovered, 16
  - Structural industry
    - applications, 19
  - Subcritical crack growth, 114-116, 124(F), 125(F, T)
  - Subzero temperatures
    - casting alloys, 211
    - effect on mechanical properties, 71, 80
    - liquids used for tensile tests, 211
    - mechanical properties, 107-114(F, T)
    - notch toughness, 107-114(F, T)
  - Supersaturated solid (SS) solution, 65
  - Supersaturation, 65
    - relief of, 64
  - Surface defects
    - solidification, 1
  - Surface finish, 7, 15
    - aluminum-magnesium alloys, 14
  - Surface tension, 16
  - Symbols, 299
- ## T
- Tear resistance, 103, 110-112, 116-120(F, T)
    - definition, 297
  - Tears, 1
  - Tear strength, 110, 116(F)
    - permanent mold castings, 117(T), 119(T)
    - premium engineered castings, 117(T), 119(T)

- sand castings, 117(T), 119(T)
  - Tear tests, 111-114, 117(T), 119-120(T), 125(F)
  - Tear-yield ratio, 110
  - Technological improvements
    - market growth, 2
  - Technology roadmap, 4
  - Temperature gradients
    - aluminum-magnesium alloys, 14
    - heat treatments, ranges, 61(F)
    - tensile stress-strain curves, 202-204(F)
  - Temper designations, 9, 62, 64
  - Temper(s)
    - definition, 297
    - designations, 9, 62, 64
    - selection of, 5-6, 61
  - Tens-50. *See* Alloy Index, 358.0.
  - Tensile efficiency, 104
  - Tensile properties
    - casting alloys, 3
    - higher, 1
    - solidification, 1
  - Tensile strength, 21
    - aging response curves, 133, 134-146(F), 148(F)
    - alloying element effects, 15
    - aluminum-copper alloys, 13
    - aluminum-magnesium alloys, 14
    - aluminum-silicon alloys, 13, 17
    - aluminum-silicon-copper alloys, 13, 17
    - aluminum-silicon-copper-magnesium alloys, 18
    - aluminum-silicon-magnesium alloys, 14
    - aluminum-tin alloys, 14
    - casting alloys, 1-3, 212-242(T)
    - definition, 297
    - die castings, 236-240(T)
    - elevated-temperature alloys, 19
    - high-strength alloys, 20
    - permanent mold castings, 214(T), 218-222(T), 229(T), 231(T), 233-236(T)
    - porosity, inclusion, and shrinkage effects, 52(F), 53(F)
    - sand castings, 212-213(T), 215-218(T), 223-226(T), 228(T), 230(T), 232(T), 241-242(T)
  - Tensile stress-strain curves, 194-195(F), 197-207(F), 209(F)
  - Tensile tests, 113-114, 117(T), 119-120(T)
    - uniaxial, 133
  - Tensile uniaxial true stress-strain curve, 201(F)
  - Tensile yield strength, 106, 108(F), 115(F), 198(F), 207(F), 209(F)
    - aging response curves, 133-173(F)
    - aluminum metal-matrix composites, 128(T)
    - casting alloys, 224(T)
    - high-integrity die casting, 92(F)
    - hot isostatic processing effect, 56, 57(T)
    - insulated mold castings, 194-195(F), 197(F), 205(F), 207(F)
    - modified vs. unmodified eutectic alloys, 44(T)
    - notch-yield ratio, 104
    - permanent mold castings, 105(T), 109-110(T), 112(F), 117(T), 118(F), 123(T), 194-195(F), 197(F), 205(F), 207(F)
    - premium engineered castings, 88(F), 105-106(T), 110(T), 112(F), 117-118(F), 121-123(F, T)
    - sand castings, 105(T), 109(T), 112-113(F), 117-118(F), 121-123(F, 194-195(F), 197(F), 205(F), 207(F), 224(T), T)
    - weldments, 106(T)
  - Tenzaloy. *See* Alloy Index, 713.0.
  - Ternalloy 5. *See* Alloy Index, 705.0.
  - Ternalloy 7. *See* Alloy Index, 707.0.
  - Test bars
    - specification values, 71
  - Test specimen drawings, 301-304
  - Thermal analysis, 44
  - Thermal conductivity, 19, 21
    - aluminum metal-matrix composites, 124, 127(T)
    - casting alloys, 2
    - die castings, 78(T)
    - elevated-temperature alloys, 19
    - permanent mold castings, 74(T), 76(T), 78(T)
    - sand castings, 72(T), 74(T)
  - Thermal fatigue, 22
  - Thermally treated (heat treatment designation), 9
  - Thermal stability, 21
  - Thermal stresses
    - aluminum-tin alloys, 14
  - Thixocasting, 21
  - Thixocasting. *See also* Semisolid casting.
  - Threshold stress intensity, 115, 124(F), 125(T)
  - Tilt mold pour process, 95(T)
  - Tilt permanent mold casting(s), 115, 124(F), 125(T)
  - Tin, 67
    - as alloying element, 10(T), 11(T), 14, 16
    - cast using extractive metallurgy, 21
    - mechanical properties, 80(T)
    - physical properties, 80(T)
  - Tinius Olsen hydraulic testing machines, 111
  - Titanium
    - as alloying element, 10(T), 11(T), 16-17
    - boron treatment of, 15
    - content effect in premium engineered castings, 34
    - content effect in rotor casting, 31
    - effect in/out of solution on resistivity, 80(T)
    - mechanical properties, 80(T)
    - physical properties, 80(T)
  - Titanium aluminides, 15, 16, 40
  - Titanium borides, 15-17, 40
  - Tolerance
    - definition, 297
  - Tooling costs, 21, 22
  - Toughness, 21
    - solidification, 1
  - Toxicity
    - antimony additions, 14
    - beryllium-containing compounds, 15
  - Transduced ultrasonic energy
    - grain refinement, 40
  - Transition phases, 65
  - Troughing, 15
  - True strain, 201(F)
  - T temper
    - aging, 66
    - designations, 62, 64
  - T4 temper
    - aging response curves, 133, 134-173(F)
  - Turbulence, 23, 29, 30
    - hydrogen porosity, 48, 49
    - porosity, 50
  - Typical values
    - uniaxial tensile tests, 211
- ## U
- Ultimate strength, 104
    - die castings, 84(T), 88(T), 91(T)
    - permanent mold castings, 82-84(T), 86-88(T), 90-91(T)
    - premium engineered castings, 92(T), 93(T)
    - sand castings, 81-82(T), 85-86(T), 89-90(T)
    - semisolid castings, 94(T)
    - squeeze castings, 94(T)
  - USCAR program castings, 95(T)
  - Ultimate strength. *See also* Tensile strength.
  - Ultimate tensile strength, 66-67, 198(F), 209(F)
    - aging response curves, 133-173(F)
    - aluminum metal-matrix composites, 128(T)
    - casting alloys, 224(T)
    - high-integrity die casting, 92(F)
    - hot isostatic processing effect, 56, 57(T)
    - insulated mold castings, 194-195(F), 197(F), 205(F), 207(F)
    - investment mold castings, 204(F)
    - modified vs. unmodified eutectic alloys, 44(T)
    - permanent mold castings, 105(T), 109-110(T), 117(T), 194-195(F), 197(F), 205(F), 207(F)
    - premium engineered castings, 105-106(T), 110(T), 117(T), 121(T)



### 340 / Aluminum Alloy Castings: Properties, Processes, and Applications

sand castings, 105(T), 109(T), 113(T), 117(T), 121(T), 194-195(F), 197(F), 205(F), 207(F), 224(T)  
weldments, 106(T)  
Ultimate tensile strength. *See also* Tensile strength.  
Underaging, 67  
Undercooling at the solidus, 45  
Uniaxial creep rupture tests, 243-252(T)  
Uniaxial tensile tests, 133, 211-242(T)  
Unified Numbering System (UNS) alloy designation system, 9, 12(T)  
United States Automotive Materials Partnership (USAMP), 3, 4  
United States Council for Automotive Research (USCAR) program, 3, 4, 92, 95(T)  
    mechanical properties, 95(T)  
Unit propagation energy (UPE), 110-112, 114-116(F), 118-120(F), 125(F), T)  
    definition, 110, 297  
    permanent mold castings, 117-120(F, 123(T), T)  
    premium engineered castings, 117(T), 118(F), 123(T)  
    sand castings, 117-119(F, 123(T), T)  
UNS. *See* Unified Numbering System.  
UPE. *See* Unit propagation energy.  
U.S. Department of Energy, 3, 4  
USAMP. *See* United States Automotive Materials Partnership.  
USCAR. *See* United States Council for Automotive Research.

## V

Vacancies, 64  
Vacuum casting process, 92(F), 95(T)  
    definition, 298  
Vacuum density tests, 51(T)  
Vacuum die casting, 31  
Vacuum gas test, 51(T)  
Vacuum mold (V-mold) casting, 21, 26(F)  
Vacuum riserless casting (VRC), 21, 28(F), 34  
    applications, 28(F)  
    casting fatigue, 257(F)  
Vacuum riserless casting (VRC)/pressure riserless casting (PRC), 56, 57(T), 60(F), 92, 95(T)  
    castings, 115, 124(F), 125(T)  
Vacuum solidification test, 49  
Vanadium  
    boron treatment of, 15  
    content effect in rotor casting, 31  
    effect in/out of solution on resistivity, 80(T)  
Vanasil. *See* Alloy Index, 393.0.  
Vapor pressure, 16  
Vibration damping performance  
    aluminum metal-matrix composites, 125, 130(F)  
Voids, 7, 47-48, 50, 53(F), 55-56  
    centerline, 50  
    hydrogen, 51-52  
    internal, 1  
    piping, 50  
    shrinkage, 7, 27, 29, 49-52(F), 55  
    shrinkage fraction, 50  
Volatilization  
    cadmium additions, 15  
Volume fraction, 19  
    solidified, 16  
Volume of production, 21, 22  
Volume sand casting, 22  
VRC. *See* Vacuum riserless casting.  
VRC/PRC. *See* Vacuum riserless casting (VRC)/pressure riserless casting (PRC).

## W

Wear  
    mold, 22

Wear resistance, 19, 21, 70(T)  
    aluminum-silicon-copper alloys, 13  
    elevated-temperature alloys, 19  
Weight  
    aluminum-tin alloys, 14  
Weldability, 17, 21, 70(T)  
    aluminum-magnesium alloys, 14  
Welding  
    cost, 21  
    definition, 298  
Welding rod  
    definition, 298  
Welding wire  
    definition, 298  
Weldments, 120(F, T)  
    mechanical properties, 102-115(F, T)  
Whiskers  
    designation, 13  
Work hardening, 15-16  
Wrought alloys  
    applications, 1  
    ductility, 3  
    grain structure, 3  
    mechanical properties, 97, 101  
Wrought product  
    definition, 298

## X

X-ray fluorescence, 67  
X-ray testing, 53-54

## Y

Yield strength, 19, 66-67  
    aging response curves, 133, 134-173(F)  
    casting alloys, 1, 2, 3, 211, 212-242(T)  
    definition, 298  
    die castings, 84(T), 88(T), 91(T), 236-240(T)  
    notch-yield ratio, 104  
    permanent mold castings, 82-84(T), 86-88(T), 90-91(T), 214(T), 218-222(T), 229(T), 231(T), 233-236(T)  
    premium engineered castings, 92(T), 93(T)  
    sand castings, 81-82(T), 85-86(T), 89-90(T), 212-213(T), 215-218(T), 223-226(T), 228(T), 230(T), 232(T), 241-242(T)  
    semisolid castings, 94(T)  
    squeeze castings, 94(T)  
    USCAR program castings, 95(T)  
Yield strength 0.2% offset, 211  
    investment mold castings, 204(F)  
Young's modulus  
    investment mold castings, 204(F)

## Z

Zinc  
    as alloying element, 10(T), 11(T), 17  
    cast using extractive metallurgy, 21  
    content in casting alloys, 8  
    die casting, 30  
    effect in/out of solution on resistivity, 80(T)  
    mechanical properties, 80(T)  
    physical properties, 80(T)  
Zircon, 24  
Zirconium  
    boron treatment of, 15  
    effect in/out of solution on resistivity, 80(T)  
    mechanical properties, 80(T)  
    physical properties, 80(T)