

PROPERTIES OF ALUMINUM ALLOYS

Fatigue Data and the Effects of
Temperature, Product Form, and
Processing

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CHAPTER 1

Introduction and Background

A LOOK AT the sources of fatigue data, presentation, and their applicability to real structural components are presented in this book along with descriptions of specimens and test procedures. An extensive sequence of curves by alloy is provided in Chapter 3, and subsequent chapters provide general observations and comparisons of fatigue properties of various alloys, tempers and products. The influence of production process variables on fatigue properties, effects of microstructure and microporosity, and the influence of fabrication finishing variables on fatigue properties are included along with the effects of temperature, environment, and stress concentrations.

1.1 Source of Fatigue Data

For many years, high-cycle fatigue characteristics of aluminum alloys have been evaluated, examined, and published on the basis of plots of applied cyclic stress (S) versus the number of repeated cycles to failure (N); the familiar S - N plots small-specimen rotating-bending, axial-stress, and flexure-type sheet tests. The Aluminum Association, Inc. has used, for at least 50 years, rotating-bending fatigue endurance limits as its one general index of fatigue performance of the individual alloys (Ref 1).

While it is widely recognized that such high-cycle small-specimen tests do not provide much useful information to the designer of a complex structure containing joints and other stress-concentrating details, they are recognized as useful indicators of the effects of variations in composition, production process, and finishing process variables. For example, they are quite useful in comparing the inherent fatigue resistance of one alloy versus another or for investigating the effects of surface finishes on those inherent fatigue properties.

Many thousands of such tests have been performed over the past 60 years. In the total scope of test parameters, some, but not many, have been published until now. Through the generosity and foresight of Alcoa Laboratories' scientists and management, many of the accumulated years of test results have been released to ASM International and archived for posterity.

That mass of data, including approximately 3000 fatigue plots, often with multiple individual fatigue curves, has been examined and the most useful thousand or so plots selected for publication herein. While many other sources of the fatigue properties of aluminum alloys exist, the scope of this book is

confined to small-specimen data generated at Alcoa Laboratories under very consistent procedures, which are documented herein as well, so that comparisons of alloys, tempers, product forms, and production or fabrication variables may usefully be made.

In the paragraphs that follow, the fatigue-testing specimens and procedures are introduced, and the effects of many variables in composition, temper, product form, and production or fabrication variables are discussed. The fatigue curves themselves are presented as data sets representing the various alloys and tempers, with all types of fatigue loading for each one presented together. The index at the end of the book guides the reader to all of the pertinent fatigue curves for each alloy, temper, and variable.

For additional background, it is appropriate to note that all of the fatigue data included in this book were generated at Alcoa Laboratories under procedures consistent with ASTM International standards (Ref 2). The tests were performed over the period from approximately 1945 through 1980, after which more focus was placed on variable-program fatigue studies and fatigue crack growth studies. The majority of the tests were carried out in the Mechanical Testing and, subsequently, the Engineering Properties and Design Divisions of Alcoa Laboratories, under the leadership, sequentially, of Francis Howell, Marshall Holt, author J. Gilbert Kaufman, Ronald Kelsey, Bill Herbein, and Ron Wygonik. Among the lead fatigue test engineers during much of that period were John O. Lyst, John L. Miller, Bernard Walker, Philip Jacobus, and Frank George. All of these individuals had extensive training and experience in the operations of the various testing machines (Fig. 1.1) and in plotting and analysis of fatigue data. Some of the data were also generated in Alcoa's Casting Research Laboratories in Cleveland, OH, under the direction of Walter Sicha.

It was through the generosity and forward thinking of Drs. Robert J. Bucci and Ralph Sawtell of Alcoa Laboratories that the data were made available for permanent archiving and publication.

Readers interested in more in-depth discussion and guidance on the design of aluminum structures for fatigue are referred to the works of Sharp, Nordmark, and Menzemer (Ref 3) and Kissell (Ref 4). Those interested in fatigue crack growth and its application to aluminum alloys are directed to the works of Bucci and Reinhart in *Fatigue and Fracture*, Volume 19 of *ASM Handbook* (Ref 5,6). These subjects are beyond the scope of this book, which is primarily a compendium of small-specimen fatigue data and their interpretation. Other general references that may be of interest to the reader are listed at the end of this chapter.

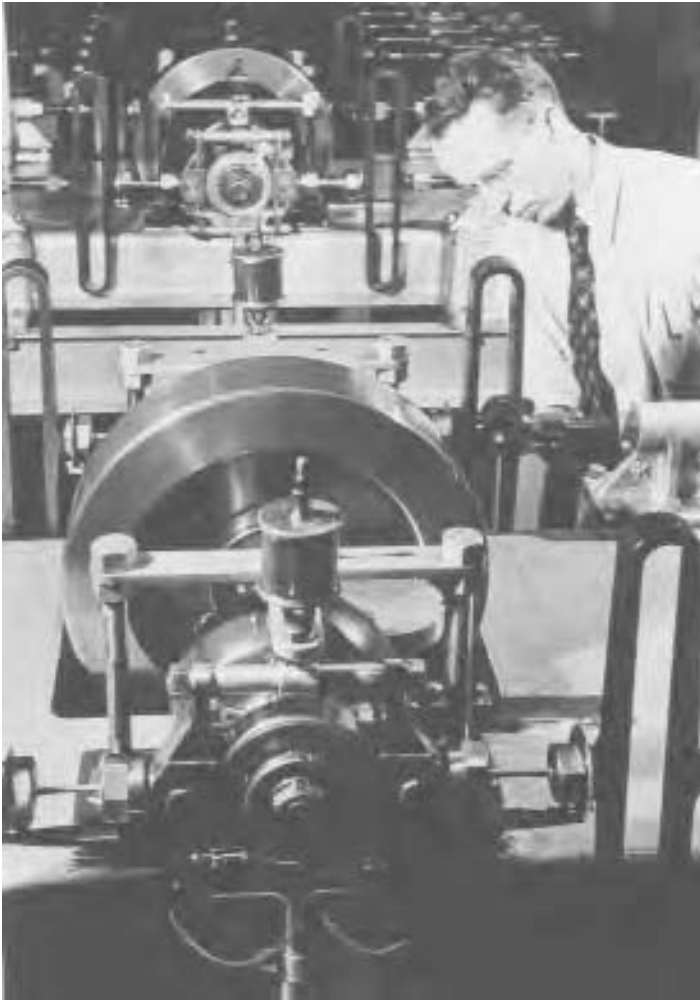


Fig. 1.1 Torsional fatigue testing machines at Alcoa Research Laboratory

1.2 Style of Presentation of Fatigue Data

1.2.1 Aluminum Association Alloy and Temper Designation Systems

Throughout this book, the Aluminum Association, Inc. alloy and temper designation systems, published in *Aluminum Standards & Data* (Ref 1,7), are used exclusively. For readers unfamiliar with these systems, a brief summary of the numeric system for alloys and the alphanumeric system for fabrication practices or tempers is contained in Appendix 1.

1.2.2 Units Systems

With only a few exceptions, the customary or engineering units system is used as the primary system in this book, with the Système International d'Unité's (SI) as the secondary system. While this is a variance from the usual ASM International publishing practice, it is done recognizing that all of the data presented herein were originally generated, analyzed, and plotted graphically in the customary system. It would have been burdensome to make a full conversion to the SI system and would likely have resulted in some loss of precision from the original graphical presentations contained herein. The units on the left side and bottom of the

curve are the units of the source document. The conversion of 1 ksi = 7 MPa serves as a guide and permits the use of a common grid.

The principal exceptions are the Goodman diagrams presented herein, most of which had already been replotted in the SI system for use in Ref 8 and so are represented herein without change. Goodman diagrams represent a synthesis of the raw information in the individual *S-N* curves and are logically represented in the current publication style.

For readers interested in making their own conversions of any of the other information in this book, appropriate SI conversion factors are compiled in Appendix 2.

1.3 Applicability and Cautions in Use of the Data

1.3.1 Applicability of Small-Specimen Fatigue Data

It is important to note at the outset that small-specimen, constant load, or constant deflection data have little, if any, direct applicability to the design of commercial structures. Real structural components experience variable loads, and their performance is generally governed far more by the presence and locations of design discontinuities such as joints, attachments, openings, and other structural features.

However, there is significant value in small-specimen fatigue data for the following purposes:

- Examining differences in inherent fatigue properties related to composition and microstructure
- Examining the effects of fabrication variables such as mechanical working or thermal processes on the inherent fatigue strength of an alloy
- Exploring the relative effects of such finishing and fabrication practices as surface coating and joining on the inherent fatigue strength
- Comparing the relative sensitivity to stress raisers during fatigue loading

Even in these cases, the magnitude of the effects must be considered relative or directional, not absolute or directly applicable to any design. For example, any negative effect of anodizing the surface of sheet on its inherent fatigue properties may be insignificant because of design discontinuities such as rivet holes, welds, or other structural features in the structural component for which the sheet is used. However, the small-specimen data will often indicate possible trends of which to be aware.

1.3.2 Residual-Stress Effects May Be Present

Sometimes, adding to the difficulty in interpreting small-specimen fatigue data is the fact that at least some of the test specimens may have contained unsuspected residual stresses that would influence their performance in the tests.

It was common practice, especially in the earlier years of research, to use 3/4 in. (19 mm) diameter rolled and drawn rod as the principal source of specimens for tests of wrought alloys and to use cast-to-shape specimens to evaluate the fatigue strengths of

casting alloys. Both of these products were later recognized to be more susceptible than specimens machined from other products to residual stresses resulting from the production process combined with the applicable solution heat treatment and quenching typically given the high-strength alloys.

For rolled and drawn rod of wrought alloys, which was often stretched to straighten or to relieve residual stresses as a last step, the effects should have been relatively small, because to produce the 0.3 in. (7.6 mm) diameter test sections from 3/4 in. (19 mm) diameter rod, a considerable amount of the surface material was machined away. The symmetry of the original product and final specimen still leaves open the possibility of small effects that could contribute to larger-than-expected scatter in the data and, occasionally, higher-than-normal results (since the residual stresses would be expected to be compressive and therefore contribute to an increase in load-carrying capacity).

In the case of castings, where specimens were cast to or near final shape, the effect could be more significant (Ref 9). Once again, the residual stresses created from the specimens cooling from the casting process are expected to have been compressive, contributing to higher-than-normal results; such effects may explain some of the seemingly unrealistically high fatigue strengths shown herein, for example, for Fig. 380.RB01 for 380.0-F die cast test bars.

In presenting the data, there has been no basis for screening or censoring the data, and all are presented for the readers' use and interpretation with appropriate caution.

1.3.3 Current versus Inactive Alloys

Among the aluminum alloys and tempers for which data are presented herein are a number that are now designated inactive, that is, no longer considered in current use, by the Aluminum Association, Inc. (Ref 7). The reason for including them is the fact that, for some at least, for example, 2020 and 7079, many structures were made of some of these alloys during the period when they were in use and before they were replaced by other alloys. Therefore, there is some possibility that investigators of service failures or those involved in attempting to extend the life of existing structures may be looking for data for such alloys that may be helpful in some analytical way, and so they are included. Inactive alloys are all clearly identified, along with the data presentations.

In a few cases, alloys are included that, during their commercial life, may not have advanced beyond an experimental, or "X," designation, for example, X7106. Because of uncertainties of whether or not such a change was made and, if so, when, all such alloys are shown herein without the "X" but are, where appropriate, indicated to be inactive.

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CHAPTER 2

Descriptions of Specimens and Test Procedures

DESCRIPTIONS OF THE VARIOUS TYPES of tests and the associated specimens and analyses are presented in the following sequence:

- 2.1, “Rotating-Beam Reversed-Bending Fatigue Tests at Room Temperature”
- 2.2, “Rotating-Beam Reversed-Bending Fatigue Tests at Elevated Temperatures, with and without Prior Holding at Various Temperatures”
- 2.3, “Flexural Fatigue Tests at Room Temperature”
- 2.4, “Axial-Stress Fatigue Tests at Room, Subzero, and Elevated Temperatures”
- 2.5, “Torsional Fatigue Tests”
- 2.8, “Modified Goodman Fatigue Diagrams”

All specimen designs are shown in Appendix 6, Fig. A6.1 through A6.6, as referenced in the following paragraphs. In describing the severity of the notch geometry for the notched specimens for which data are shown herein, the theoretical stress-concentration factor, K_t , calculated in accordance with the Neuber nomograph (Ref 1), is used throughout. Where specimens are referred to simply as sharply notched, the reader may have confidence that this involved a notch-tip radius less than 0.001 in. (0.025 mm) and a theoretical stress-concentration factor in accordance with Neuber of >12 .

2.1 Rotating-Beam Reversed-Bending Fatigue Tests at Room Temperature

All rotating-bending fatigue tests at room temperature were carried out in R.R. Moore rotating-beam machines using specimens of the designs in Fig. A6.1(a and c). The stress ratio, R , the ratio of minimum stress in each cycle to the maximum stress, was -1.0 . That is, the compressive stress is equal in magnitude to the tensile stress.

When notched specimens were tested, the notch-tip radius was generally less than 0.001 in. (0.025 mm) and actually measured in the range of 0.0002 to 0.0005 in. (0.005 to 0.013 mm); this provides a theoretical stress-concentration factor, K_t , in accordance with Neuber (Ref 1), in the range of 12 to 19, generally referred to herein as greater than 12 (>12). As noted earlier, where some figure captions refer simply to sharply notched specimens

without defining a stress-concentration factor, it is safe to assume it was >12 .

The very short-life tests (≤ 10 cycles) were often carried out by rotating the beam specimens by hand. Most tests were carried out at the standard rates of 3750 cycles per minute (cpm) or, for relatively long lives ($>100,000$ cycles), 10,000 cpm. Generally, tests to determine the endurance limit were run out to 500,000,000 cycles, the fatigue strength that is generally defined as the endurance limit for aluminum alloys (Ref 2) (Section 4.3 in Chapter 4 of this book).

Relatively small-diameter wire of several alloys used in electrical conductor applications was also tested in rotating bending, using Haigh-Robertson long-span rotating-beam fatigue machines (Ref 3, 4). Approximately 36 in. (91 cm) lengths of uniform-diameter wire were clamped in grips that could be placed in controlled rotated positions to apply constant bending moment to the wire specimens. All data reported for wire herein were obtained by using this testing system.

2.2 Rotating-Beam Reversed-Bending Fatigue Tests at Elevated Temperatures, with and without Prior Holding at Various Temperatures

All rotating-bending fatigue tests at temperatures above room temperature (hereinafter referred to as high or elevated temperatures) were carried out in cantilever-beam rotating-bending machines of Alcoa design and construction, using specimens of the designs in Fig. A6.1(b). The very short-life tests (≤ 10 cycles) were often carried out by rotating the cantilever-beam specimen by hand. All other tests were carried out at the standard rates of 3750 cpm.

In the high-temperature tests, the specimens were contained in electrically heated furnaces throughout the test, with temperatures within $\pm 1^\circ\text{F}$ (0.6°C) of the target test temperature, with no more than $\pm 2^\circ\text{F}$ (1.1°C) variation in temperature throughout the test section. Generally, tests at high temperatures were carried out after permitting the specimens to stabilize in the testing machine furnace for 1/2 h, but some tests were carried out after specifically defined stabilizing periods of up to tens of thousands of hours representing long service exposures. In reporting the results

of such tests, the specified stabilizing periods are always defined; if no special stabilization period is included with the data, it is safe to assume the stabilizing period was 1/2 h.

The test sections of the smooth and notched specimens used in the high-temperature tests were identical to those used at room temperature.

2.3 Flexural Fatigue Tests at Room Temperature

All sheet-flexure reversed-bending fatigue tests were carried out in either Alcoa-designed constant-amplitude machines operating at 1750 cpm or Sonntag constant-load machines. The two types of machines were used interchangeably, since tests had shown no significant or consistent difference in results related to their use (see Section 2.9 in this chapter).

The flexural sheet-type specimens were of the design in Fig. A6.2, designed to provide constant moment and therefore stress over the reduced test section. Sheet-flexure tests were made only at room temperature.

2.4 Axial-Stress Fatigue Tests at Room, Subzero, and Elevated Temperatures

Axial-stress fatigue tests at room temperature were carried out in Krause fatigue machines. The very short-life tests (≤ 10 cycles) were often carried out by cycling the load by hand. Most tests were carried out at the standard rates of 3750 cpm. Generally, tests to determine the endurance limit were run out to at least 100,000,000 cycles; as noted earlier, it has been customary to define the fatigue limit in rotating-bending tests as the stress that the material will sustain for at least 500,000,000 cycles.

The axial-stress specimens were of the designs in Fig. A6.3 to A6.5. Those in Fig. A6.3 were standard for products 1/2 in. (12.7 mm) thick or thicker and those in Fig. A6.4 for sheet and relatively thin extruded shapes. The specimen designs in Fig. A6.5 were for special situations of sheet-type designs machined from weldments or cylindrical specimens used for short-transverse tests of plate, forgings, or extrusions between 2.5 and 3.5 in. (6.4 and 8.9 cm) in thickness, requiring shorter-than-standard specimens.

Axial-stress fatigue tests were carried out at a wide range of stress ratios, R , ranging from $-\infty$ to $+0.5$. In most cases, tests were run at stress ratios of -1.0 , 0.0 , and $+0.5$; if only one stress ratio was used, it was usually 0.0 but sometimes $+0.1$.

When notched cylindrical specimens were tested in axial-stress machines (Fig. A6.3d), notch-tip radii of <0.001 or 0.013 in. (0.025 or 0.330 mm) were usually used, leading to stress-concentration factors, K_t , of >12 or 3 , respectively. For certain specific tests, other notch-tip radii were used, and the stress-concentration factors are defined with the data. When notched-sheet-type specimens were used in axial-stress tests, a notch-tip radius of 0.05 in. (1.27 mm) was used, equating to a theoretical stress-concentration factor of 3 .

Most axial-stress fatigue tests were made at room temperature, but, as indicated in the individual figures, some were made at sub-

zero or elevated temperatures. The subzero tests were all made at -320 °F (-196 °C) and were carried out using a cryostat in which the specimens and grips were immersed in liquid nitrogen for at least 1/2 h before each test and throughout the duration of the test. Temperature was monitored with thermistors and was found to stay within ± 2 °F (1.1 °C) of the target temperature throughout the test. In the tests at high temperatures, the specimens were contained inside electrically heated furnaces in which the test section was held within ± 1 °F (0.6 °C) of the target temperature throughout the test.

2.5 Torsional Fatigue Tests

All torsional fatigue specimen tests were carried out in torsional fatigue machines of an Alcoa Laboratories design and manufacture (Ref 5), as seen in Fig. 1.1. This is a constant-deflection machine in which torques are applied by a yoke driven by an eccentric and measured by means of a calibrated weigh-bar. Adjustments are made to the yoke and weigh-bar settings such that the angle of twist may be varied from complete reversal to one direction only. The frequency of repeated loading was 1450 cycles per minute.

The torsional fatigue specimens were of the design in Fig. A6.6, with 0.375 in. (9.5 mm) diameter test sections uniform over a 1 in. (25 mm) length. All torsional fatigue tests were carried out at room temperature.

2.6 Testing Laboratory Environment

Except as noted previously in tests at high or subzero temperature, all tests for which data are presented herein were generated in ambient laboratory environment in which temperature and humidity were maintained as constant and uniform as possible but in which air conditioning and humidity were not as tightly controlled as would now be required.

While it is therefore possible that some of the scatter in the data may have been associated with unrecognized variations in testing environment, the advantage provided by these data is that they were all obtained in the same laboratory and same testing machines under consistent conditions year to year over a period of many years and therefore should be useful in relative comparisons. However, the environmental factor should be recognized, especially when comparing with results from different investigators and laboratories.

2.7 S-N Plots of Stress versus Fatigue Life

For all of the types of tests described previously, it was the practice to present the results in plots of the applied nominal stress (i.e., calculated using the initial dimensions of the specimens) versus the fatigue life of the specimen at that stress, commonly referred to as S - N curves. Stress is presented on the ordinate in cartesian coordinates, while life is presented on the abscissa on a log scale, usually out to 10^9 cycles.

It is the usual practice when data for multiple lots of material are presented to include the bands representing the majority of the

data other than obvious outliers. These bands are then used as bases for comparison of one alloy or group of alloys with others. These bands have usually been drawn by “eyeballing” the data, not by the use of any statistical methods. Generally, when such bands are developed to be representative of a given alloy and/or temper, data from only longitudinal (L) and long-transverse (LT) specimens are considered. The subject of variations in fatigue strength with specimen direction is discussed in detail in Section 4.4 of Chapter 4.

Most of the graphs provided herein are of the S - N type. Most others are of the modified Goodman type described in the next section.

2.8 Modified Goodman Fatigue Diagrams

Modified Goodman diagrams were constructed from the raw S - N curves for a number of alloys, using the format defined originally for the *NACA Handbook* (subsequently MIL-HDBK-5 and currently known as MMPDS-02) (Ref 6). In this type of diagram, fatigue strengths are plotted on cartesian scales, with maximum stress in a cycle on the ordinate and the minimum stress on the abscissa. Lines of common life are then drawn, enabling life estimates at all stress ratios.

For some plots made earlier, maximum stress was plotted as a function of mean stress during the cycle. These are commonly called range-of-stress curves, and that terminology is used herein to indicate the type of curve in the figure title. As noted earlier, Goodman diagrams are presented with SI units as the principal system.

2.9 Effects of Testing Machine Variables

Among the test results included herein are some from experiments designed to determine whether or not variables in testing practices may influence the results. These are itemized as follows.

2.9.1 Sheet-Flexural Testing Machines

As noted previously, the sheet-flexure tests presented herein were determined on either Alcoa-designed constant-amplitude machines or Sonntag constant-load machines. As illustrated in Fig. 3003.FL01, tests of 3003-O showed no significant differences between the results from the two types of machine.

The 6061-T6 in Fig. 6061.FL03 leaves some doubt on this matter; fatigue strengths from 10^4 through 10^6 cycles are essentially identical in the two types of machine, but at 10^7 cycles, there appears to be an indication that higher values may result from tests in the constant-amplitude machines at very long lives. Regrettably, no tests were run to longer lives on the constant-amplitude machines for comparison; however, most tests were limited to lives less than 10^7 cycles where any difference seems negligible.

2.9.2 Rotating Simple versus Rotating Cantilever Beam

As noted previously, the room-temperature rotating-bending ($R = -1.0$) tests were made in R.R. Moore rotating simple-beam

fatigue machines, while the elevated-temperature tests were made in Alcoa-designed rotating cantilever-beam fatigue machines. A comparison of results obtained at room temperature for the two types of machines is shown in Fig. 2017.RB03. It appears that there is no difference in results dependent on the type of rotating-bending machine used, and so the room- and elevated-temperature test results presented herein may be compared without bias.

2.9.3 Specimen Preparation Variables

In order to judge the effect of chemical sizing of specimens as contrasted to machined surfaces, 1/16 in. (1.6 mm) thick sheet-type axial-stress specimens were prepared by taking 1/16 in. (1.6 mm) off of each side of 3/16 in. (4.8 mm) thick sheet by the two methods. The chemical milling was done by two different companies. As the results in Fig. 2024.AS34 illustrate, chemical milling resulted in consistently lower fatigue strengths; the difference was largest at the endurance limit, where the chemical-milled specimens had 6 to 12 ksi (41 to 83 MPa) lower limits.

Similar tests of other alloys confirmed this finding (Section 8.1.5 in Chapter 8). Chemical milling was therefore not used for specimen preparation.

2.9.4 Preparation for Cast Specimens and Relation to Residual Stresses

As noted in the cautions in Chapter 1, many of the data for cast aluminum alloys contained herein were determined from fatigue tests of specimens that were cast to finished specimen size or with only polishing of the surface. From the variations sometimes observed, there is reason to believe there were favorable residual stresses in the as-cast surface that may have had misleadingly positive influence on the fatigue life and strength (Ref 8).

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 and 0.025 in. (0.25 and 0.64 mm) removed as shown in Fig. 380.RB02. The endurance limits for specimens with the surface machined off were lower, with the difference increasing with the greater amount of the surface machined as seen in Table 2.1.

Other illustrations of such differences are found for permanent-mold-cast 242.0-T571 and for sand-cast 355.0-T7, 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 Table 2.2, the fatigue endurance limits were significantly lower for specimens machined from the castings than for the as-cast test bars.

The net effect of these findings is that the method of casting to size for fatigue specimen preparation seems to have had a significant effect on the fatigue behavior of aluminum alloy castings, generally through compressive residual stresses, providing potentially

Table 2.1 Endurance limits for some 380.0 cast test bars

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

See Fig. 380.RB02

Table 2.2 Endurance limits of some 242.0 and 355.0 cast test bars

Alloy and temper	Figure No.	Fatigue specimens	Endurance limit	
			ksi	MPa
242.0-T571	242.RB03	As-cast test bars	15.0	103
	242.RB05	Machined from cast pistons	9.5	66
355.0-T7, T71	355.RB13	As-cast test bars	10.5	72
	355.RB18	Machined from cast crankshaft	6.0	42

unrealistically high fatigue strengths. Greater confidence may be placed and a more conservative judgment may be made based on those data for which the specimens were machined from specific cast components in preference to those from cast-to-shape test bars.

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CHAPTER 3

Presentation of Fatigue Data

FATIGUE DATA for aluminum alloys are presented in the data sets at the end of this chapter and in the sequence “Master Index of Fatigue Curves by Alloy” at the end of this book. The data are presented by alloy grouping, each with a heading covering the alloy and the temper type.

Reference tables of published typical mechanical properties of wrought and cast aluminum alloys are presented in Tables 3.1 (Ref 1) and 3.2 (Ref 2–7), respectively.

For the compositions of the aluminum alloys covered herein, readers may consult Ref 1 and 7 for wrought and cast alloys, respectively. For the compositions of obsolete alloys, readers will need to consult early editions of Ref 8.

3.1 Alloy Presentation Sequence

The sequence scheme for presenting the alloys requires some explanation, because they are not presented in normal numeric sequence based on the four digits in the Aluminum Association designation system (Ref 1), as one may expect.

The Aluminum Association alloy designation system includes the provision that the second digit for wrought alloys (e.g., the “1” in 2124) and the letter for casting alloys (e.g. “C” in C355.0) indicate modifications of the original composition indicated by the two digits that follow. So, for example, 7075, 7175, and 7475 are all related, because 7175 is the first modification of 7075 and 7475 is the fourth modification (with 7275 and 7375 no longer being in current use, i.e., are obsolete).

The sequence of alloy presentation takes this factor into account, and, for example, data for 7075, 7175, and 7475 are presented together in that sequence, with 7178, 7079, and 7080 following in that sequence. In other words, for wrought alloys, the sequence of presentation of the alloys is by the last two digits of the wrought alloy designation.

For cast alloys, the sequence is determined by the first three numeric digits of the cast alloy designation, with the modifications presented immediately after in sequence. So, for example, 356.0, A356.0, and D356.0 are presented together in that sequence.

Table 3.1 Typical mechanical properties of wrought aluminum alloys

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 2 in. (50 mm), %		Hardness(a), HB	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	ksi	MPa	ksi	MPa	1/16 in. (1.6 mm) thick specimen	1/2 in. (1.3 mm) diam specimen		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
1060-O	10	70	4	30	43	...	19	7	50	3	20	10.0	69
1060-H12	12	85	11	75	16	...	23	8	55	4	30	10.0	69
1060-H14	14	95	13	90	12	...	26	9	60	5	35	10.0	69
1060-H16	16	110	15	105	8	...	30	10	70	6.5	45	10.0	69
1060-H18	19	130	18	125	6	...	35	11	75	6.5	45	10.0	69
1100-O	13	90	5	35	35	45	23	9	60	5	35	10.0	69
1100-H12	16	110	15	105	12	25	28	10	70	6	40	10.0	69
1100-H14	18	125	17	115	9	20	32	11	75	7	50	10.0	69
1100-H16	21	145	20	140	6	17	38	12	85	9	60	10.0	69
1100-H18	24	165	22	150	5	15	44	13	90	9	60	10.0	69
1350-O	12	85	4	30	...	(d)	...	8	55	...	...	10.0	69
1350-H12	14	95	12	85	...	...	...	9	60	...	...	10.0	69
1350-H14	16	110	14	95	...	...	...	10	70	...	...	10.0	69
1350-H16	18	125	16	110	...	...	...	11	75	...	...	10.0	69
1350-H19	27	185	24	165	...	(e)	...	15	105	7	50	10.0	69
2011-T3	55	380	43	295	...	15	95	32	220	18	125	10.2	70
2011-T8	59	405	45	310	...	12	100	35	240	18	125	10.2	70

(continued)

Note: Table values are not intended for design. The typical values for all except the O-temper materials are higher than specified minimum values. For O-temper products, typical ultimate and yield values are slightly lower than specified (maximum) values. (a) 500 kg load and 0.4 in. (10 mm) ball. (b) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-O wire will have an elongation of approximately 23% in 10 in. (250 mm). (e) 1350-H19 wire will have an elongation of approximately 1.5% in 10 in. (250 mm). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural-type testing of sheet specimens. (h) Based on 1/4 in. (6.3 mm) thick specimen. (i) T7451, although not previously registered, has appeared in literature and in some specifications as T73651. Source: Ref. 1.

Table 3.1 (continued)

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 2 in. (50 mm), %		Hardness(a), HB	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	ksi	MPa	ksi	MPa	1/16 in. (1.6 mm) thick specimen	1/2 in. (1.3 mm) diam specimen		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
2014-O	27	185	14	95	...	18	45	18	125	13	90	10.6	73
2014-T4, T451	62	425	42	290	...	20	105	38	260	20	140	10.6	73
2014-T6, T651	70	485	60	415	...	13	135	42	290	18	125	10.6	73
Alclad 2014-O	25	175	10	70	21	...	...	18	125	...	...	10.5	72
Alclad 2014-T3	63	435	40	275	20	...	...	37	255	...	...	10.5	72
Alclad 2014-T4, T451	61	420	37	255	22	...	...	37	255	...	...	10.5	72
Alclad 2014-T6, T651	68	470	60	415	10	...	...	41	285	...	...	10.5	72
2017-O	26	180	10	70	...	22	45	18	125	13	90	10.5	72
2017-T4, T451	62	425	40	275	...	22	105	38	260	18	125	10.5	72
2018-T61	61	420	46	315	...	12	120	39	270	17	115	10.8	74
2024-O	27	185	11	75	20	22	47	18	125	13	90	10.6	73
2024-T3	70	485	50	345	18	...	120	41	285	20	140	10.6	73
2024-T4, T351	68	470	47	325	20	19	120	41	285	20	140	10.6	73
2024-T361(f)	72	495	57	395	13	...	130	42	290	18	125	10.6	73
Alclad 2024-O	26	180	11	75	20	...	...	18	125	...	...	10.6	73
Alclad 2024-T3	65	450	45	310	18	...	...	40	275	...	...	10.6	73
Alclad 2024-T4, T351	64	440	42	290	19	...	...	40	275	...	...	10.6	73
Alclad 2024-T361(f)	67	460	53	365	11	...	...	41	285	...	...	10.6	73
Alclad 2024-T81, T851	65	450	60	415	6	...	...	40	275	...	...	10.6	73
Alclad 2024-T861(f)	70	485	66	455	6	...	...	42	290	...	...	10.6	73
2025-T6	58	400	37	255	...	19	110	35	240	18	125	10.4	71
2036-T4	49	340	28	195	24	...	...	...	...	18(g)	125(g)	10.3	71
2117-T4	43	295	24	165	...	27	70	28	195	14	95	10.3	71
2124-T851	70	485	64	440	...	8	...	...	...	...	...	10.6	73
2218-T72	48	330	37	255	...	11	95	30	205	...	...	10.8	74
2219-O	25	175	11	75	18	...	...	...	...	...	...	10.6	73
2219-T42	52	360	27	185	20	...	...	...	...	...	...	10.6	73
2219-T31, T351	52	360	36	250	17	...	...	...	...	...	...	10.6	73
2219-T37	57	395	46	315	11	...	...	...	...	...	...	10.6	73
2219-T62	60	415	42	290	10	...	...	...	...	15	105	10.6	73
2219-T81, T851	66	455	51	350	10	...	...	...	...	15	105	10.6	73
2219-T87	69	475	57	395	10	...	...	...	...	15	105	10.6	73
2618-T61	64	440	54	370	...	10	115	38	260	18	125	10.8	74
3003-O	16	110	6	40	30	40	28	11	75	7	50	10.0	69
3003-H12	19	130	18	125	10	20	35	12	85	8	55	10.0	69
3003-H14	22	150	21	145	8	16	40	14	95	9	60	10.0	69
3003-H16	26	180	25	170	5	14	47	15	105	10	70	10.0	69
3003-H18	29	200	27	185	4	10	55	16	110	10	70	10.0	69
Alclad 3003-O	16	110	6	40	30	40	...	11	75	...	...	...	...
Alclad 3003-H12	19	130	18	125	10	20	...	12	85	...	...	10.0	69
Alclad 3003-H14	22	150	21	145	8	16	...	14	95	...	...	10.0	69
Alclad 3003-H16	26	180	25	170	5	14	...	15	105	...	...	10.0	69
Alclad 3003-H18	29	200	27	185	4	10	...	16	110	...	...	10.0	69
3004-O	26	180	10	70	20	25	45	16	110	14	95	10.0	69
3004-H32	31	215	25	170	10	17	52	17	115	15	105	10.0	69
3004-H34	35	240	29	200	9	12	63	18	125	15	105	10.0	69
3004-H36	38	260	33	230	5	9	70	20	140	16	110	10.0	69
3004-H38	41	285	36	250	5	6	77	21	145	16	110	10.0	69
Alclad 3004-O	26	180	10	70	20	25	...	16	110	...	...	10.0	69
Alclad 3004-H32	31	215	25	170	10	17	...	17	115	...	...	10.0	69
Alclad 3004-H34	35	240	29	200	9	12	...	18	125	...	...	10.0	69
Alclad 3004-H36	38	260	33	230	5	9	...	20	140	...	...	10.0	69
Alclad 3004-H38	41	285	36	250	5	6	...	21	145	...	...	10.0	69
3105-O	17	115	8	55	24	...	...	12	85	...	...	10.0	69
3105-H12	22	150	19	130	7	...	...	14	95	...	...	10.0	69

(continued)

Note: Table values are not intended for design. The typical values for all except the O-temper materials are higher than specified minimum values. For O-temper products, typical ultimate and yield values are slightly lower than specified (maximum) values. (a) 500 kg load and 0.4 in. (10 mm) ball. (b) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-O wire will have an elongation of approximately 23% in 10 in. (250 mm). (e) 1350-H19 wire will have an elongation of approximately 1.5% in 10 in. (250 mm). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural-type testing of sheet specimens. (h) Based on 1/4 in. (6.3 mm) thick specimen. (i) T7451, although not previously registered, has appeared in literature and in some specifications as T73651. Source: Ref. 1.

Table 3.1 (continued)

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 2 in. (50 mm), %		Hardness(a), HB	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	ksi	MPa	ksi	MPa	1/16 in. (1.6 mm) thick specimen	1/2 in. (1.3 mm) diam specimen		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
3105-H14	25	170	22	150	5	...	...	15	105	...	...	10.0	69
3105-H16	28	195	25	170	4	...	...	16	110	...	...	10.0	69
3105-H18	31	215	28	195	3	...	...	17	115	...	...	10.0	69
3105-H25	26	180	23	160	8	...	...	15	105	...	...	10.0	69
4032-T6	55	380	46	315	...	9	120	38	260	16	110	11.4	79
5005-O	18	125	6	40	25	...	28	11	75	...	...	10.0	69
5005-H12	20	140	19	130	10	...	...	14	95	...	...	10.0	69
5005-H14	23	160	22	150	6	...	...	14	95	...	...	10.0	69
5005-H16	26	180	25	170	5	...	...	15	105	...	...	10.0	69
5005-H18	29	200	28	195	4	...	...	16	110	...	...	10.0	69
5005-H32	20	140	17	115	11	...	36	14	95	...	...	10.0	69
5005-H34	23	160	20	140	8	...	41	14	95	...	...	10.0	69
5005-H36	26	180	24	165	6	...	46	15	105	...	...	10.0	69
5005-H38	29	200	27	185	5	...	51	16	110	...	...	10.0	69
5050-O	21	145	8	55	24	...	36	15	105	12	85	10.0	69
5050-H32	25	170	21	145	9	...	46	17	115	13	90	10.0	69
5050-H34	28	195	24	165	8	...	53	18	125	13	90	10.0	69
5050-H36	30	205	26	180	7	...	58	19	130	14	95	10.0	69
5050-H38	32	220	29	200	6	...	63	20	140	14	95	10.0	69
5052-O	28	195	13	90	25	30	47	18	125	16	110	10.2	70
5052-H32	33	230	28	195	12	18	60	20	140	17	115	10.2	70
5052-H34	38	260	31	215	10	14	68	21	145	18	125	10.2	70
5052-H36	40	275	35	240	8	10	73	23	160	19	130	10.2	70
5052-H38	42	290	37	255	7	8	77	24	165	20	140	10.2	70
5056-O	42	290	22	150	...	35	65	26	180	20	140	10.3	71
5056-H18	63	435	59	405	...	10	105	34	235	22	150	10.3	71
5056-H38	60	415	50	345	...	15	100	32	220	22	150	10.3	71
5083-O	42	290	21	145	...	22	...	25	170	...	...	10.3	71
5083-H321, H116	46	315	33	230	...	16	...	...	...	23	160	10.3	71
5086-O	38	260	17	115	22	...	...	23	160	...	...	10.3	71
5086-H32, H116	42	290	30	205	12	...	...	...	...	...	...	10.3	71
5086-H34	47	325	37	255	10	...	...	27	185	...	...	10.3	71
5086-H112	39	270	19	130	14	...	...	...	...	...	...	10.3	71
5154-O	35	240	17	115	27	...	58	22	150	17	115	10.2	70
5154-H32	39	270	30	205	15	...	67	22	150	18	125	10.2	70
5154-H34	42	290	33	230	13	...	73	24	165	19	130	10.2	70
5154-H36	45	310	36	250	12	...	78	26	180	20	140	10.2	70
5154-H38	48	330	39	270	10	...	80	28	195	21	145	10.2	70
5154-H112	35	240	17	115	25	...	63	...	...	17	115	10.2	70
5252-H25	34	235	25	170	11	...	68	21	145	...	...	10.0	69
5252-H38, H28	41	285	35	240	5	...	75	23	160	...	...	10.0	69
5254-O	35	240	17	115	27	...	58	22	150	17	115	10.2	70
5254-H32	39	270	30	205	15	...	67	22	150	18	125	10.2	70
5254-H34	42	290	33	230	13	...	73	24	165	19	130	10.2	70
5254-H36	45	310	36	250	12	...	78	26	180	20	140	10.2	70
5254-H38	48	330	39	270	10	...	80	28	195	21	145	10.2	70
5254-H112	35	240	17	115	25	...	63	...	...	17	115	10.2	70
5454-O	36	250	17	115	22	...	62	23	160	...	...	10.2	70
5454-H32	40	275	30	205	10	...	73	24	165	...	...	10.2	70
5454-H34	44	305	35	240	10	...	81	26	180	...	...	10.2	70
5454-H111	38	260	26	180	14	...	70	23	160	...	...	10.2	70
5454-H112	36	250	18	125	18	...	62	23	160	...	...	10.2	70
5456-O	45	310	23	160	...	24	...	...	...	...	...	10.3	71
5456-H25	45	310	24	165	...	22	...	...	...	...	...	10.3	71
5456-H112	45	310	24	165	...	22	...	...	...	...	...	10.3	71
5456-H321, H116	51	350	37	255	...	16	90	30	205	...	...	10.3	71
5457-O	19	130	7	50	22	...	32	12	85	...	...	10.0	69
5457-H25	26	180	23	160	12	...	48	16	110	...	...	10.0	69
5457-H38, H28	30	205	27	185	6	...	55	18	125	...	...	10.0	69
5652-O	28	195	13	90	25	30	47	18	125	16	110	10.2	70
5652-H32	33	230	28	195	12	18	60	20	140	17	115	10.2	70

(continued)

Note: Table values are not intended for design. The typical values for all except the O-temper materials are higher than specified minimum values. For O-temper products, typical ultimate and yield values are slightly lower than specified (maximum) values. (a) 500 kg load and 0.4 in. (10 mm) ball. (b) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-O wire will have an elongation of approximately 23% in 10 in. (250 mm). (e) 1350-H19 wire will have an elongation of approximately 1.5% in 10 in. (250 mm). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural-type testing of sheet specimens. (h) Based on 1/4 in. (6.3 mm) thick specimen. (i) T7451, although not previously registered, has appeared in literature and in some specifications as T73651. Source: Ref. 1.

Table 3.1 (continued)

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 2 in. (50 mm), %		Hardness(a), HB	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	ksi	MPa	ksi	MPa	1/16 in. (1.6 mm) thick specimen	1/2 in. (1.3 mm) diam specimen		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
5652-H34	38	260	31	215	10	14	68	21	145	18	125	10.2	70
5652-H36	40	275	35	240	8	10	73	23	160	19	130	10.2	70
5652-H38	42	290	37	255	7	8	77	24	165	20	140	10.2	70
5657-H25	23	160	20	140	12	...	40	14	95	...	...	10.0	69
5657-H38, H28	28	195	24	165	7	...	50	15	105	...	...	10.0	69
6061-O	18	125	8	55	25	30	30	12	85	9	60	10.0	69
6061-T4, T451	35	240	21	145	22	25	65	24	165	14	95	10.0	69
6061-T6, T651	45	310	40	275	12	17	95	30	205	14	95	10.0	69
Alclad 6061-O	17	115	7	50	25	...	...	11	75	...	...	10.0	69
Alclad 6061-T4, T451	33	230	19	130	22	...	...	22	150	...	...	10.0	69
Alclad 6061-T6, T651	42	290	37	255	12	...	...	27	185	...	...	10.0	69
6063-O	13	90	7	50	...	...	25	10	70	8	55	10.0	69
6063-T1	22	150	13	90	20	...	42	14	95	9	60	10.0	69
6063-T4	25	170	13	90	22	...	...	...	...	...	...	10.0	69
6063-T5	27	185	21	145	12	...	60	17	115	10	70	10.0	69
6063-T6	35	240	31	215	12	...	73	22	150	10	70	10.0	69
6063-T83	37	255	35	240	9	...	82	22	150	...	...	10.0	69
6063-T831	30	205	27	185	10	...	70	18	125	...	...	10.0	69
6063-T832	42	290	39	270	12	...	95	27	185	...	...	10.0	69
6066-O	22	150	12	85	...	18	43	14	95	...	...	10.0	69
6066-T4, T451	52	360	30	205	...	18	90	29	200	...	...	10.0	69
6066-T6, T651	57	395	52	360	...	12	120	34	235	16	110	10.0	69
6070-T6	55	380	51	350	10	...	...	34	235	14	95	10.0	69
6101-H111	14	95	11	75	...	...	...	...	...	...	...	10.0	69
6101-T6	32	220	28	195	15(h)	...	71	20	140	...	...	10.0	69
6262-T9	58	400	55	380	...	10	120	35	240	13	90	10	69
6351-T4	36	250	22	150	20	...	...	...	...	...	...	10.0	69
6351-T6	45	310	41	285	14	...	95	29	200	13	90	10.0	69
6463-T1	22	150	13	90	20	...	42	14	95	10	70	10.0	69
6463-T5	27	185	21	145	12	...	60	17	115	10	70	10.0	69
6463-T6	35	240	31	215	12	...	74	22	150	10	70	10.0	69
7049-T73	75	515	65	450	...	12	135	44	305	...	...	10.4	72
7049-T7352	75	515	63	435	...	11	135	43	295	...	...	10.4	72
7050-T73510, T73511	72	495	63	435	...	12	...	...	...	...	...	10.4	72
7050-T7451(i)	76	525	68	470	...	11	...	44	305	...	...	10.4	72
7050-T7651	80	550	71	490	...	11	...	47	325	...	...	10.4	72
7075-O	33	230	15	105	17	16	60	22	150	...	...	10.4	72
7075-T6, T651	83	570	73	505	11	11	150	48	330	23	160	10.4	72
Alclad 7075-O	32	220	14	95	17	...	...	22	150	...	...	10.4	72
Alclad 7075-T6, T651	76	525	67	460	11	...	...	46	315	...	...	10.4	72
7175-T74	76	525	66	455	...	11	135	42	290	23	160	10.4	72
7178-O	33	230	15	105	15	16	...	...	...	...	...	10.4	72
7178-T6, T651	88	605	78	540	10	11	...	...	...	...	...	10.4	72
7178-T76, T7651	83	575	73	505	...	11	...	...	...	...	...	10.3	71
Alclad 7178-O	32	220	14	95	16	...	...	...	...	...	...	10.4	72
Alclad 7178-T6, T651	81	560	71	490	10	...	...	...	...	...	...	10.4	72
7475-T61	82	565	71	490	11	...	...	...	...	...	...	10.2	70
7475-T651	85	585	74	510	...	13	...	...	...	...	...	10.4	72
7475-T7351	72	495	61	420	...	13	...	...	...	...	...	10.4	72
7475-T761	75	520	65	450	12	...	...	...	...	...	...	10.2	70
7475-T7651	77	530	67	460	...	12	...	...	...	...	...	10.4	72
Alclad 7475-T61	75	520	66	455	11	...	...	...	...	...	...	10.2	70
Alclad 7475-T761	71	490	61	420	12	...	...	...	...	...	...	10.2	70
8176-H24	17	115	14	95	15	...	...	10	70	...	...	10.0	69

Note: Table values are not intended for design. The typical values for all except the O-temper materials are higher than specified minimum values. For O-temper products, typical ultimate and yield values are slightly lower than specified (maximum) values. (a) 500 kg load and 0.4 in. (10 mm) ball. (b) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-O wire will have an elongation of approximately 23% in 10 in. (250 mm). (e) 1350-H19 wire will have an elongation of approximately 1.5% in 10 in. (250 mm). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural-type testing of sheet specimens. (h) Based on 1/4 in. (6.3 mm) thick specimen. (i) T7451, although not previously registered, has appeared in literature and in some specifications as T73651. Source: Ref. 1.

Table 3.2 Typical mechanical properties of aluminum alloy castings at room temperature

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

Alloy and temper	Tension					Hardness(b), HB	Shear ultimate strength		Fatigue endurance limit(c)		Modulus of elasticity(d)	
	Ultimate strength		Yield strength(a)		Elongation in 2 in. (50 mm) or 4D, %		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
	ksi	MPa	ksi	MPa								
Sand casting												
201.0-T6	65	450	55	380	8	130	...	...	...	...	...	...
201.0-T7	68	470	60	415	6	...	...	...	14	95	...	...
201.0-T43	60	415	37	255	17	...	...	...	...	...	...	...
204.0-T4	45	310	28	195	6	...	...	...	...	...	...	...
A206.0-T4	51	350	36	250	7	...	40	275	...	...	...	...
208.0-F	21	145	14	655	3	...	17	115	11	75	...	...
213.0-F	24	165	15	105	2	70	20	140	9	60	...	...
222.0-O	27	185	20	140	1	80	21	145	9.5	65	...	...
222.0-T61	41	285	40	275	<0.5	115	32	220	8.5	60	10.7	74
224.0-T72	55	380	40	275	10	123	35	240	9	60	10.5	73
240.0-F	34	235	28	195	1	90	...	...	...	...	...	...
242.0-F	31	145	20	140	1	...	...	...	...	...	10.3	71
242.0-O	27	185	18	125	1	70	21	145	8	55	10.3	71
242.0-T571	32	220	30	205	1	85	26	180	11	75	10.3	71
242.0-T61	32	220	20	140	...	90–120	...	...	...	...	10.3	71
242.0-T77	30	205	23	160	2	75	24	165	10.5	70	10.3	71
A242.0-T75	31	215	...	...	2	...	...	...	...	...	...	...
295.0-T4	32	220	16	110	9	80	26	180	7	50	10.0	69
295.0-T6	36	250	24	165	5	75	30	205	7.5	50	10.0	69
295.0-T62	41	285	32	220	2	90	33	230	8	55	10.0	69
295.0-T7	29	200	16	110	3	55–85	...	...	...	...	10.0	69
319.0-F	27	185	18	125	2	70	22	150	10	70	10.7	74
319.0-T5	30	205	26	180	2	80	24	165	11	75	10.7	74
319.0-T6	36	250	24	165	2	80	29	200	11	75	10.7	74
328.0-F	25	170	14	95	1	45–75	...	...	...	...	...	...
328.0-T6	34	235	21	145	1	65–95	...	...	...	...	...	...
354.0-T62	55	380	45	310	3	...	...	...	...	...	...	...
355.0-F	23	160	12	85	3	...	...	...	...	...	10.2	70
355.0-T51	28	195	23	160	2	65	22	150	8	55	10.2	70
355.0-T6	35	240	25	170	3	80	28	195	9	60	10.2	70
355.0-T61	35	240	35	240	1	90	31	215	9.5	65	10.2	70
355.0-T7	38	260	26	180	1	85	28	195	10	70	10.2	70
355.0-T71	35	240	29	200	2	75	26	180	10	70	10.2	70
C355.0-T6	39	270	29	200	5	85	...	...	...	...	...	...
356.0-F	24	165	18	125	6	...	...	...	...	...	10.5	73
356.0-T51	25	170	20	140	2	60	20	140	8	55	10.5	73
356.0-T6	33	230	24	165	4	70	26	180	8.5	60	10.5	73
356.0-T7	34	235	30	205	2	75	24	165	9	60	10.5	73
356.0-T71	28	195	21	145	4	60	20	140	8.5	60	10.5	73
A356.0-F	23	160	12	85	6	...	...	...	...	...	10.5	73
A356.0-T51	26	180	18	125	3	...	...	...	...	...	10.5	73
A356.0-T6	40	275	30	205	6	75	...	...	...	...	10.5	73
A356.0-T71	30	205	20	140	3	...	...	...	...	...	10.5	73
357.0-F	25	170	13	90	5	...	...	...	...	...	...	...
357.0-T51	26	180	17	115	3	...	...	...	...	...	...	...
357.0-T6	50	345	43	295	2	...	...	...	...	...	...	...
357.0-T7	40	275	34	235	3	60	...	...	...	...	...	...
A357.0-T6	46	315	36	250	3	85	40	275	12	85	...	...
359.0-T62	50	345	42	290	5	...	...	...	16	110	...	...
A390.0-F	26	180	26	180	<1.0	100	...	...	...	...	...	...
A390.0-T5	26	180	26	180	<1.0	100	...	...	...	...	...	...
A390.0-T6	40	275	40	275	<1.0	140	...	...	13	...	...	...
A3090-T7	36	250	36	250	<1.0	115	...	...	...	...	...	...
443.0-F	19	130	8	55	8	40	14	95	8	55	10.3	71
B443.0-F	17	115	6	40	3	25–55	...	...	...	...	...	...
A444.0-F	21	145	9	60	9	44	...	...	...	...	...	...
A444.0-T4	23	160	9	60	12	45	...	...	...	...	...	...
511.0-F	21	145	12	85	3	50	17	115	8	55	...	...
512.0-F	20	140	13	90	2	50	17	115	9	60	...	...
514.0-F	25	170	12	85	9	50	20	140	7	50	...	...
520.0-T4	48	330	26	180	16	75	34	235	8	55	...	...
535.0-F	35	240	18	125	9	60–90	...	...	...	...	...	...
535.0-T5	35	240	18	125	9	60–90	...	...	...	...	...	...

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 0.4 in. (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 2–5.

Table 3.2 (continued)

Alloy and temper	Tension					Hardness(b), HB	Shear ultimate strength		Fatigue endurance limit(c)		Modulus of elasticity(d)	
	Ultimate strength		Yield strength(a)		Elongation in 2 in. (50 mm) or 4D, %		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
	ksi	MPa	ksi	MPa								
Sand casting (continued)												
A535.0-F	36	250	18	125	9	65	...	...	...	...	...	...
707.0-T5	33	230	22	150	2	70–100	...	...	...	...	...	...
707.0-T7	37	255	30	205	1	65–95	...	...	...	...	...	...
710.0-F	32	220	20	140	2	60–90	...	...	...	...	...	...
710.0-T5	32	220	20	140	2	60–90	...	...	...	...	...	...
712.0-F	34	235	25	170	4	60–90	...	...	...	...	...	...
712.0-T5	34	235	25	170	4	60–90	...	...	...	...	...	...
713.0-F	32	220	22	150	3	60–90	...	...	...	...	...	...
713.0-T5	32	220	22	150	3	60–90	...	...	...	...	...	...
771.0-T5	32	220	27	185	3	70–100	...	...	...	...	...	...
771.0-T52	36	250	30	205	2	70–100	...	...	...	...	...	...
771.0-T53	36	250	27	185	2	...	...	...	...	...	...	...
771.0-T6	42	290	35	240	5	75–105	...	...	...	...	...	...
771.0-T71	48	330	45	310	2	105–135	...	...	...	...	...	...
850.0-T5	20	140	11	75	8	45	14	95	...	...	10.3	71
851.0-T5	20	140	11	75	5	45	14	95	...	...	10.3	71
852.0-T5	27	185	22	150	2	65	18	125	10	60	10.3	71
Permanent mold casting												
201.0-T6	65	450	55	380	8	130	...	...	...	...	...	...
201.0-T7	68	470	60	415	6	...	...	...	14	95	...	...
201.0-T43	60	415	37	255	17	...	...	...	...	...	...	...
204.0-T4	48	330	29	200	8	...	...	...	...	...	...	...
A206.0-T4	62	430	38	260	17	...	42	290	...	...	...	...
A206.0-T7	63	435	50	345	12	...	37	255	...	...	...	...
208.0-T6	35	240	22	150	2	75–105	...	...	...	...	...	...
208.0-T7	33	230	16	110	3	65–95	...	...	...	...	...	...
213.0-F	30	205	24	165	2	85	24	165	9.5	65	...	...
222.0-T551	37	255	35	240	<0.5	115	30	205	8.5	60	10.7	74
222.0-T52	35	240	31	215	1	100	25	170	...	...	10.7	74
238.0-F	30	205	24	165	2	100	24	165	...	...	...	...
242.0-T571	40	275	34	235	1	105	30	205	10.5	73	10.3	71
242.0-T61	47	325	42	290	1	110	35	450	10	70	10.3	71
A249.0-T63	69	475	60	415	6	...	...	...	...	...	...	...
296.0-T7	39	270	20	140	5	80	30	205	9	60	10.1	70
308.0-F	28	195	16	110	2	70	22	150	13	90	...	...
319.0-F	34	235	19	130	3	85	24	165	...	...	10.7	74
319.0-T6	40	275	27	185	3	95	...	...	...	...	10.7	74
324.0-F	30	205	16	110	4	70	...	...	...	...	...	...
324.0-T5	36	250	26	180	3	90	...	...	...	...	...	...
324.0-T62	45	310	39	270	3	105	...	...	...	...	...	...
332.0-T5	36	250	28	195	1	105	...	...	...	...	...	...
328.0-T6	34	235	21	145	1	65–95	...	...	...	...	...	...
333.0-F	34	235	19	130	2	90	27	185	15	105	...	...
333.0-T5	34	235	25	170	1	100	27	185	12	85	...	...
333.0-T6	42	290	30	205	2	105	33	230	15	105	...	...
333.0-T7	37	255	28	195	2	90	28	195	12	85	...	...
336.0-T551	36	250	28	193	1	105	28	193	14	95	...	...
336.0-T65	47	325	43	295	1	125	36	250	...	...	...	...
354.0-T61	52	360	39	270	6	...	...	...	19	130	...	...
354.0-T62	55	380	45	310	3	...	...	...	...	...	...	...
355.0-F	27	185	15	105	4	...	...	...	...	...	10.2	70
355.0-T51	30	205	24	165	2	75	24	165	...	...	10.2	70
355.0-T6	42	290	27	185	4	90	34	235	10	70	10.2	70
355.0-T61	45	310	40	275	2	105	36	250	10	70	10.2	70
355.0-T7	40	275	30	205	2	85	30	205	10	70	10.2	70
355.0-T71	36	250	31	215	3	85	27	185	10	70	10.2	70
C355.0-T6	48	330	28	195	8	90	...	...	...	...	10.2	70
C355.0-T61	46	315	34	235	6	100	...	...	...	...	10.2	70
C355.0-T62	48	330	37	255	5	100	...	...	...	...	10.2	70
356.0-F	26	180	18	125	5	...	...	...	...	...	10.5	73
356.0-T51	27	185	20	140	2	...	...	...	...	...	10.5	73
356.0-T6	38	260	27	185	5	80	30	205	13	90	10.5	73
356.0-T7	32	220	24	165	6	70	25	170	11	75	10.5	73

(continued)

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 0.4 in. (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 2–5.

Table 3.2 (continued)

Alloy and temper	Tension					Hardness(b), HB	Shear ultimate strength		Fatigue endurance limit(c)		Modulus of elasticity(d)	
	Ultimate strength		Yield strength(a)		Elongation in 2 in. (50 mm) or 4D, %		ksi	MPa	ksi	MPa	10 ⁶ psi	GPa
	ksi	MPa	ksi	MPa								
Permanent mold casting (continued)												
356.0-T71	25	170	...	...	3	60–90	...	...	...	...	10.5	73
A356.0-F	27	185	13	90	8	...	...	...	...	...	10.5	73
A356.0-T51	29	200	20	140	5	...	...	...	...	...	10.5	73
A356.0-T6	41	285	30	205	12	80	...	...	...	...	10.5	73
357.0-F	28	195	15	105	6	...	...	...	...	...	...	...
357.0-T51	29	200	21	145	4	...	...	...	...	...	...	...
357.0-T6	52	360	43	295	5	100	35	240	13	90	...	...
357.0-T7	38	260	30	205	5	70	...	...	...	...	...	...
A357.0-T6	52	360	42	290	5	100	35	240	15	105	...	...
359.0-T61	48	330	37	255	6	...	...	...	...	...	...	...
359.0-T62	50	345	42	290	5	...	...	...	16	110	...	...
A390.0-F	29	200	29	200	<1.0	110	...	...	...	...	...	...
A390.0-T5	29	200	29	200	<1.0	110	...	...	...	...	...	...
A390.0-T6	45	310	45	310	<1.0	145	...	...	17	115	...	...
A390.0-T7	38	260	38	260	<1.0	120	...	...	15	105	...	...
443.0-F	23	160	9	60	10	45	16	110	8	55	10.3	71
B443.0-F	21	145	6	40	6	30–60	...	...	...	...	...	...
A444.0-F	24	165	11	75	13	44	...	...	...	...	...	...
A444.0-T4	23	160	10	70	21	45	16	110	8	55	...	...
513.0-F	27	185	16	110	7	60	22	150	10	70	...	...
535.0-F	35	240	18	125	8	60–90	...	...	...	...	...	...
705.0-T5	37	255	17	115	10	55–75	...	...	...	...	...	...
707.0-T7	45	310	35	240	3	80–110	...	...	...	...	...	...
711.0-T1	28	195	18	125	7	55–85	...	...	...	...	...	...
713.0-T5	32	220	22	150	4	60–90	...	...	...	...	...	...
850.0-T5	23	160	11	75	12	45	15	105	9	60	10.3	71
851.0-T5	20	140	11	75	5	45	14	95	9	60	10.3	71
851.0-T6	18	125	...	...	8	...	...	...	...	...	10.3	71
852.0-T5	32	220	23	160	5	70	21	145	11	75	10.3	71
Die casting												
360.0-F	44	305	25	170	3	75	28	195	20	140	10.3	71
A360.0-F	46	315	24	165	4	75	26	180	18	124	10.3	71
380.0-F	46	315	23	160	3	80	28	195	20	140	10.3	71
A380.0-F	47	325	23	160	4	80	27	185	20	140	10.3	71
383.0-F	45	310	22	150	4	75	...	...	21	145	10.3	71
384.0-F	48	330	24	165	3	85	29	200	20	140	...	...
390.0-F	40.5	280	35	240	<1	...	...	...	...	...	...	...
B390.0-F	46	315	36	250	<1	120	...	...	20	140	11.8	81
392.0-F	42	290	39	270	<1	...	...	...	...	...	...	...
413.0-F	43	295	21	145	3	80	25	170	19	130	10.3	71
A413.0-F	42	290	19	130	4	80	25	170	19	130	...	...
C443.0-F	33	230	14	95	9	65	29	200	17	115	10.3	71
518.0-F	45	310	28	193	5	80	29	200	20	140	...	...

(a) For tensile yield strengths, offset = 0.2%. (b) 500 kg load, 0.4 in. (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 2–5.

3.2 Temper Presentation Sequence

For those alloys such as 2024 and 7075 for which there are many tempers, the data presentations are grouped by type of temper. For example, for alloy 2024, there are approximately ten subgroups, including some such as 2024-T3 type, which includes 2024-T3, T31, T351, and T352. As an example, the total sequence of presentation for 2024 is illustrated as follows:

- 2024 all tempers
- 2024-O
- 2024-T3 type (includes T3, T31, T351, T351X, and T352)
- 2024-T36
- 2024-T4
- 2024-T6 type
- 2024-T81 type (includes T81, T851, and T851X)

- 2024-T84
- 2024-T86

For those alloys with fewer than approximately ten *S-N* curves for all tempers, their heading will simply be the alloy number, for example, 5050. The tempers within the group are presented in alphanumeric order.

3.3 S-N Curve and Goodman Diagram Numbering System

With the intent of facilitating readers' efforts to locate *S-N* curves of interest for specific alloys, they are numbered using the alloy number followed by a two-letter code, indicating the type of fatigue loading, or presentation plus two numbers, indicating the

number in that particular sequence. The codes for the types of curves are as follows:

- RB—rotating bending at room temperature
- HT—rotating bending at high temperatures
- FL—sheet flexure
- AS—axial stress
- TR—torsion
- GD—Goodman diagram
- GT—Goodman diagram for torsion

As an illustration, the fourth axial-stress fatigue curve for 2024 would therefore be identified as Fig. 2024.AS04.

There is no figure number breakout by temper, so the 01xx digits would go through the total range of tempers for which figures are available for any specific alloy.

To aid the reader, an “Index to Fatigue Curves by Type of Test” is found in the back of the book.

3.4 Tabular Summaries of Fatigue Strengths

Tabular summaries of the fatigue properties, generally consistent with the fatigue data presented herein, are included in the Appendix 5 tables as follows:

- Tables A5.1 and A5.2—Rotating-beam reversed-bending fatigue tests at room temperature (Ref 7, 9)
- Tables A5.3 to A5.5—Rotating-beam reversed-bending fatigue tests at elevated temperatures, with and without prior holding at various temperatures (Ref 7, 9)
- Table A5.6—Flexural fatigue tests at room temperature (Ref 9)
- Tables A5.7 and A5.8—Axial-stress fatigue tests at room, sub-zero, and elevated temperatures (Ref 7, 9)
- Table A5.9—Torsional fatigue tests

Tables A5.1 through A5.8 are taken from Ref 7 and 9. Because these tabular summaries were created from the original 3000+ graphical plots of data, it is quite possible that many are not supported by plots contained herein, which were selected for maximum usefulness from the larger group. The author apologizes for any inconvenience to readers for these differences; economics simply did not justify publication of the entire 3000+ archive.

3.5 Inactive Alloys

As noted earlier and repeated here for emphasis, some data are included in this compendium for inactive alloys (Ref 8), that is, no longer in commercial use. This was done to support the possibility that designers involved in attempting to extend the life of existing structures or investigators of service failures may occasionally be looking for data for alloys that are no longer produced today. All such inactive alloys are clearly identified in the alloy heading captions along with the data presentations.

3.6 General Notes

As stated earlier, the source of all of the data contained herein is the Alcoa Laboratories archives. In recording, reporting, and

archiving the data, the original investigators identified the individual lots of material with their own internal proprietary alphanumeric system. In preparing the data for presentation herein, all references to that system have been eliminated, because they add nothing to the interpretation of the data, and replaced with a “lot” identification.

In individual figures where data for multiple lots of material are presented together for consistency or completeness, the existence of multiple lots is indicated by the use of lot designations “A”, “B”, “C”, and so on. It is important to note that there is no relationship between the letters “A”, “B”, “C”, and so on shown in any one figure to those identifications in another; they should be interpreted as unique in each instance and used solely to demonstrate that data for multiple lots are represented in that figure.

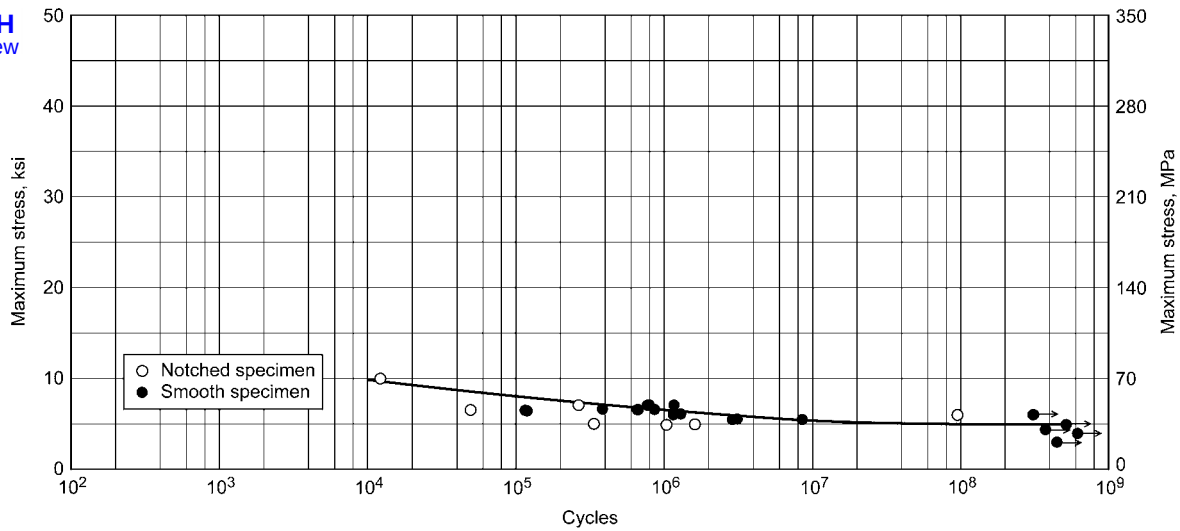
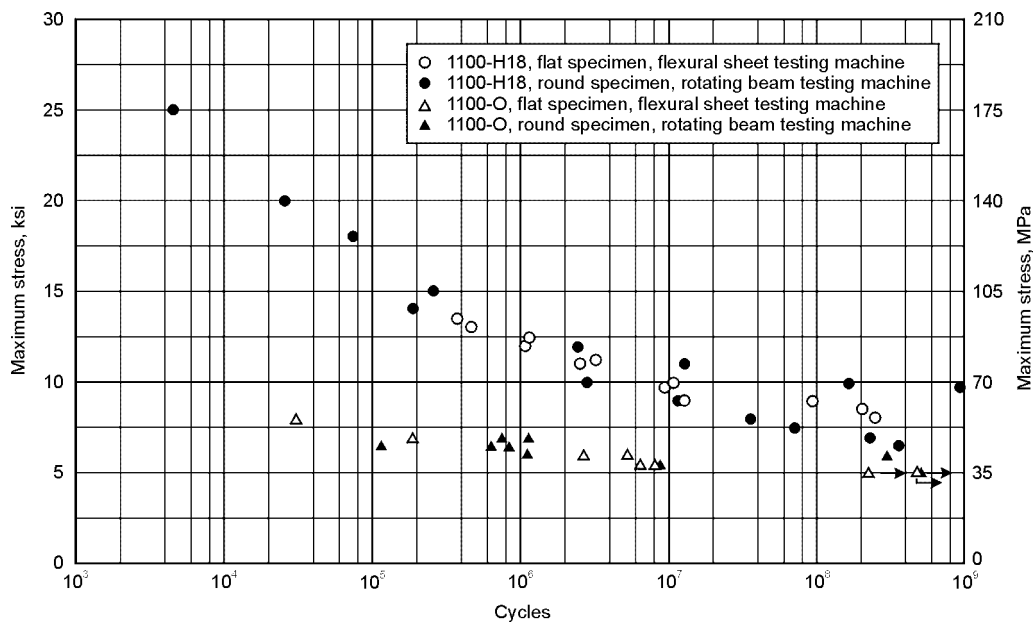
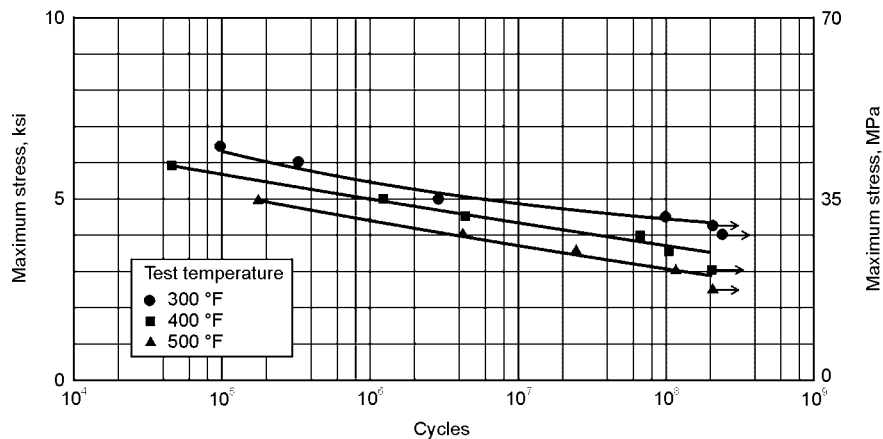
Finally, in the discussion in Chapters 4 through 10 that follows the fatigue curves, a number of illustrations of the various variables and their effects on fatigue strength and/or life are presented. However, these are not necessarily the only examples provided within the wealth of data herein. In each case, the intent is to provide representative examples where the alloy, temper, product, process, or environmental factors have been studied and to leave it to the reader to explore their particular interests in greater depth.

Definitions of the abbreviations and terms used in the examination of the small-specimen fatigue properties of aluminum alloys are provided in Appendix 3, “Glossary,” and Appendix 4, “Abbreviations and Symbols.”

REFERENCES

1. *Aluminum Standards and Data (Standard and Metric Editions)*, The Aluminum Association, Inc., Washington, D.C., 2006
2. *Standards for Aluminum Sand and Permanent Mold Casting*, The Aluminum Association, Inc., Washington, D.C., Dec 1992
3. *NADCA Product Specification Standards for Die Casting*, 5th ed., North American Die Casting Association (NADCA), Rosemont, IL, 2003
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5. D. Zalenas, Ed., *Aluminum Casting Technology*, 2nd ed., The American Foundrymen’s Society, Inc., Des Plaines, IL, 1993
6. *The NFFS Guide to Aluminum Casting Design: Sand and Permanent Mold*, Non-Ferrous Founders Society (NFFS), Des Plaines, IL, 1994
7. J.G. Kaufman and E.L. Rooy, *Aluminum Alloy Castings—Properties, Processes, and Applications*, ASM International, 2004
8. *Designations and Chemical Composition Limits for Wrought Aluminum Alloys and Aluminum Alloys in the Form of Castings and Ingot*, The Aluminum Association Alloy and Temper Registrations Records, The Aluminum Association, Inc., Washington, D.C., (updated periodically)
9. J.G. Kaufman, Ed., *Properties of Aluminum Alloys—Tensile, Creep, and Fatigue Data at High and Low Temperatures*, The Aluminum Association, Inc. and ASM International, Dec 1999

Data Set—Sequence of Curves by Alloy

**LIVE GRAPH**
[Click here to view](#)**Fig. 1100.RB01** Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1100-O rolled and drawn rod, smooth and sharply notched specimens**LIVE GRAPH**
[Click here to view](#)**Fig. 1100.FL01** Flexural fatigue ($R = -1.0$) curve for 0.064 in. thick 1100-O, H18 sheet**LIVE GRAPH**
[Click here to view](#)**Fig. 1100.HT01** Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 1100-O rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)

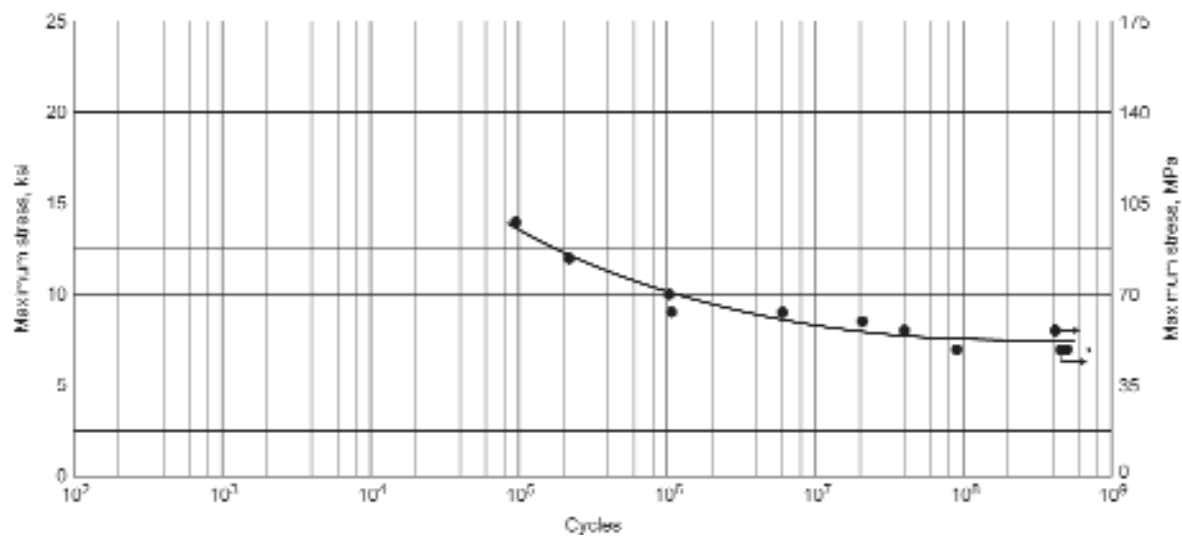


Fig. 1100.RB02 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1100-H14 rolled and drawn rod, smooth specimens

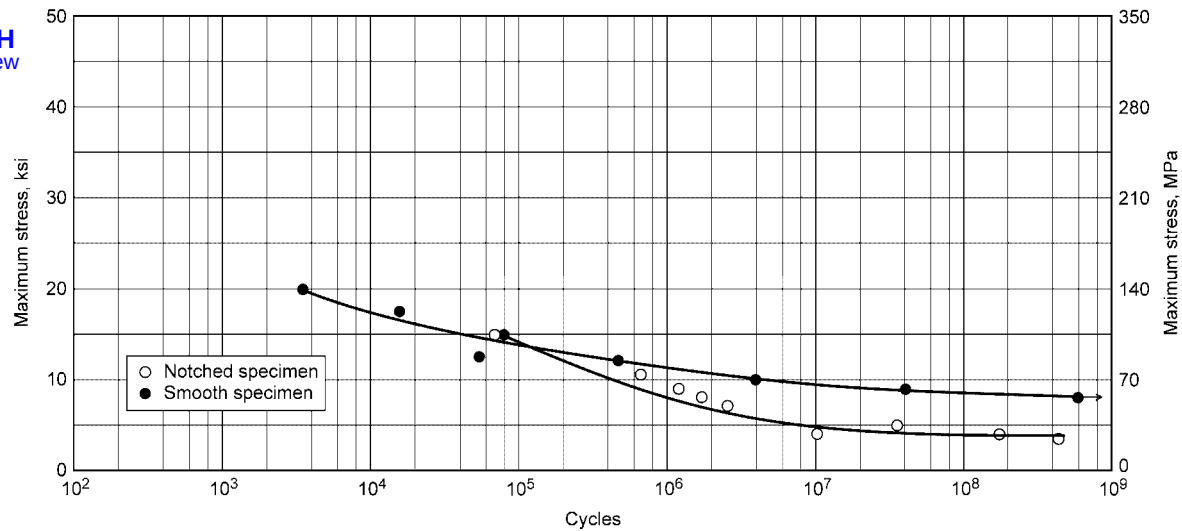


Fig. 1100.RB03 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1100-H16 rolled and drawn rod, smooth and sharply notched specimens

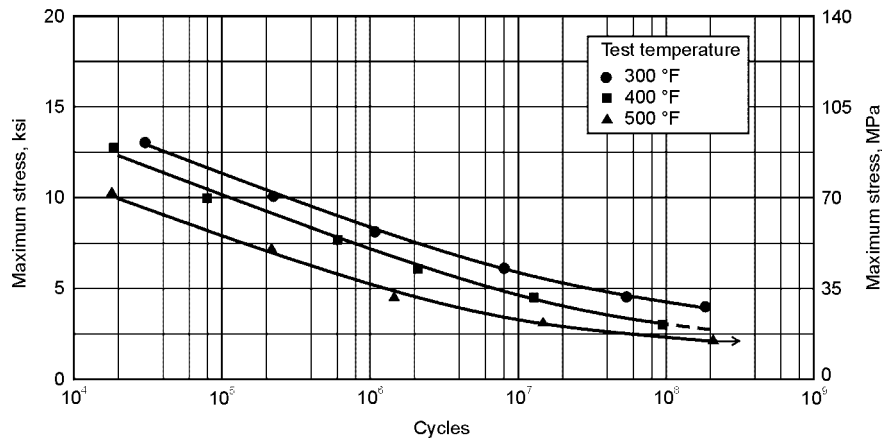


Fig. 1100.HT02 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 1100-H16 rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)

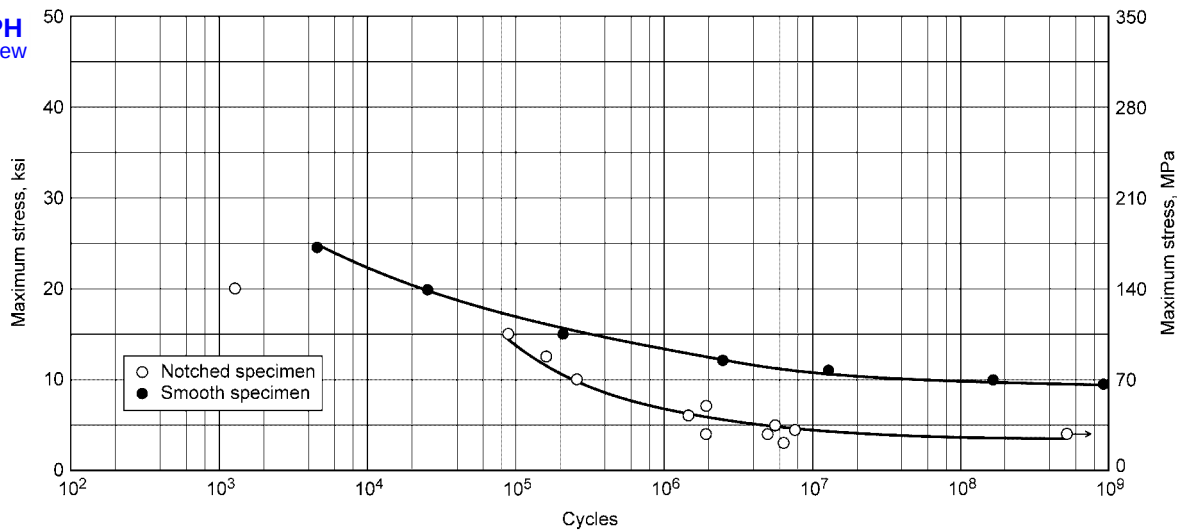


Fig. 1100.RB04 Rotating-beam ($R = -1.0$) fatigue curve for 1100-H18 3/4 in. diam rolled and drawn rod, smooth and sharply notched specimens

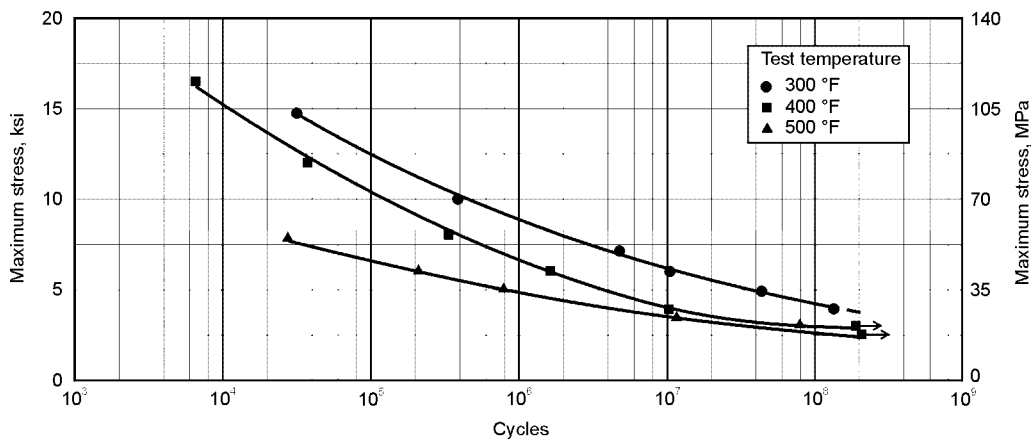


Fig. 1100.HT03 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 1100-H18 rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)

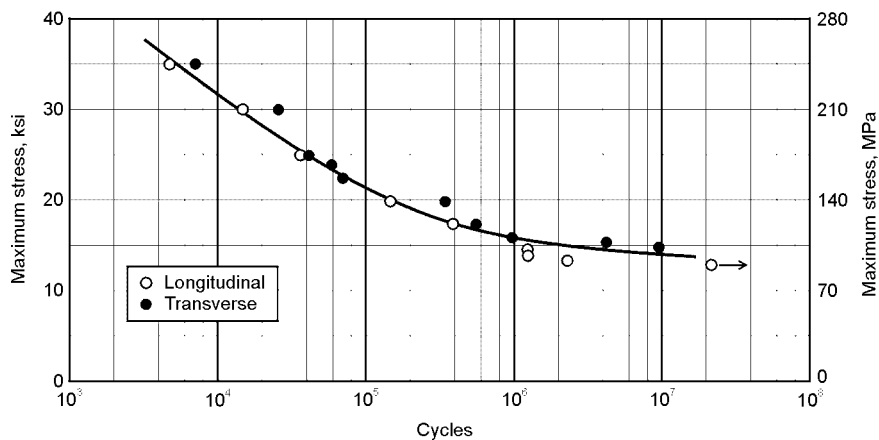


Fig. 1100.FL02 Flexural fatigue ($R = -1.0$) curve for 0.012 in. thick 1100-H19 litho sheet

 **LIVE GRAPH**
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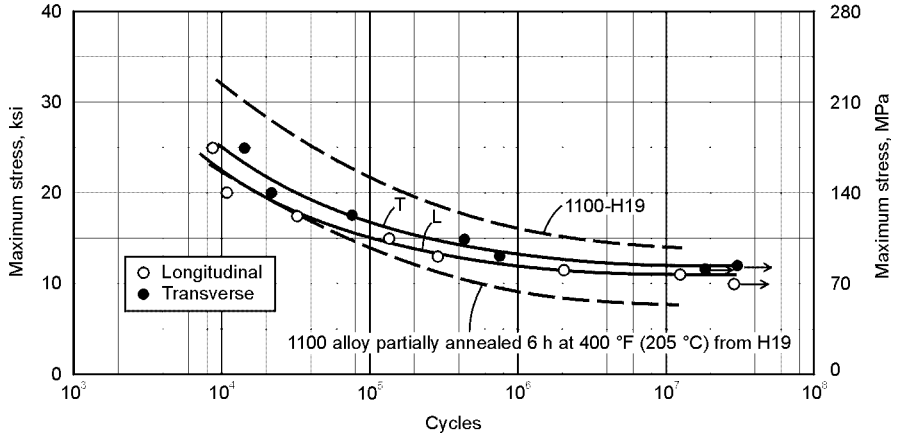


Fig. 1100.FL03 Flexural fatigue ($R = -1.0$) curve for 0.011 in. thick 1100-H19 litho sheet

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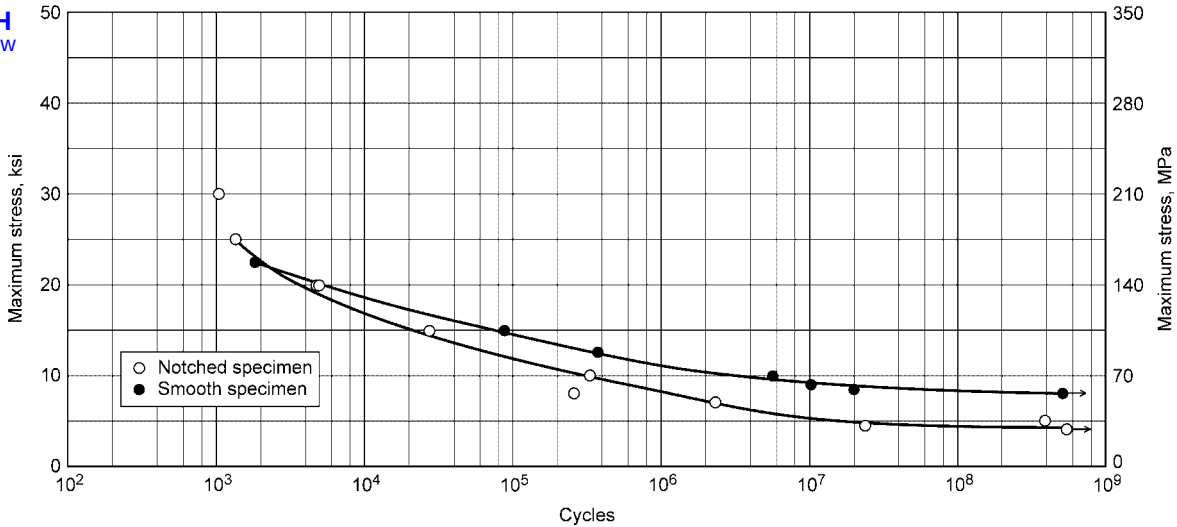


Fig. 1100.RB05 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1100-H26 rolled and drawn rod, smooth and sharply notched specimens

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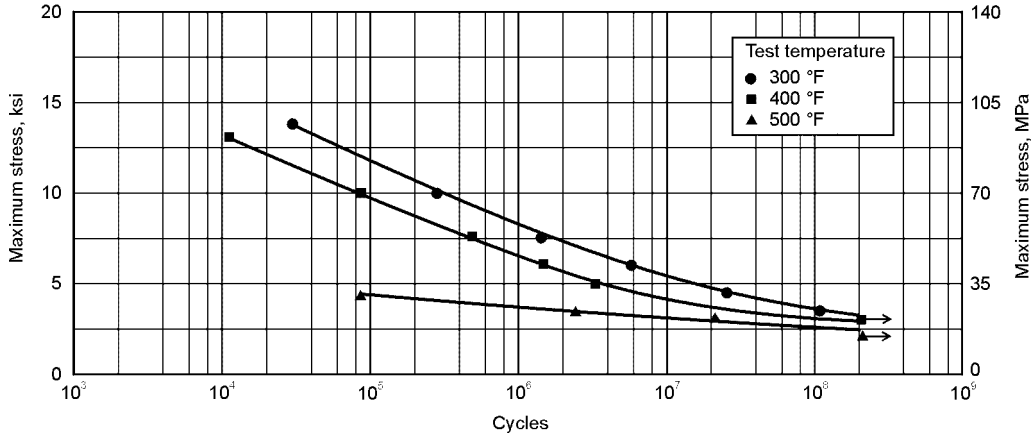


Fig. 1100.HT04 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 1100-H26 rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)



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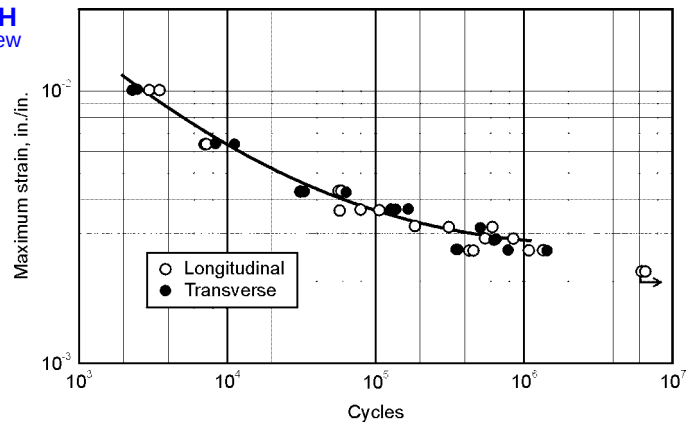


Fig. 1100.FL04 Plane bending ($R = 0.0$) fatigue curve for 0.013 in. thick 1100-H26 sheet



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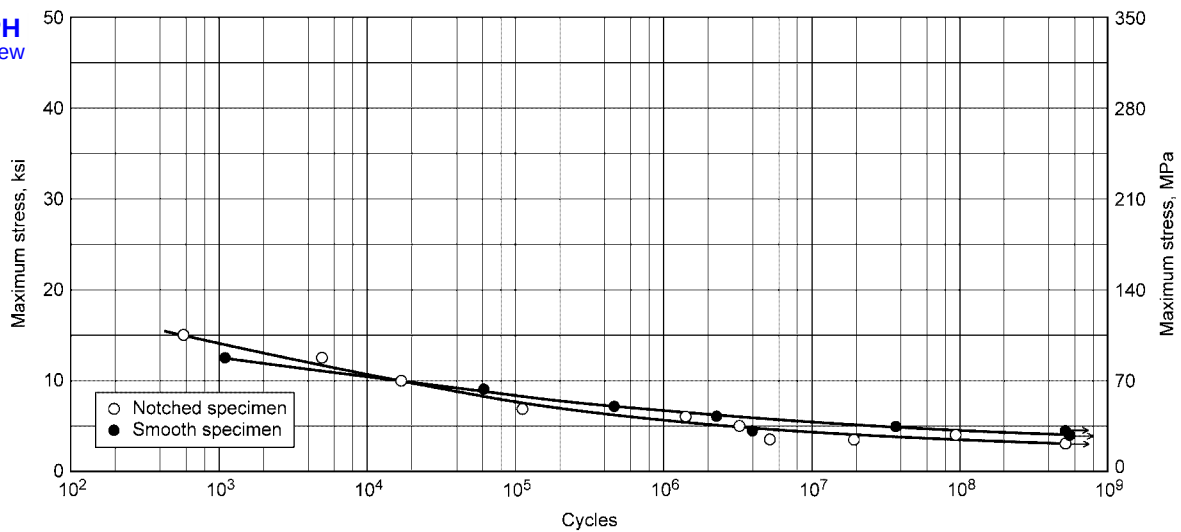


Fig. 1160.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1160-H12 rolled and drawn rod, smooth and sharply notched specimens. Inactive alloy



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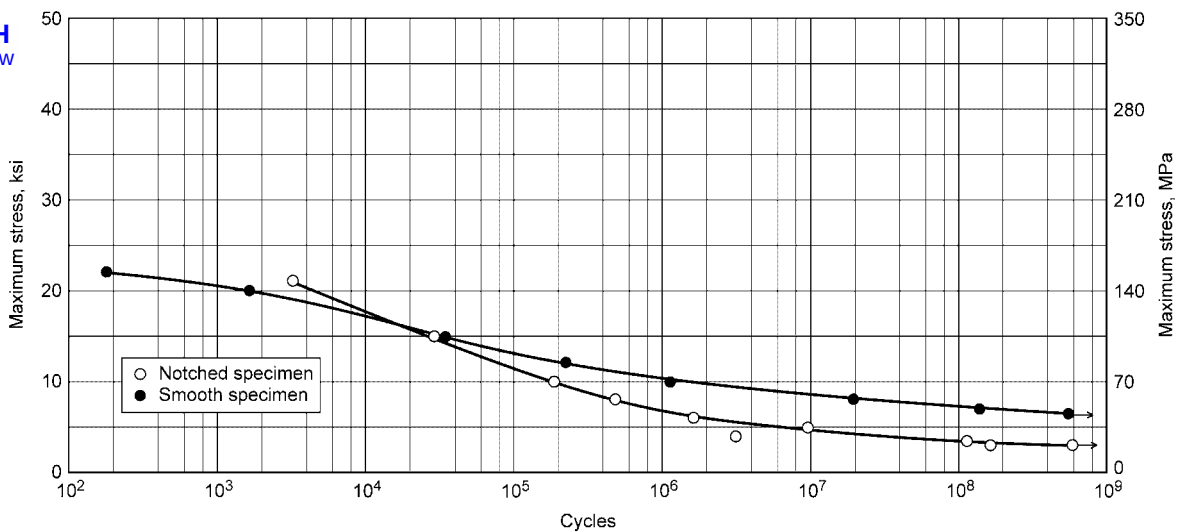


Fig. 1160.RB02 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1160-H18 rolled and drawn rod, smooth and sharply notched specimens. Inactive alloy

 **LIVE GRAPH**
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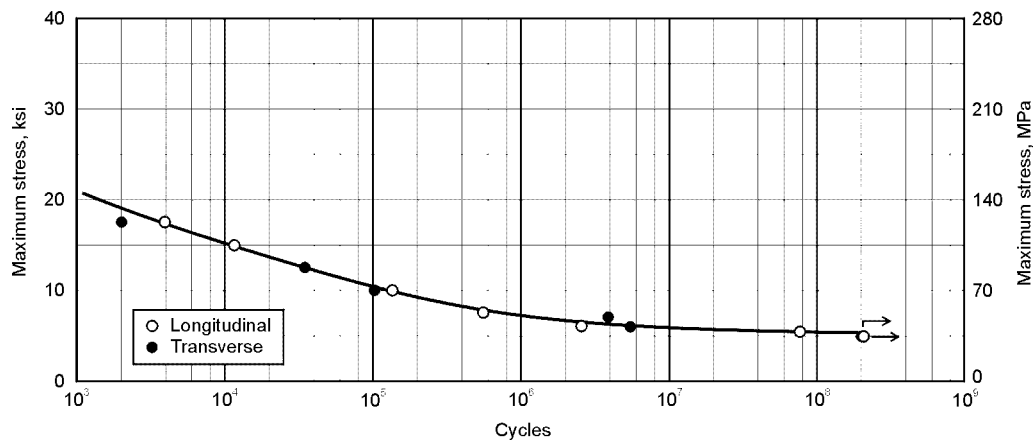


Fig. 1160.FL01 Flexural fatigue ($R = -1.0$) curve for 0.064 in. thick 1160-H14 sheet. Inactive alloy

 **LIVE GRAPH**
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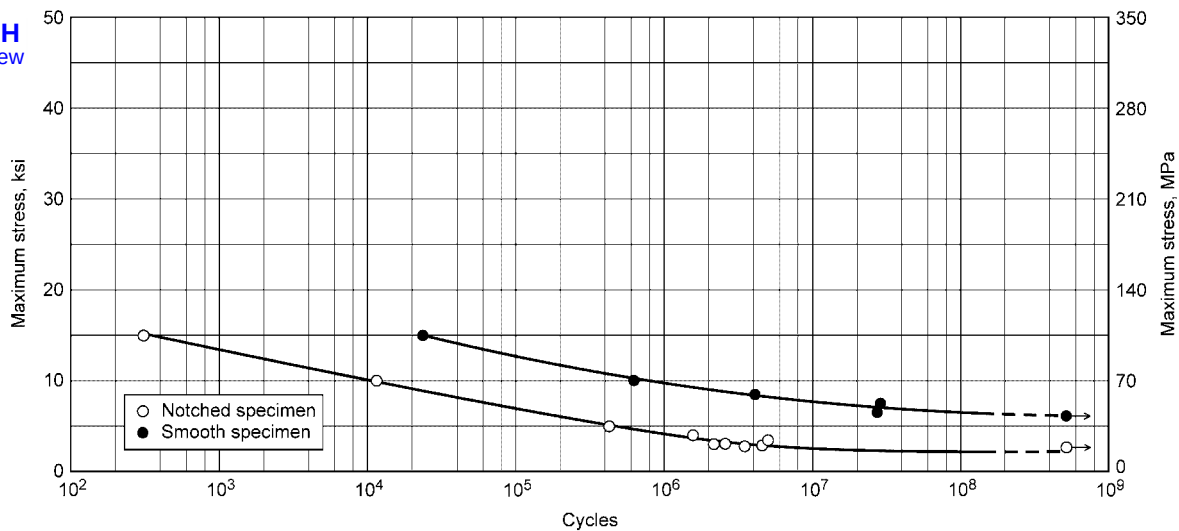


Fig. 1350.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1350-H12 rolled and drawn rod, smooth and sharply notched specimens

 **LIVE GRAPH**
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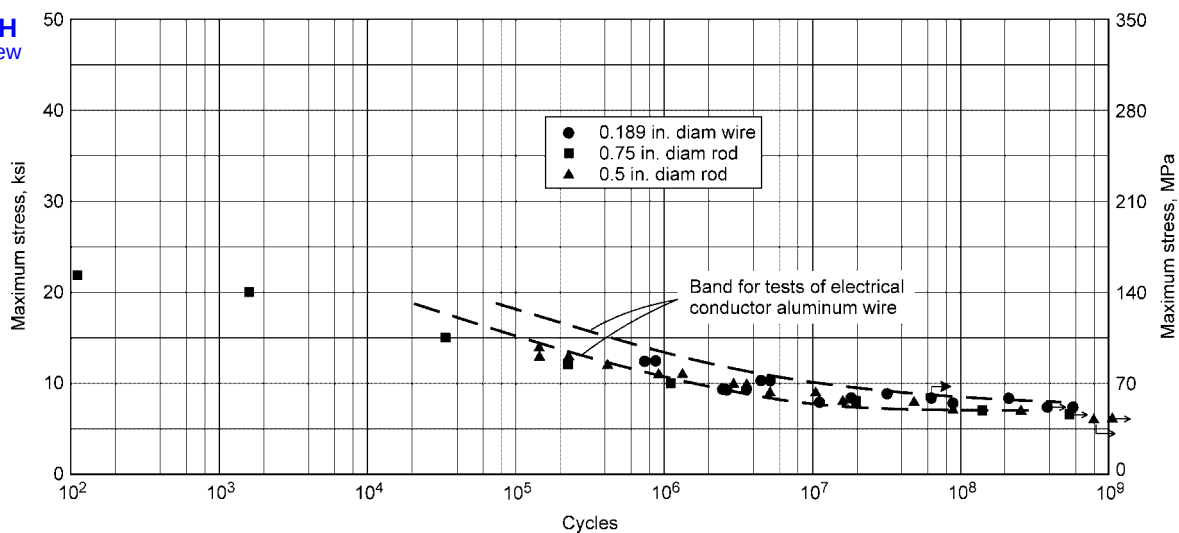


Fig. 1350.RB02 Rotating-beam ($R = -1.0$) fatigue curve for 1350-H18 wire and rolled and drawn rod, long-span smooth specimens. Diam: 0.189 to 0.75 in.

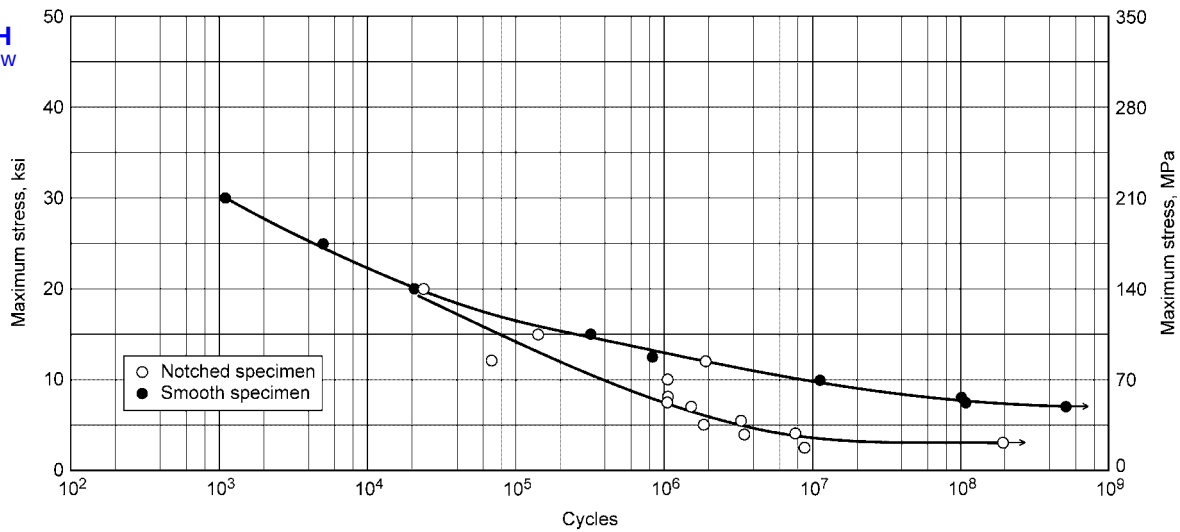


Fig. 1350.RB03 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1350-H19 rolled and drawn rod, smooth and sharply notched specimens

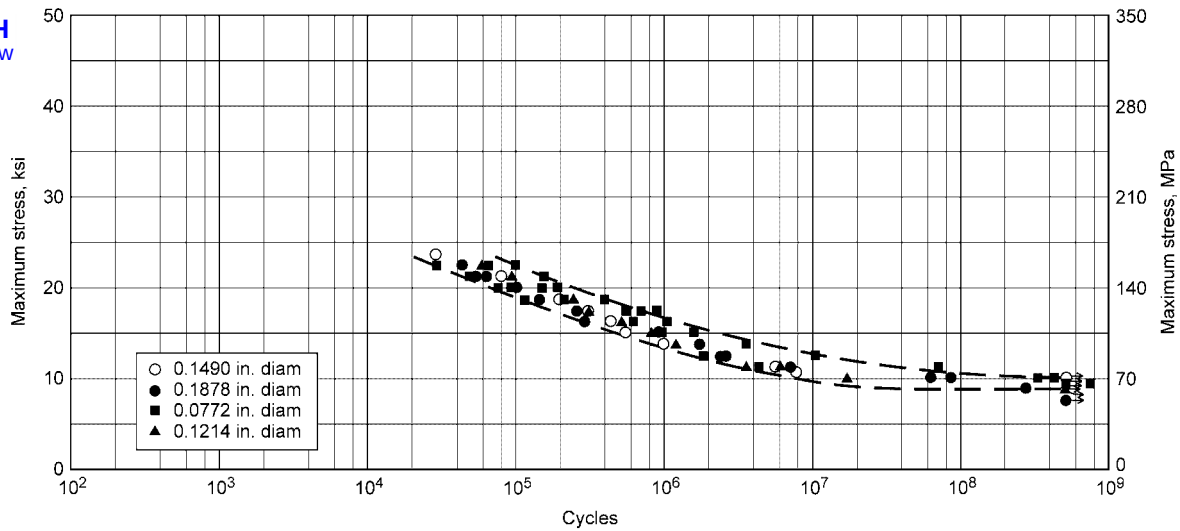


Fig. 1350.RB04 Rotating-beam ($R = -1.0$) fatigue curve for 1350-H19 wire, long-span smooth specimens. Diam: 0.0772 to 0.1878 in.

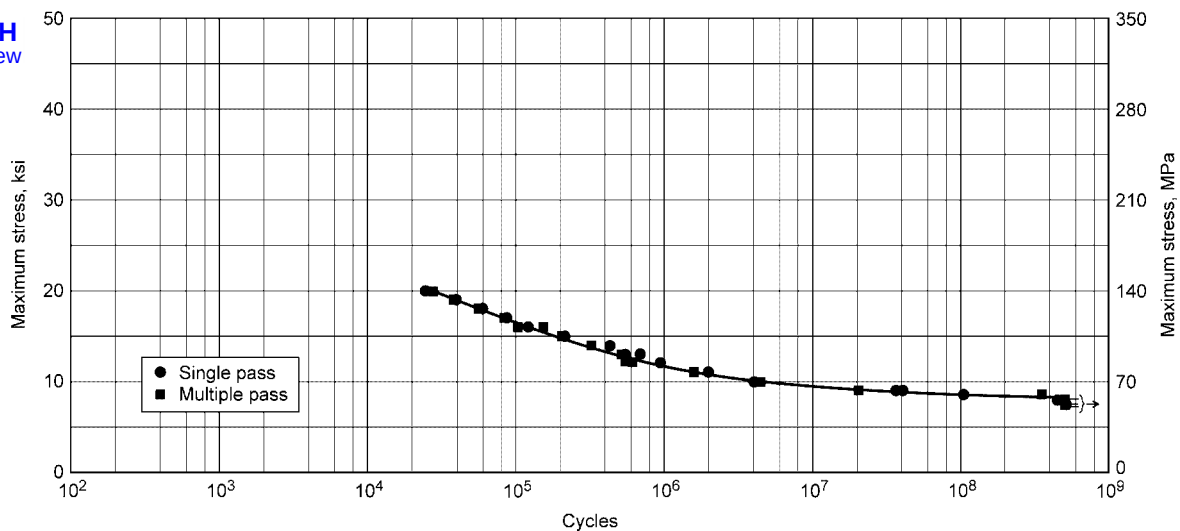


Fig. 1350.RB05 Rotating-beam ($R = -1.0$) fatigue curve for 1350-H39 wire, long-span smooth specimens

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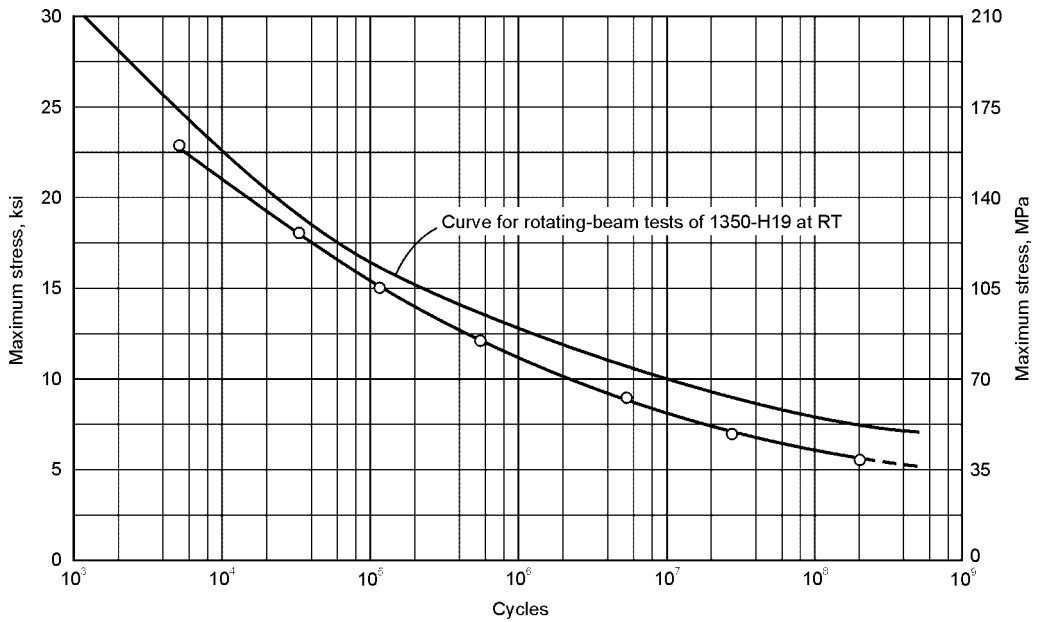


Fig. 1350.HT01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 1350-H19 rolled and drawn rod at 212 °F (100 °C)

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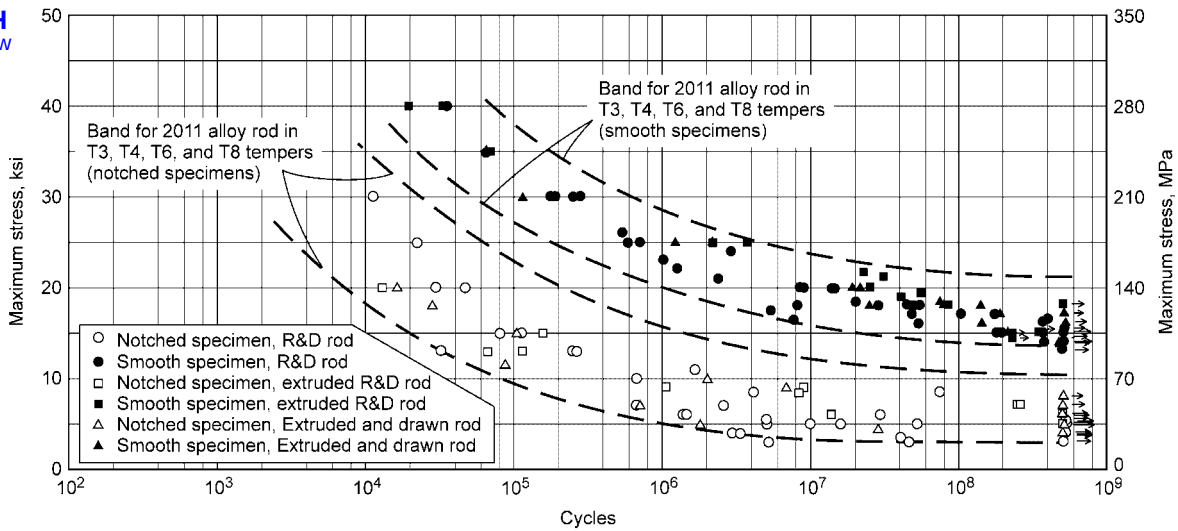


Fig. 2011.RB01 Rotating-beam ($R = -1.0$) fatigue curves for several 2011 cold finished rod products, smooth and sharply notched specimens. R&D, rolled and drawn



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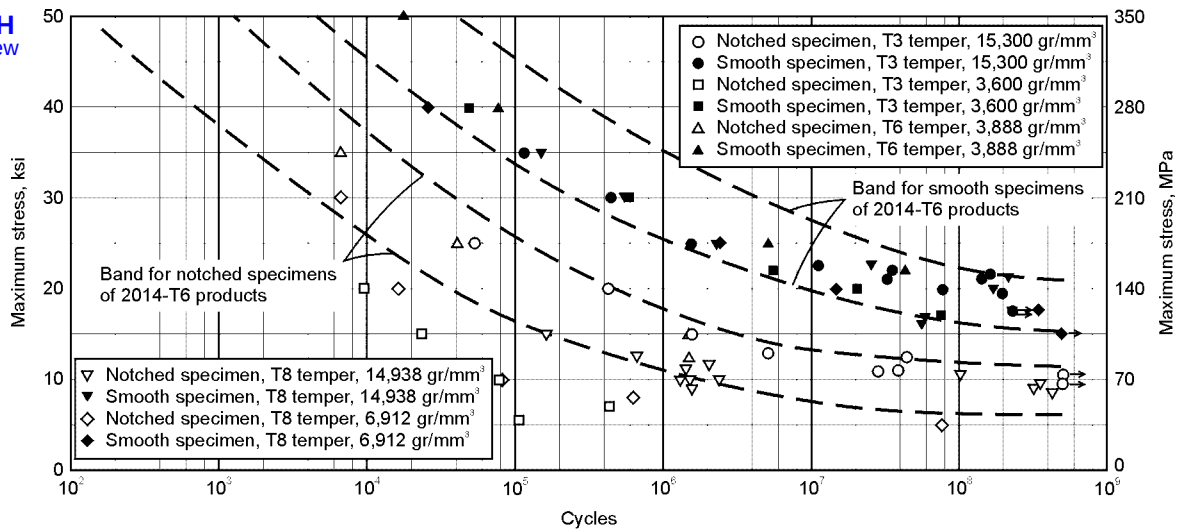


Fig. 2011.RB02 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T3, T6, and T8 rolled and drawn rod, smooth and sharply notched specimens. gr/mm³, grains/mm³



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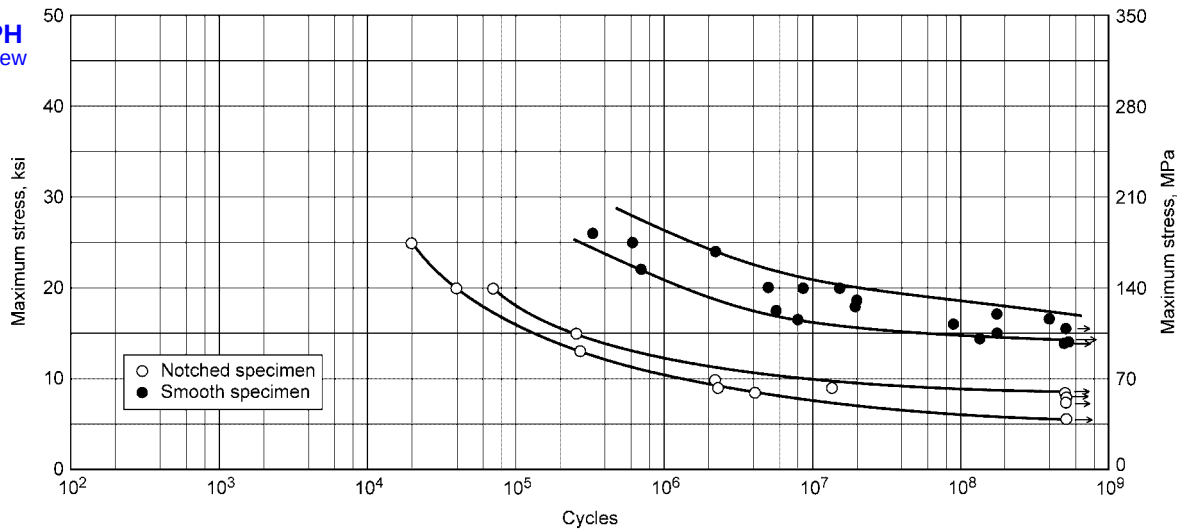


Fig. 2011.RB03 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T451 rolled and drawn rod, smooth and sharply notched specimens



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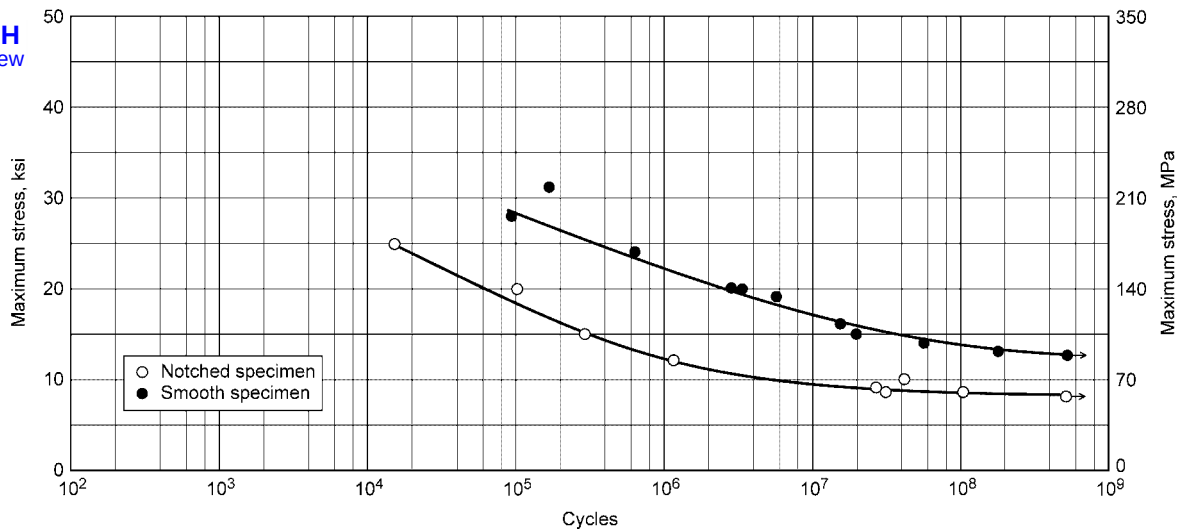


Fig. 2011.RB04 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T6 rolled and drawn rod, smooth and sharply notched specimens

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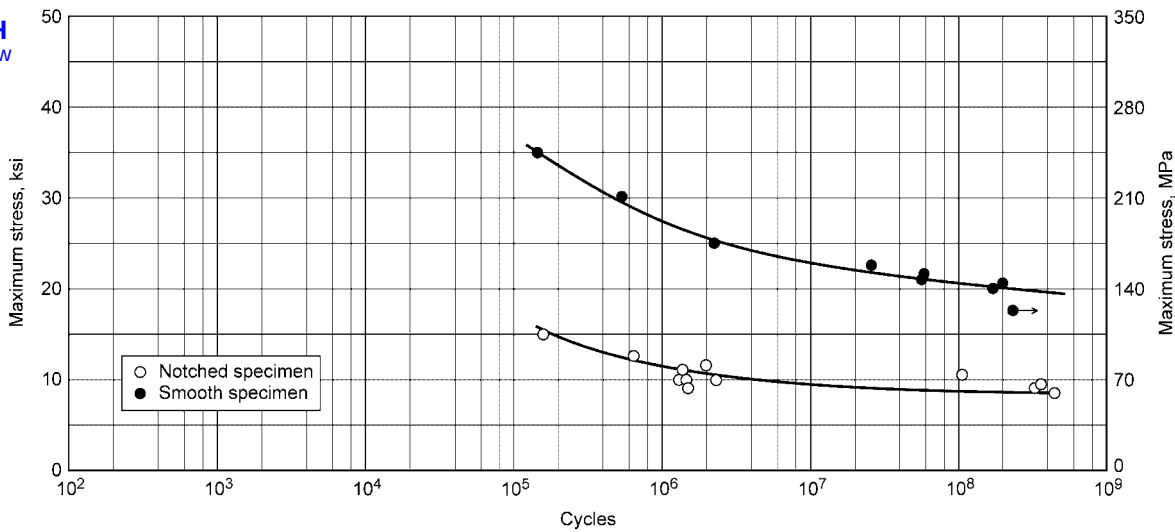


Fig. 2011.RB05 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T8 rolled and drawn rod, smooth and sharply notched specimens

 **LIVE GRAPH**
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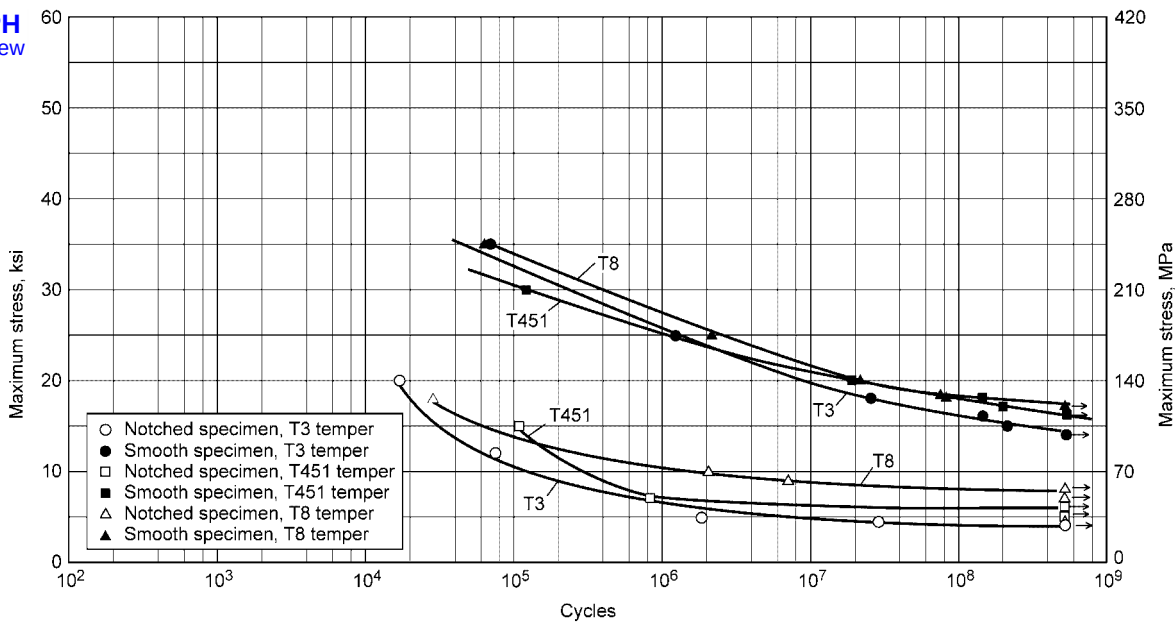


Fig. 2011.RB06 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T3, T451, and T8 extruded and drawn rod, smooth and sharply notched specimens

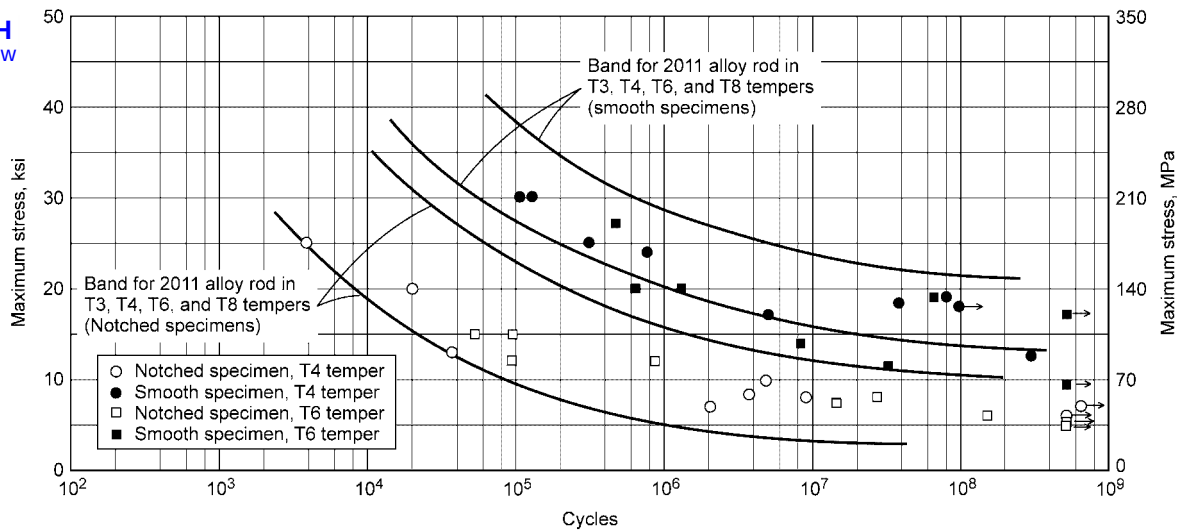


Fig. 2011.RB07 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T4 and T6 HDC cast rod, smooth and sharply notched specimens. Line through data point indicates specimens from near surface of rod. All other specimens were from center of rod.

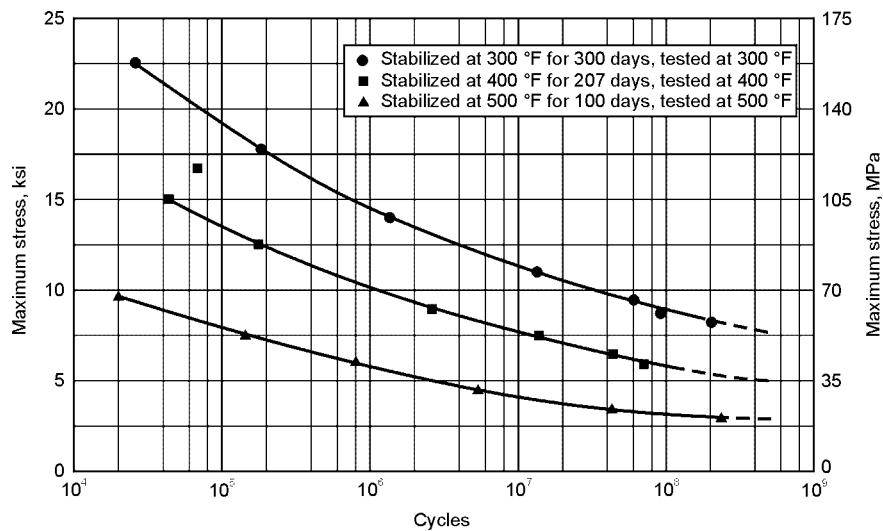


Fig. 2011.HT01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2011-T3 rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)



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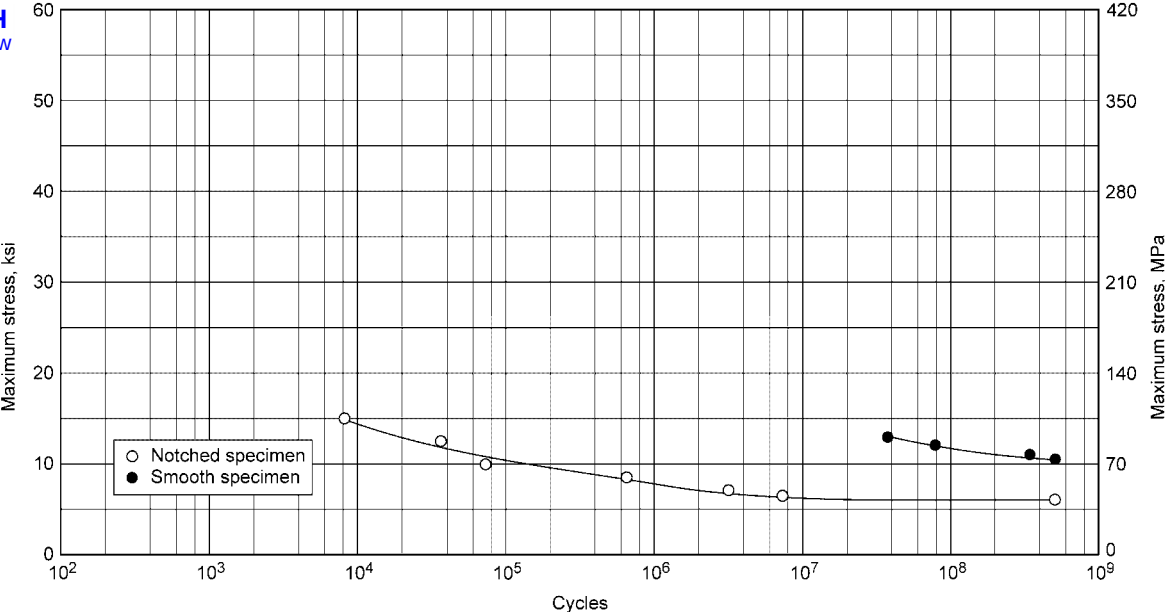


Fig. 2014.RB01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2014-O rolled and drawn rod, smooth and sharply notched specimens



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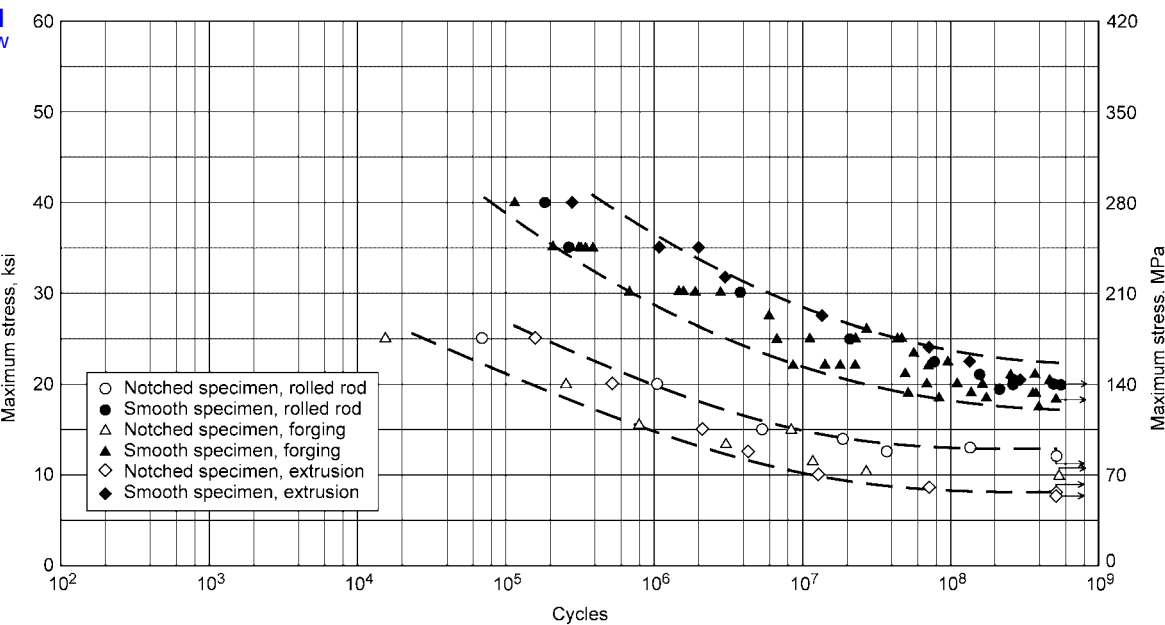


Fig. 2014.RB02 Rotating-beam ($R = -1.0$) fatigue curves for 2014-T4 rolled rod, forgings, and extrusions, smooth and sharply notched specimens



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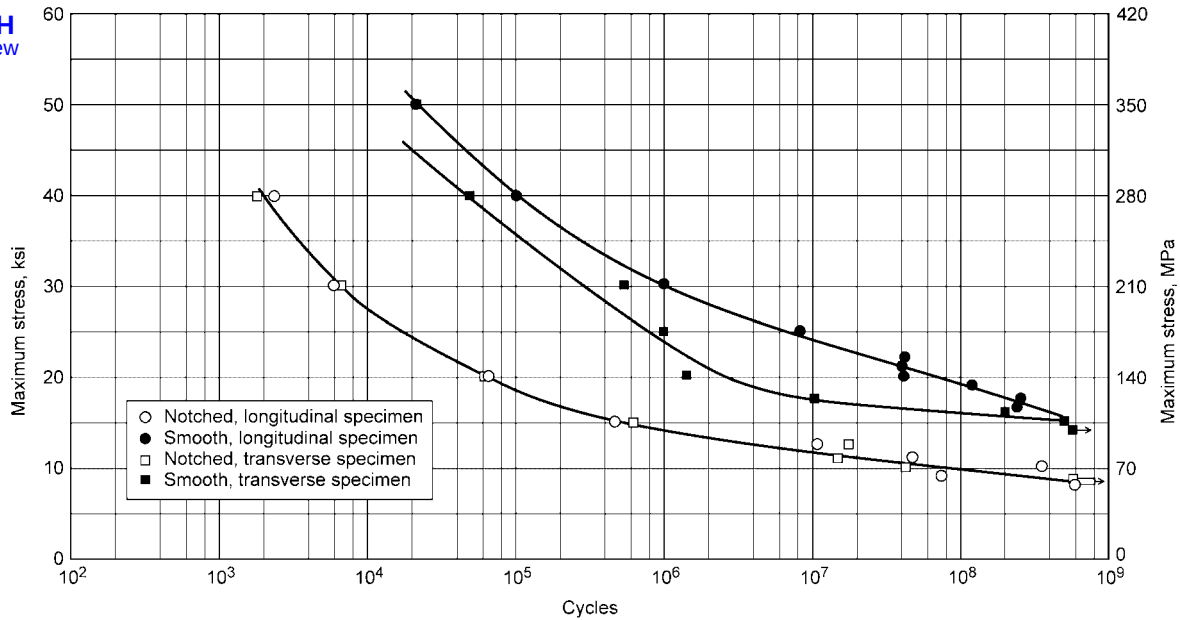


Fig. 2014.RB03 Rotating-beam ($R = -1.0$) fatigue curves for 5/8 in. thick 2014-T4 plate, smooth and sharply notched specimens. Test direction: longitudinal and transverse



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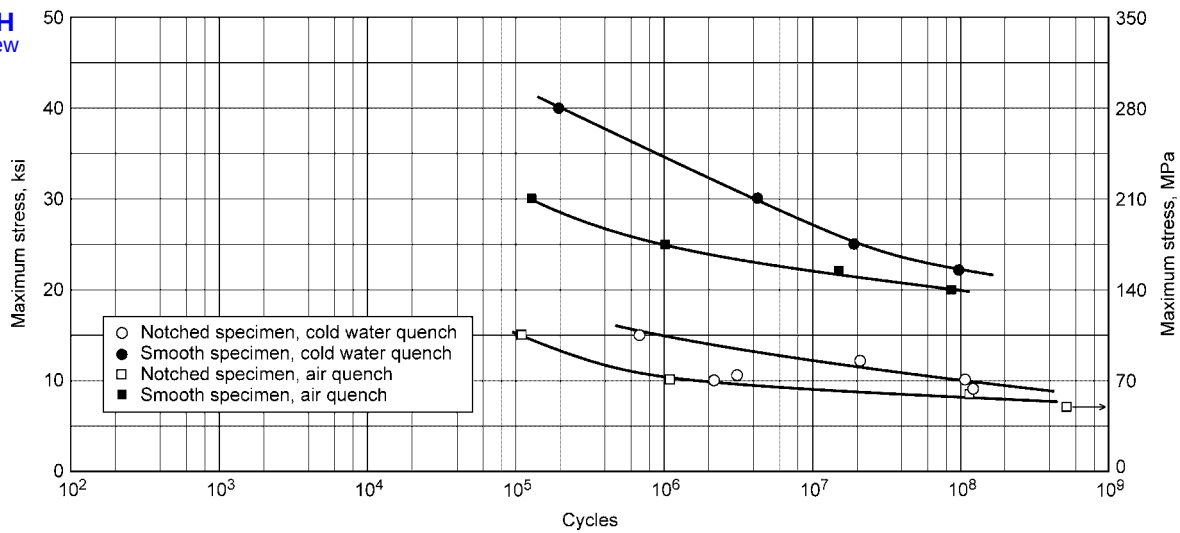


Fig. 2014.RB04 Rotating-beam ($R = -1.0$) fatigue curves for 8 in. diam 2014-T4 forging stock, smooth and sharply notched specimens. Cold water quench and air quench



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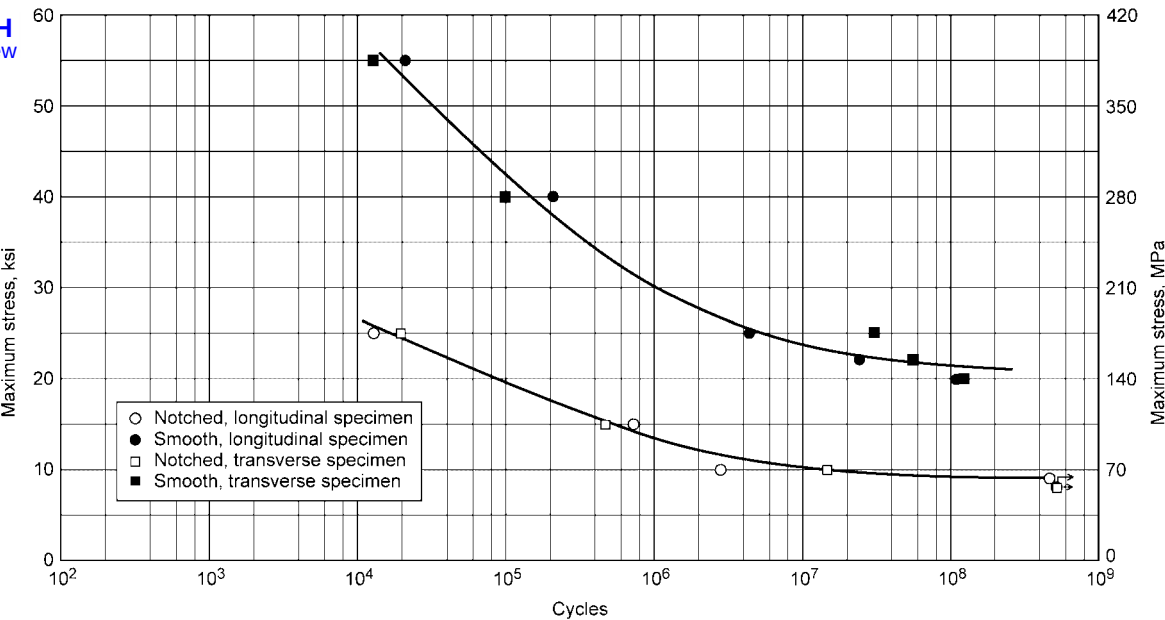


Fig. 2014.RB05 Rotating-beam ($R = -1.0$) fatigue curves for 5/8 in. by 3 1/2 in. 2014-T4 extruded bar, smooth and sharply notched specimens. Test direction: longitudinal and transverse



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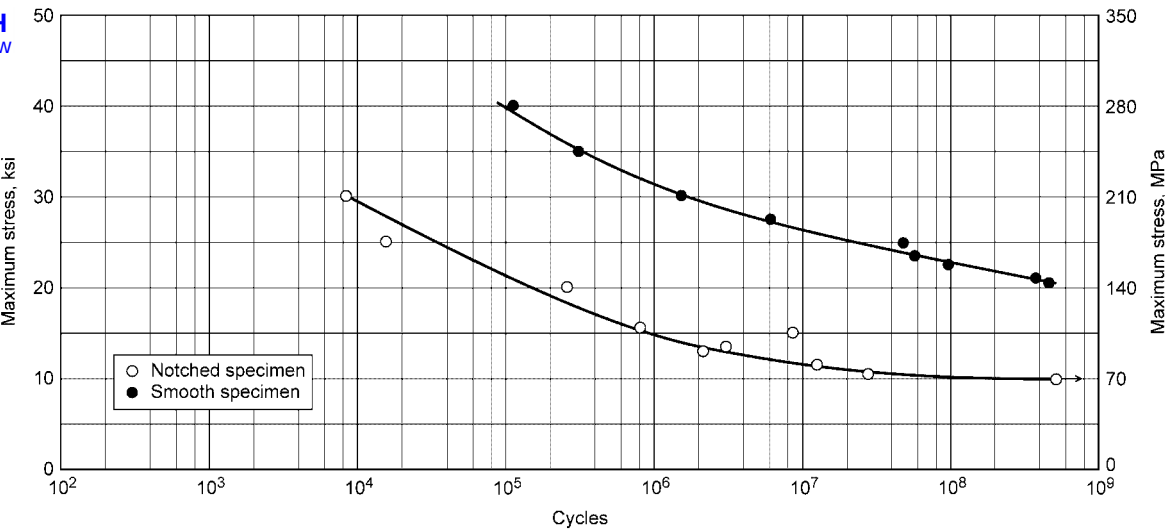


Fig. 2014.RB06 Rotating-beam ($R = -1.0$) fatigue curves for 7/8 in. diam 2014-T4 forged bar, smooth and sharply notched specimens

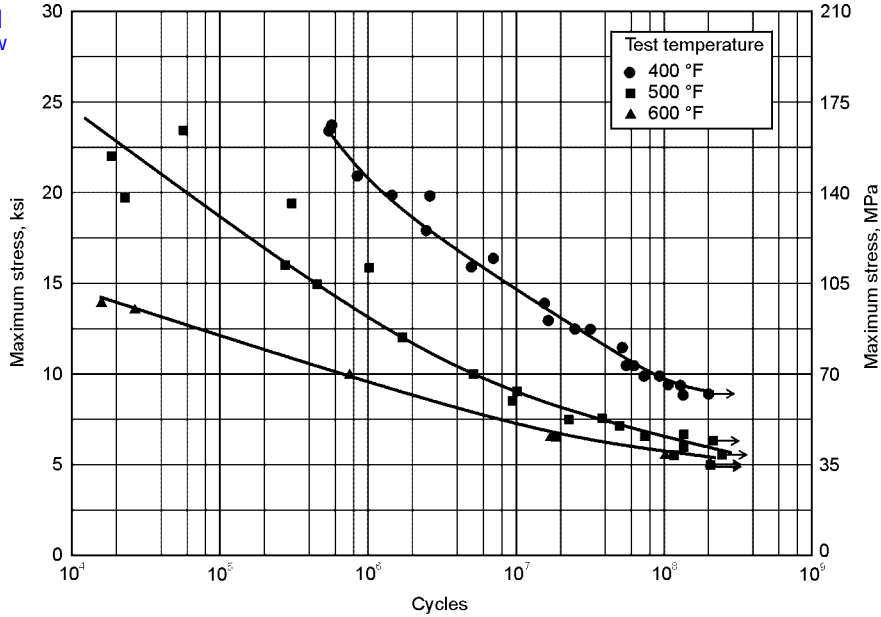


Fig. 2014.HT01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2014-T6 rolled and drawn rod at 400, 500, and 600 °F (205, 260, and 315 °C)

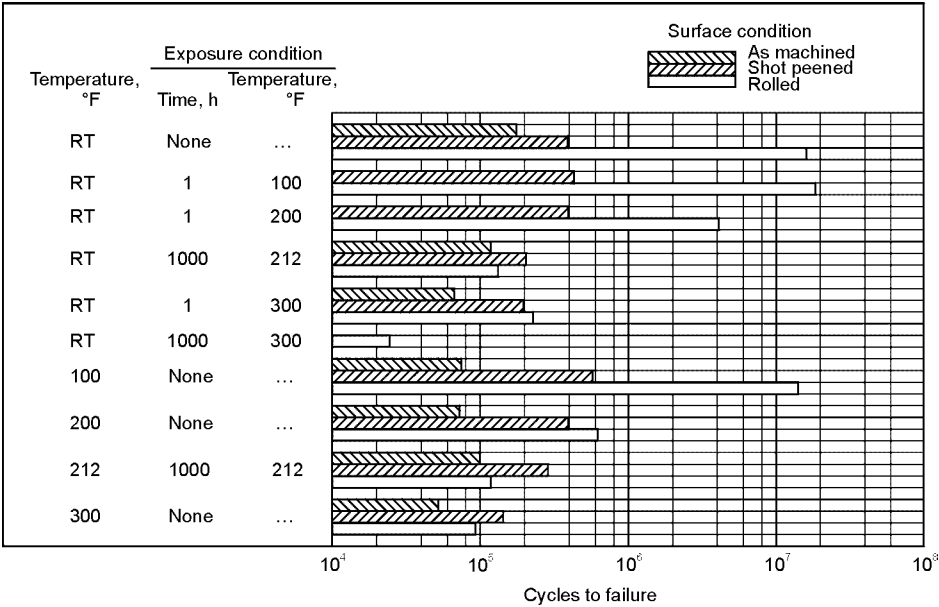


Fig. 2014.HT02 Rotating-beam ($R = -1.0$) fatigue curves for 1 in. diam 2014-T4 rolled and drawn rod shot peened rod at 40 ksi (280 MPa). Effect of shot peening and surface rolling. Longitudinal

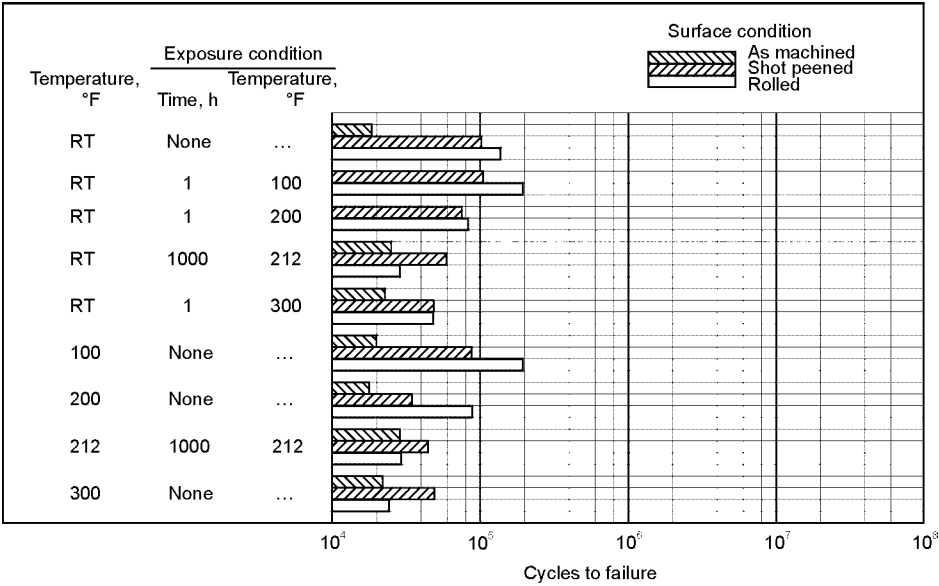


Fig. 2014.HT03 Rotating-beam ($R = -1.0$) fatigue curves for 1 in. diam 2014-T4 rolled and drawn rod shot peened rod at 50 ksi (350 MPa). Effect of shot peening and surface rolling. Longitudinal



LIVE GRAPH
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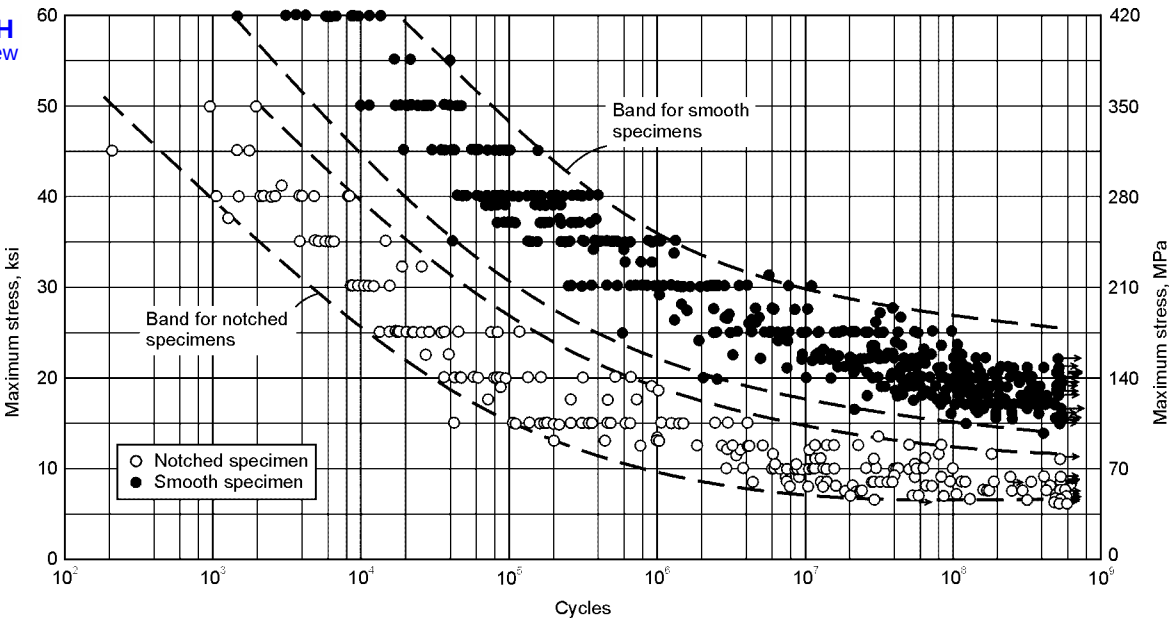


Fig. 2014.RB07 Rotating-beam ($R = -1.0$) fatigue curve for all 2014-T6 products, smooth and sharply notched specimens

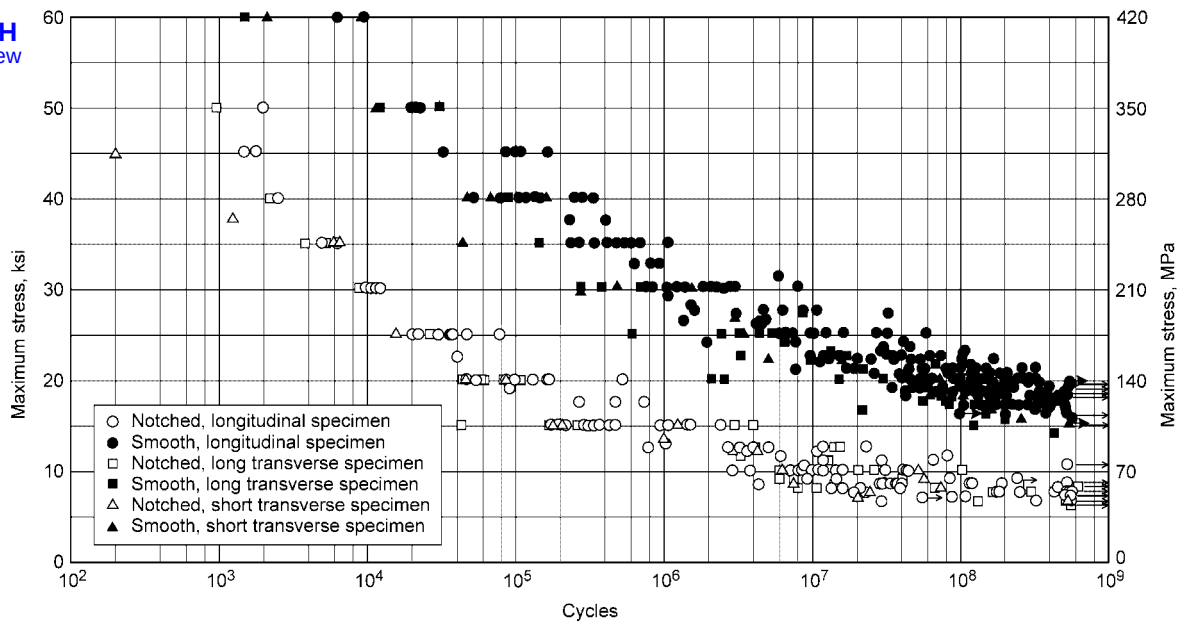


Fig. 2014.RB08 Rotating-beam ($R = -1.0$) fatigue curve for all 2014-T6 products, smooth and sharply notched specimens, effect of specimen orientation. Test direction: longitudinal, long transverse, and short transverse. Bands for data points are shown in Fig. 2014.RB09.

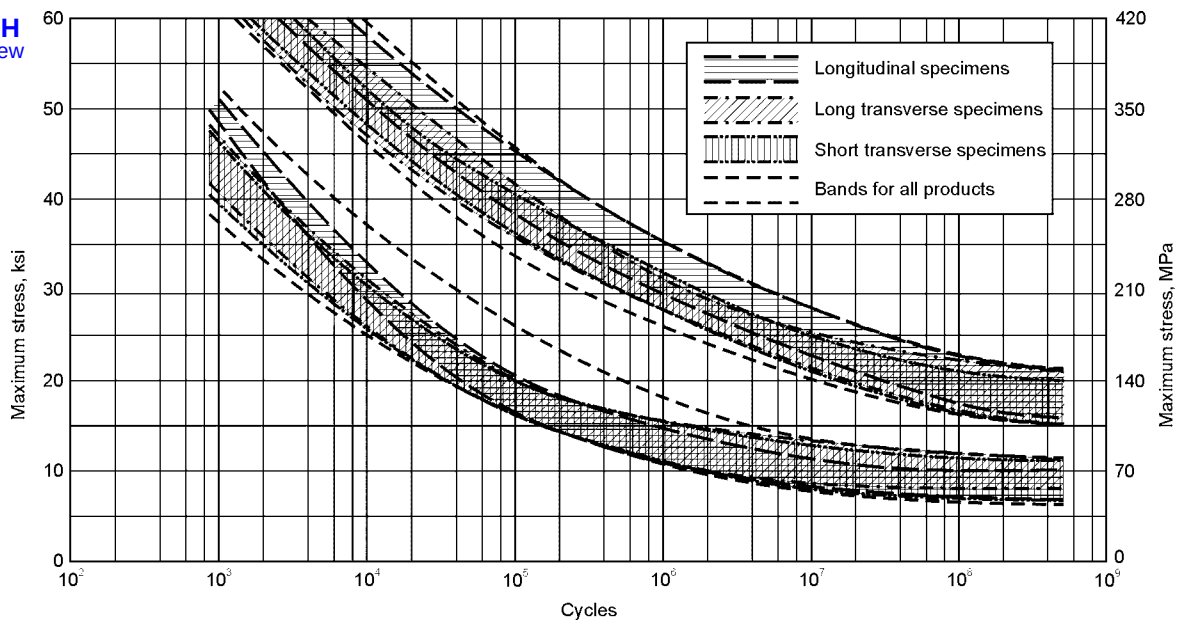


Fig. 2014.RB09 Rotating-beam ($R = -1.0$) fatigue curve for all 2014-T6 products, smooth and sharply notched specimens, effect of product form. Data points for bands are shown in Fig. 2014.RB08.

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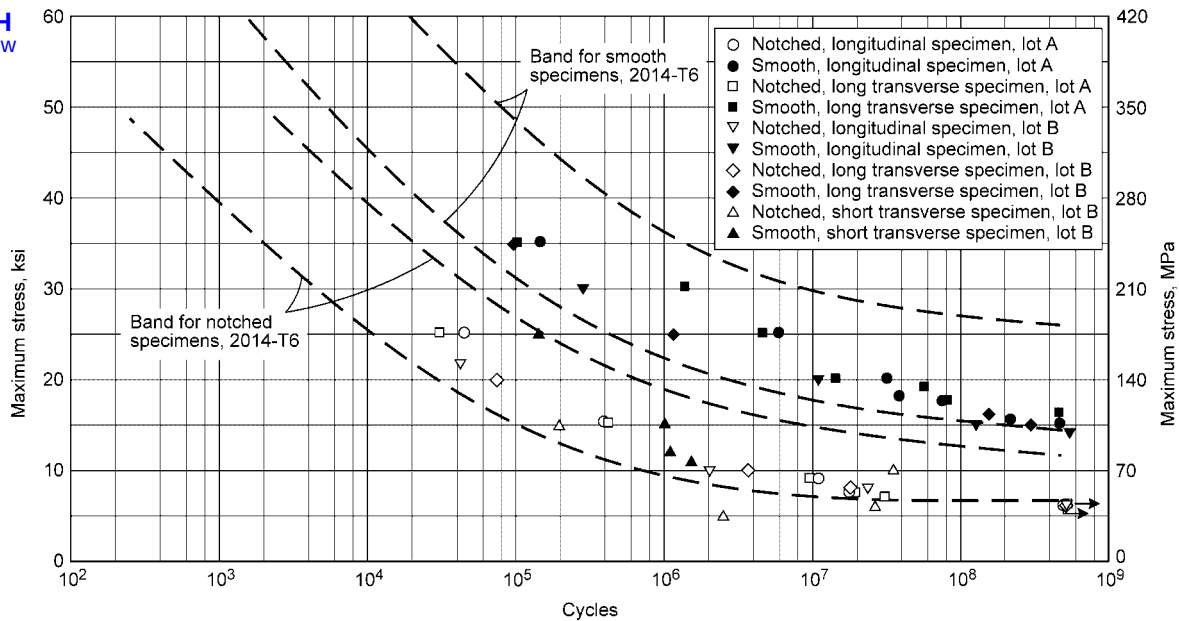


Fig. 2014.RB10 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T651 plate, smooth and sharply notched specimens. Two lots. Test direction: longitudinal, long transverse, and short transverse

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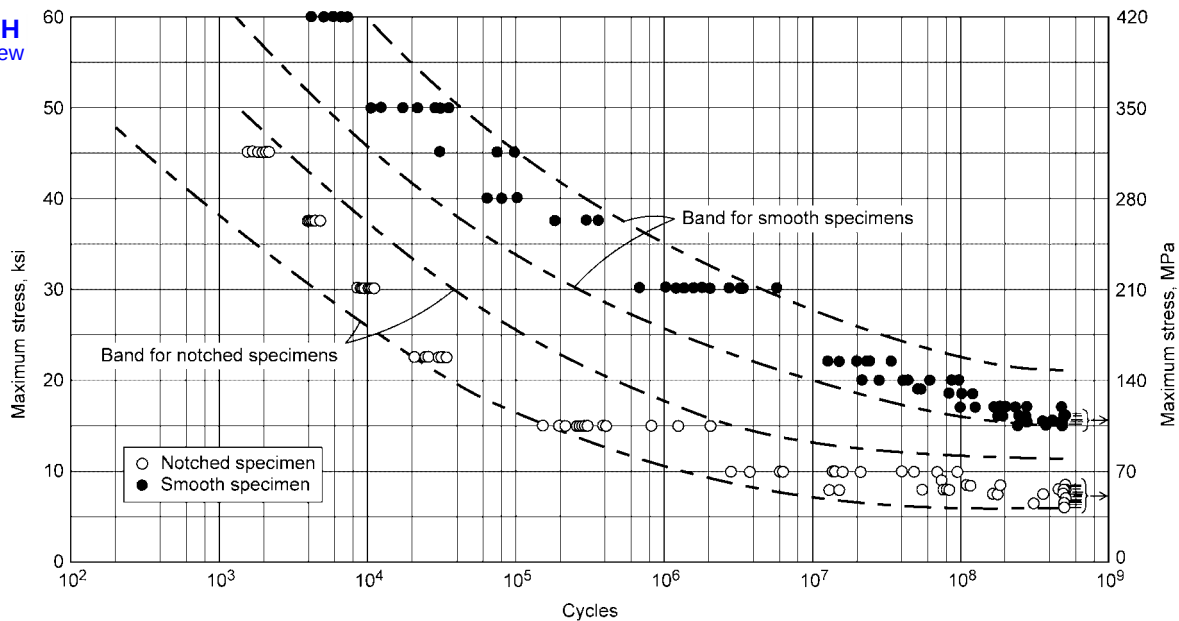


Fig. 2014.RB11 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T6 rolled spar chord, smooth and sharply notched specimens

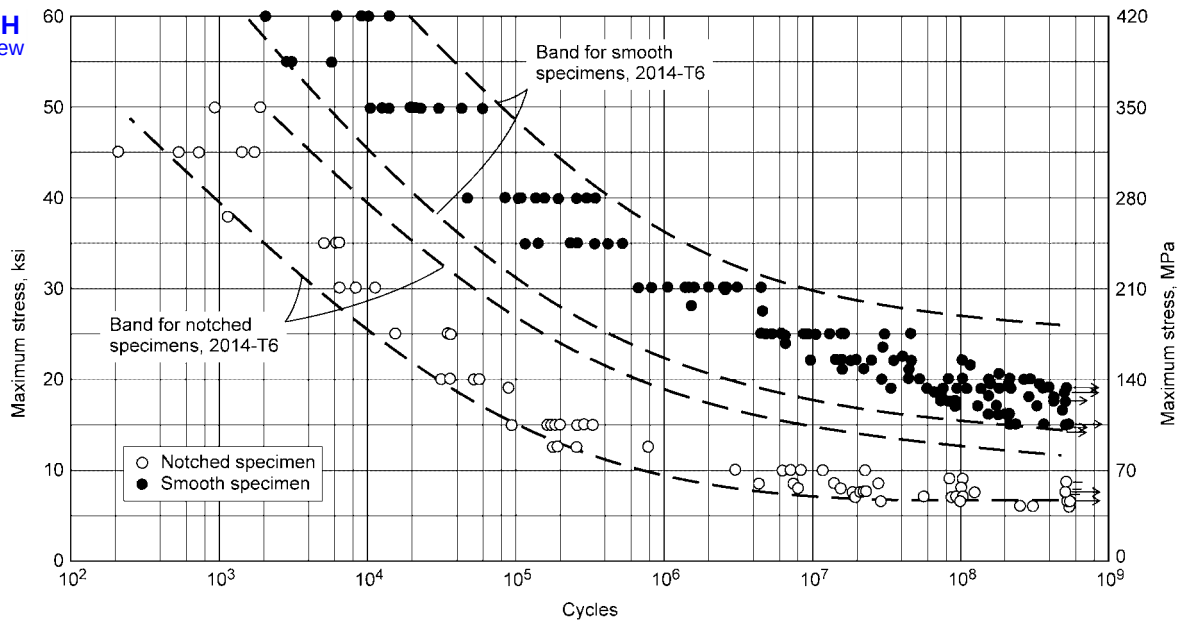


Fig. 2014.RB12 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T6 forgings, smooth and sharply notched specimens, all specimen orientations

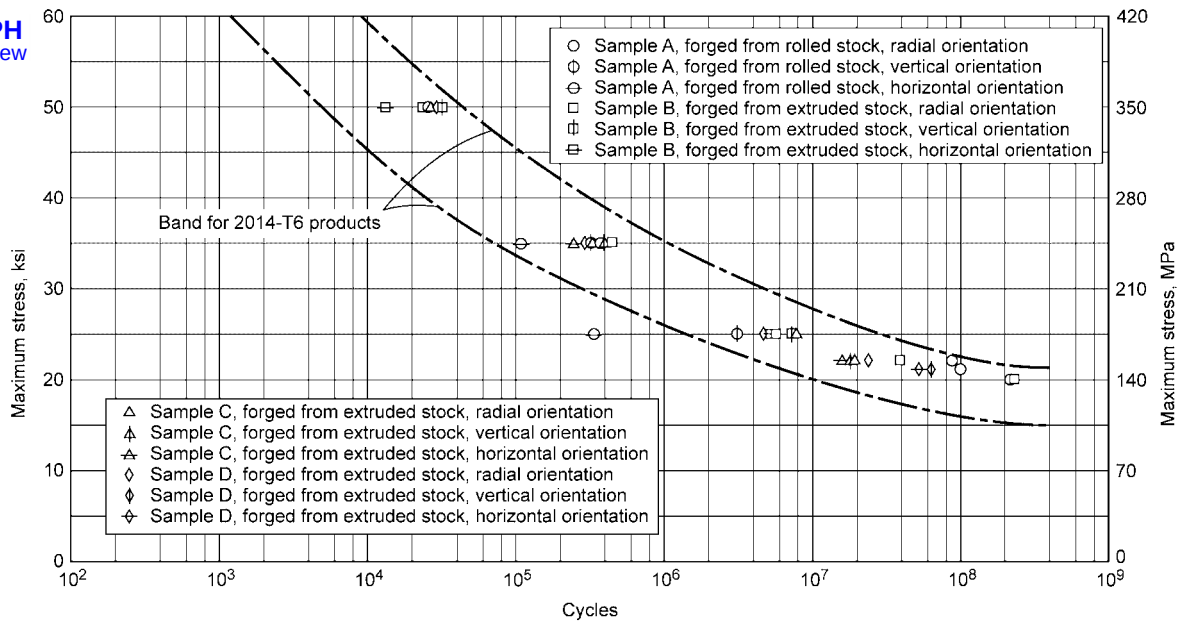


Fig. 2014.RB13 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T6 die forged impeller, smooth specimens, effect of type of forging stock



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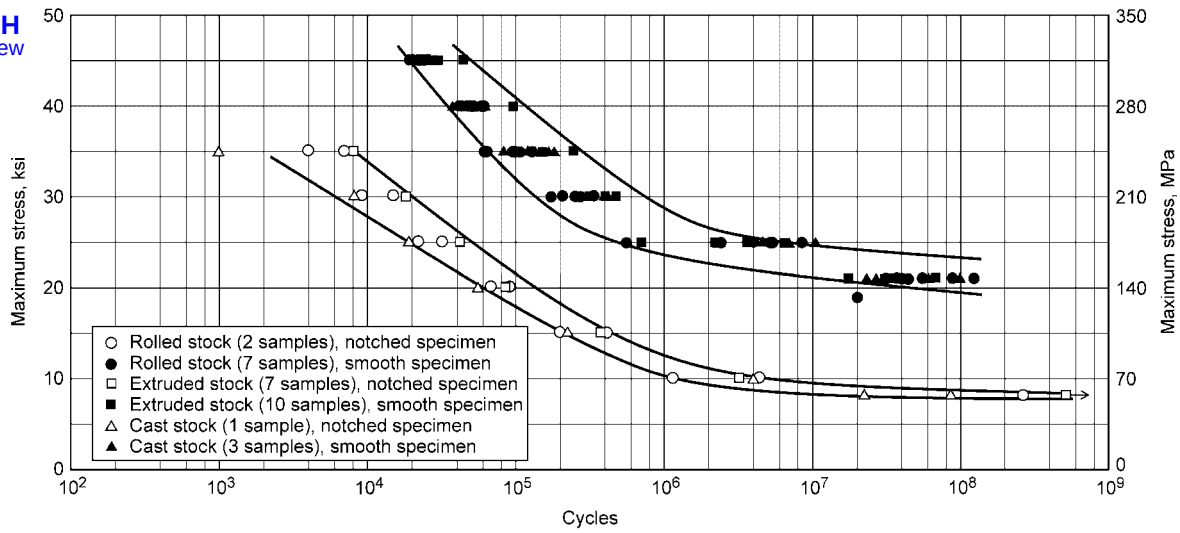


Fig. 2014.RB14 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T61 die forged aircraft wheels, smooth and sharply notched specimens, effect of forging stock



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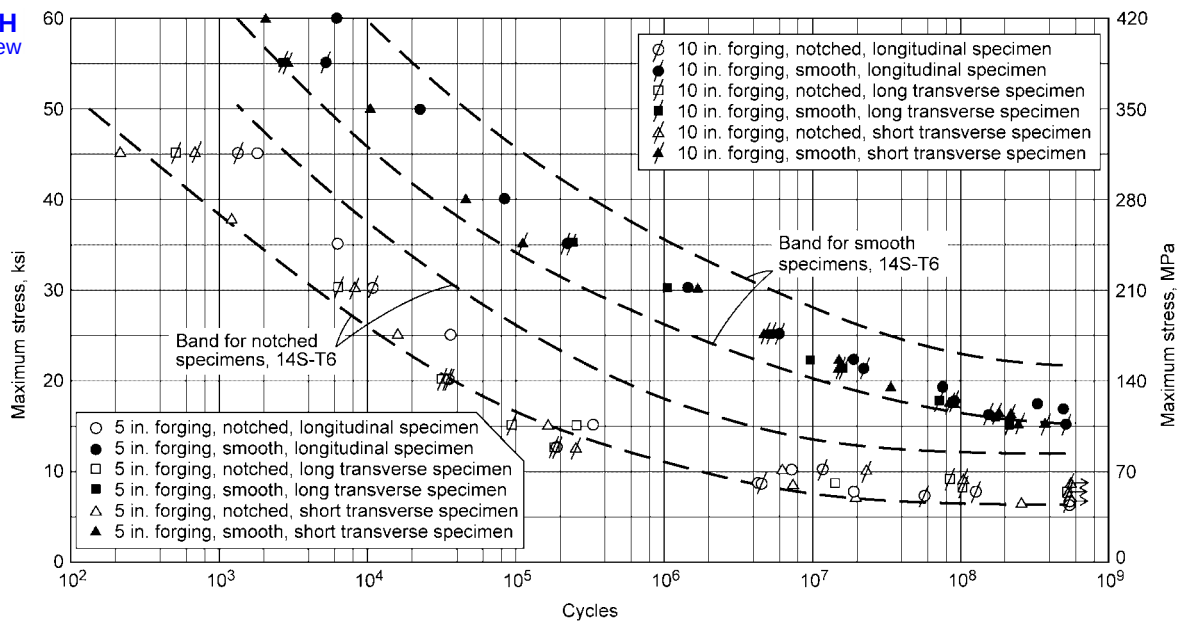


Fig. 2014.RB15 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T6 hand forgings (5 and 10 in. thick), smooth and sharply notched specimens, effect of specimen orientation

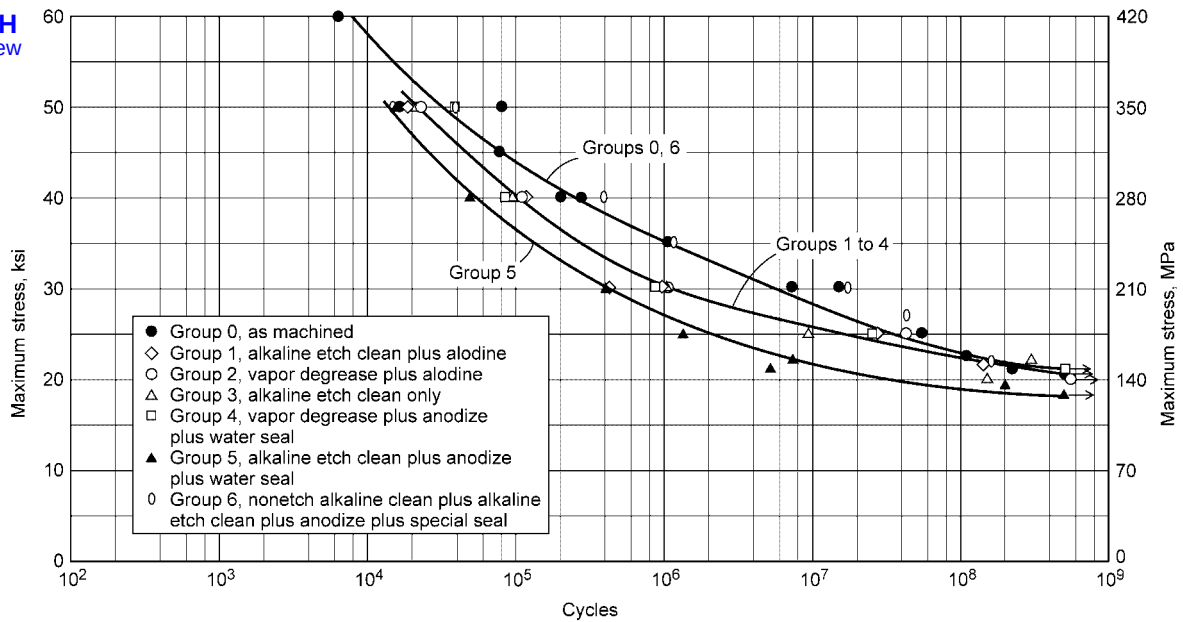


Fig. 2014.RB16 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T6 extruded rod, smooth and sharply notched specimens, effect of surface coating (treatment)

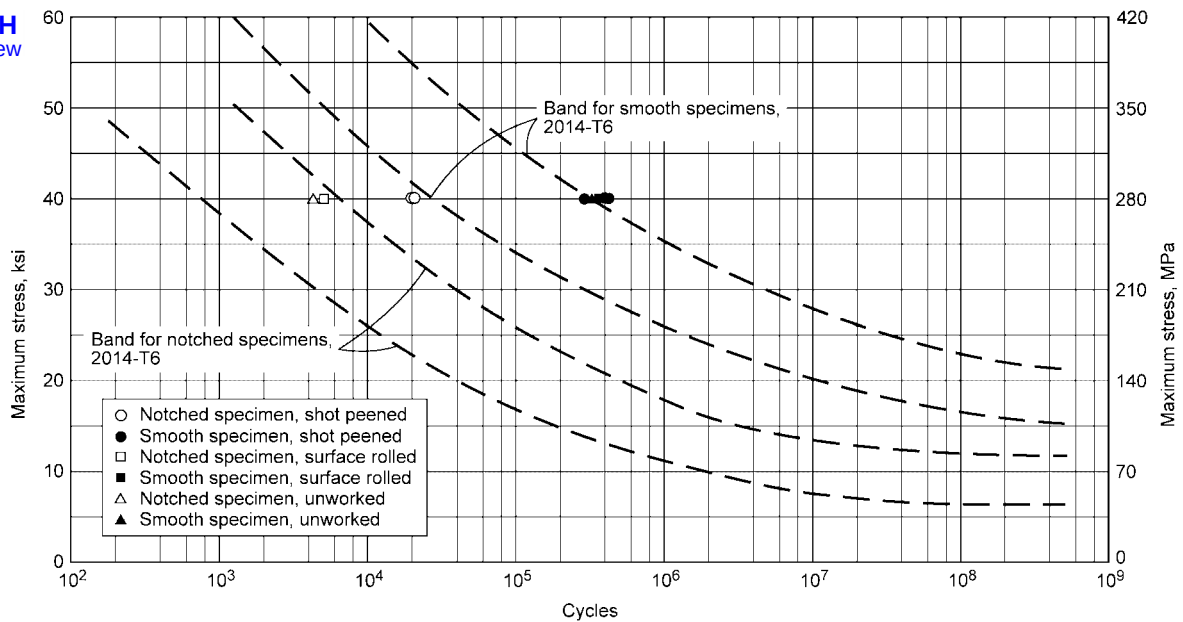


Fig. 2014.RB17 Rotating-beam ($R = -1.0$) fatigue curve for 2014-T6 extruded rod, smooth and sharply notched specimens, effect of surface working. Surface rolling: 480 lb on 1.375 in. diam roller with 0.5 contour radius

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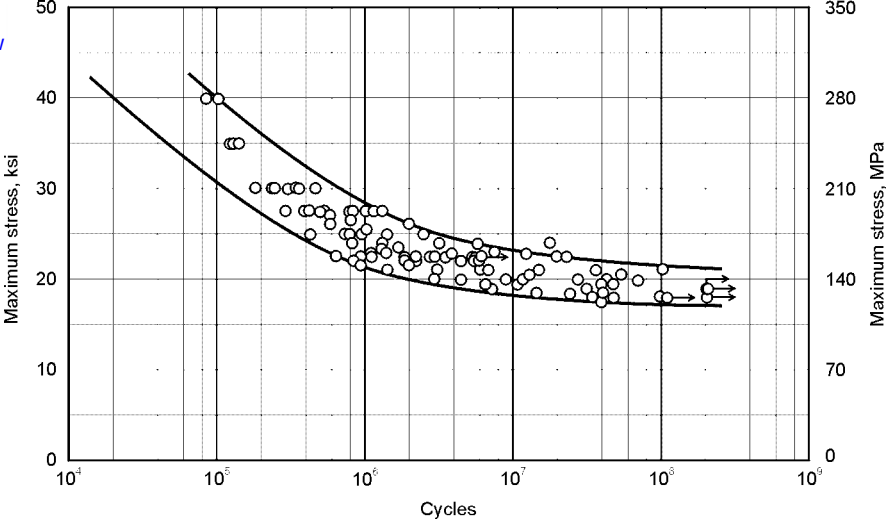


Fig. 2014.FL01 Flexural fatigue ($R = -1.0$) curve for 2014-T6 sheet and extrusions

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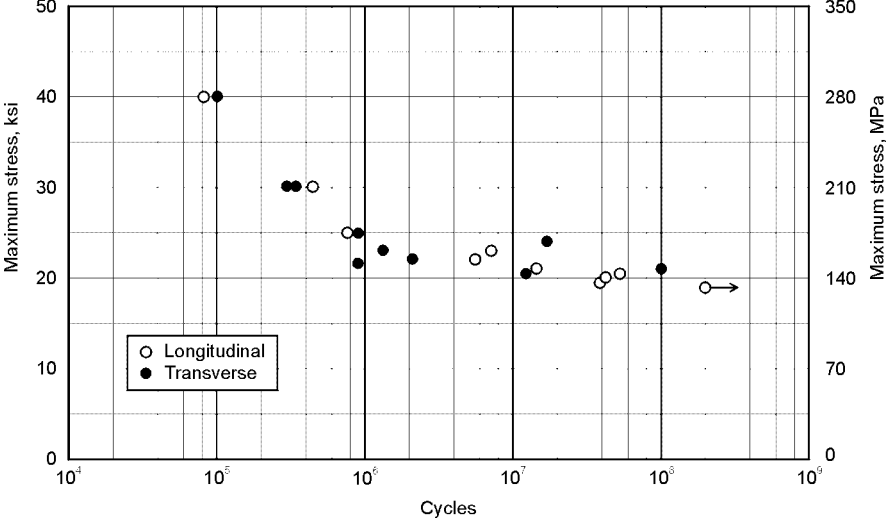


Fig. 2014.FL02 Flexural fatigue ($R = -1.0$) curve for 0.064 in. 2014-T6 sheet

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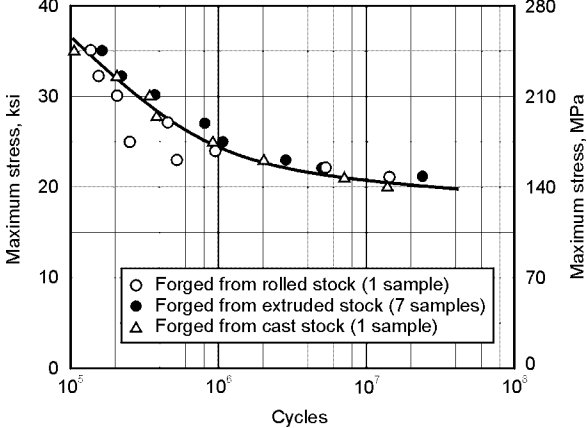


Fig. 2014.FL03 Flexural fatigue ($R = -1.0$) curve for 2014-T6 die forged aircraft wheels

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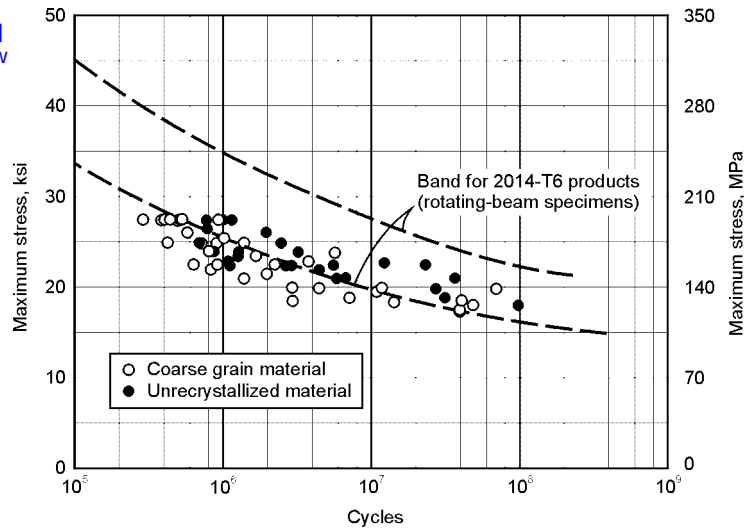


Fig. 2014.FL04 Flexural fatigue ($R = -1.0$) curve for 2014-T6 extruded rotor. Longitudinal

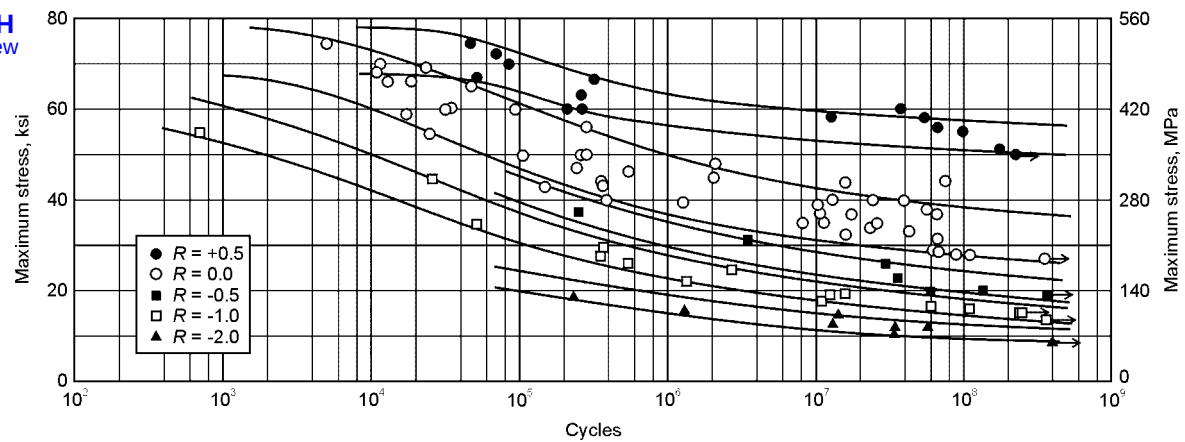


Fig. 2014.AS01 Axial stress fatigue curves for all 2014-T6 products, maximum stress, $R = -2.0, -1.0, -0.5, 0.0$, and $+0.5$

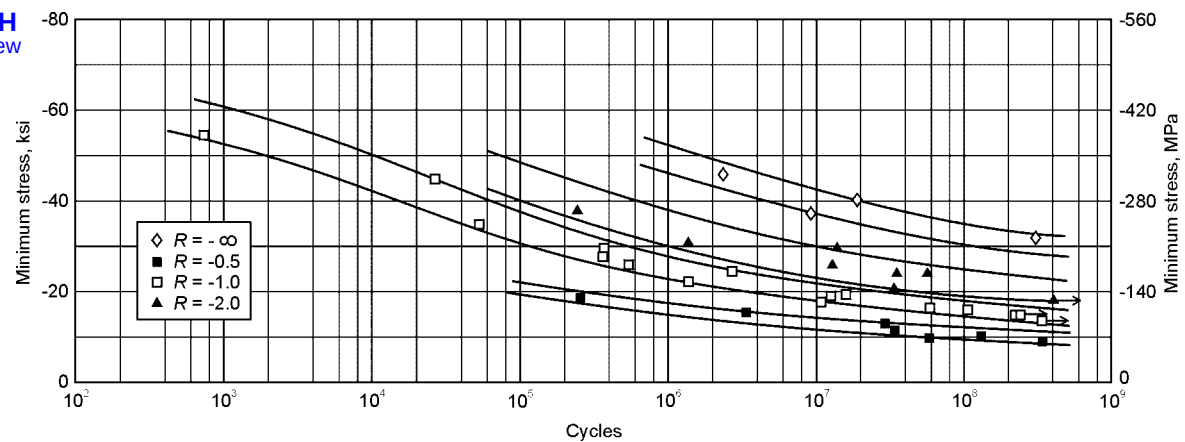


Fig. 2014.AS02 Axial compressive stress fatigue curves for all 2014-T6 products, minimum stress, $R = -\infty, -2.0, -1.0$, and -0.5

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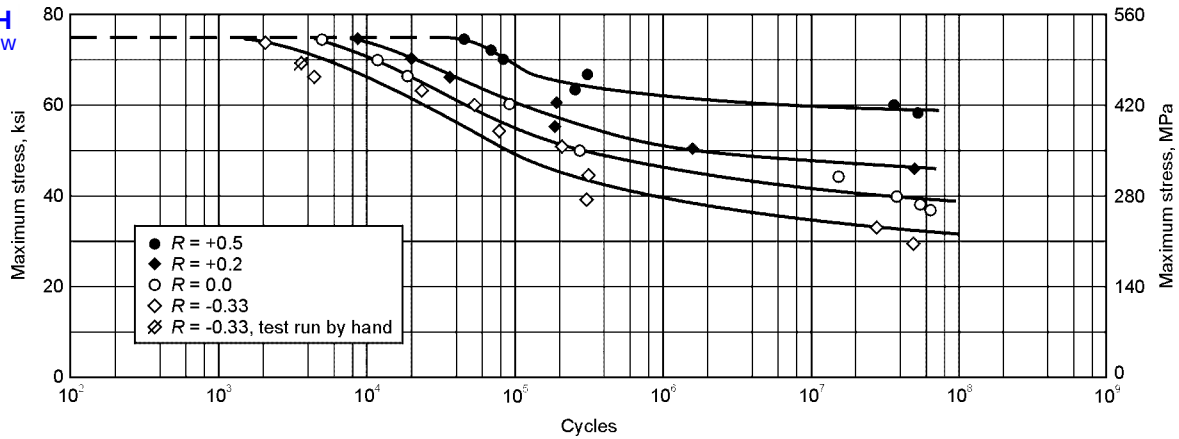


Fig. 2014.AS03 Axial stress fatigue curves for 1 1/4 x 4 in. 2014-T6 extruded bar, $R = -0.33, 0.0, +0.2$, and -0.5

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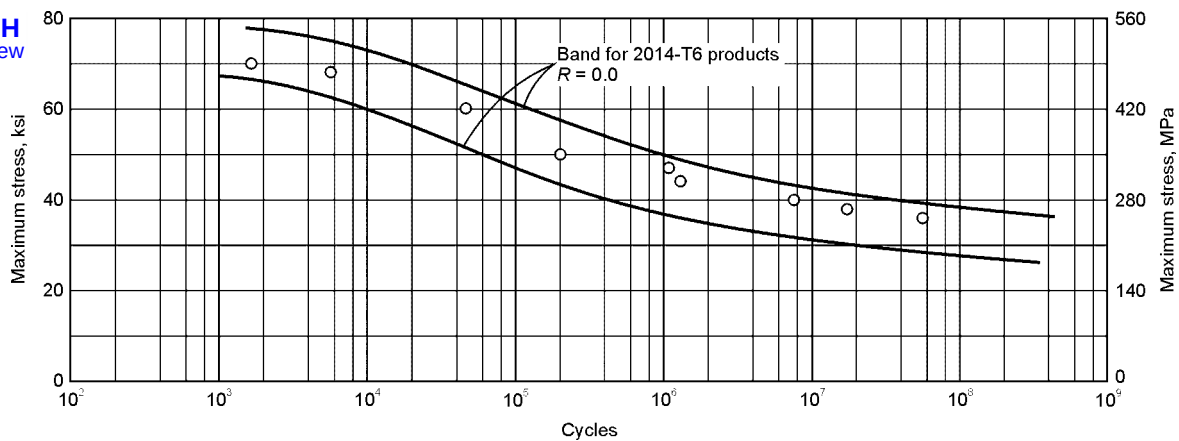


Fig. 2014.AS04 Axial stress fatigue curves for 2014-T6 extruded hollow shape, across weld, $R = 0.0$. TS = 71.3 ksi

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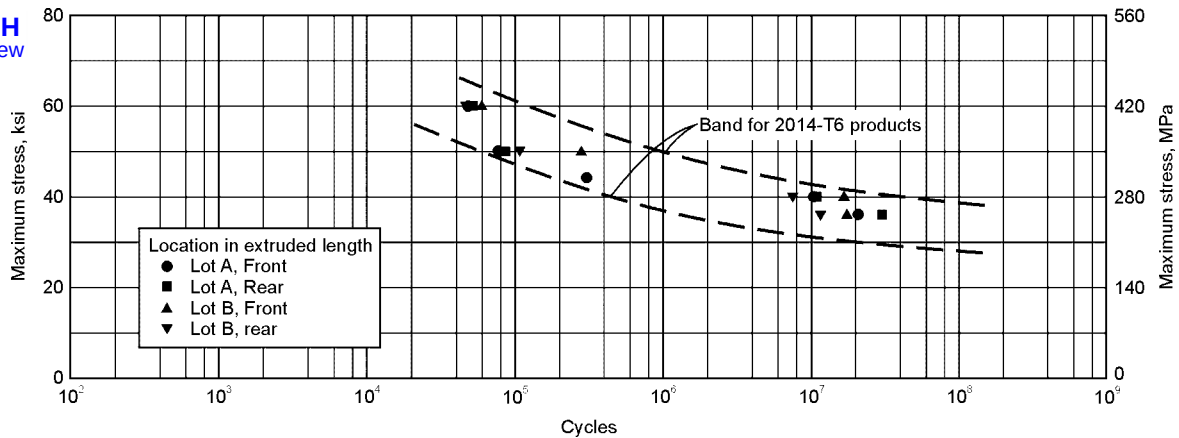


Fig. 2014.AS05 Axial stress fatigue curves for 2014-T6 extruded rotor blade, front and rear of extrusion, $R = 0.0$



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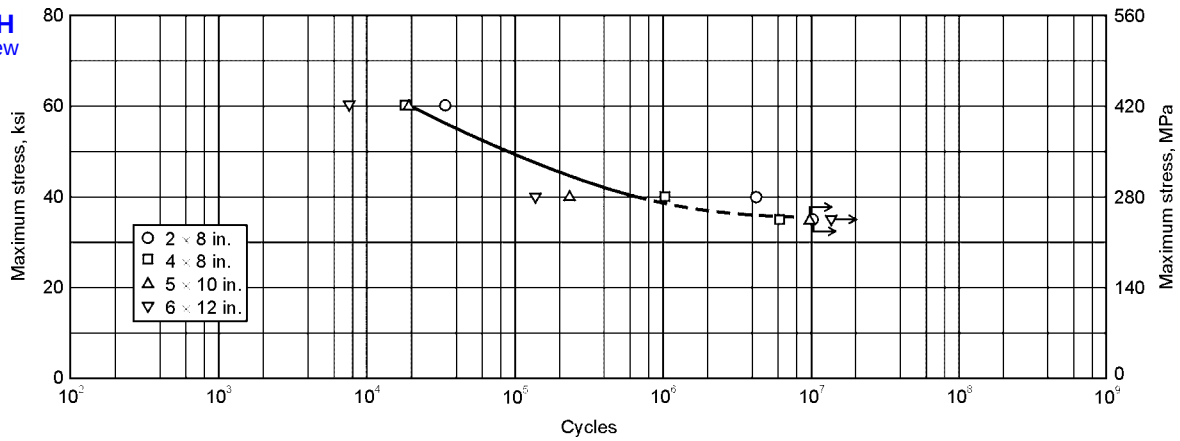


Fig. 2014.AS06 Axial stress fatigue curves for 2014-T6 hand forgings of various sizes, $R = 0.0$. Curve drawn through log-mean values. Test direction: long transverse



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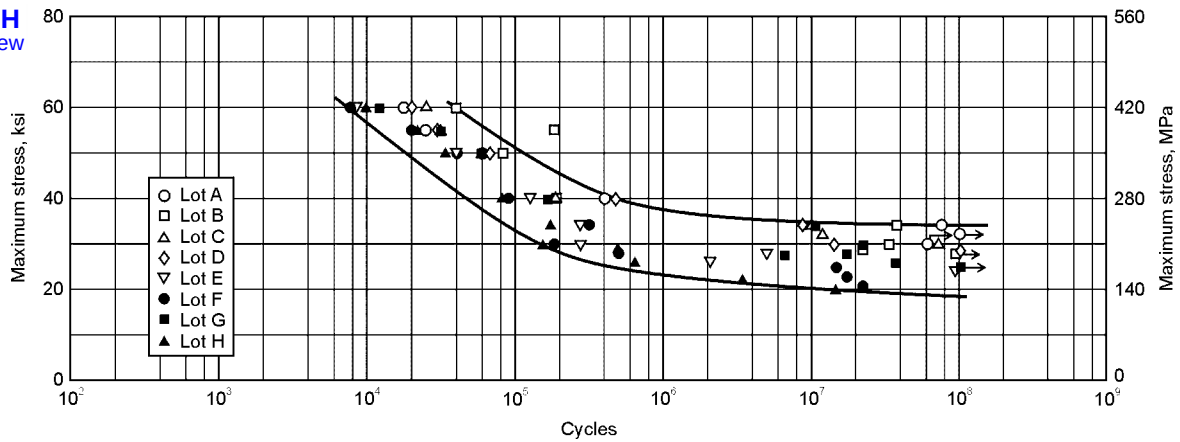


Fig. 2014.AS07 Axial stress fatigue curve for 2014-T652 forged biscuits, $R = 0.0$. Test direction: long transverse



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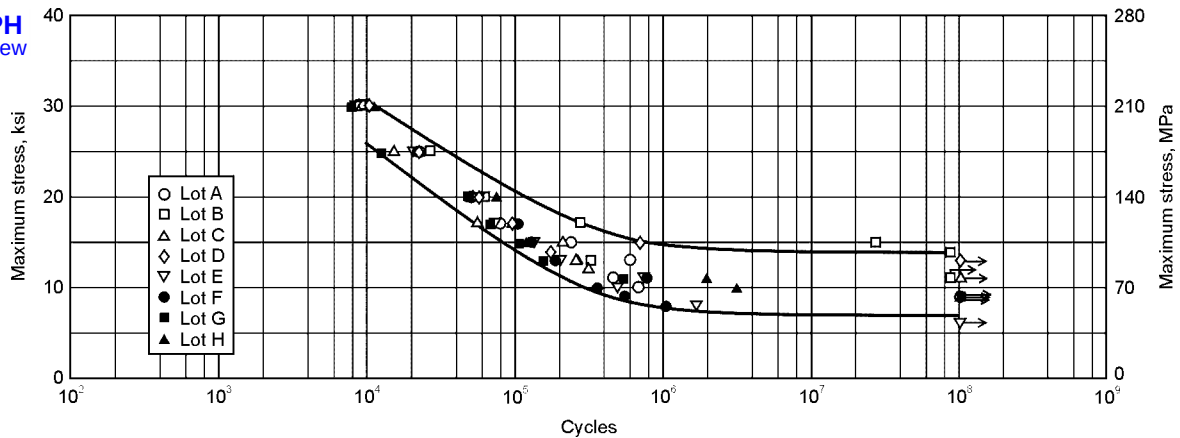


Fig. 2014.AS08 Axial stress fatigue curve for 2014-T652 forged biscuits, $R = 0.0$, notched ($K_t = 3$) specimens



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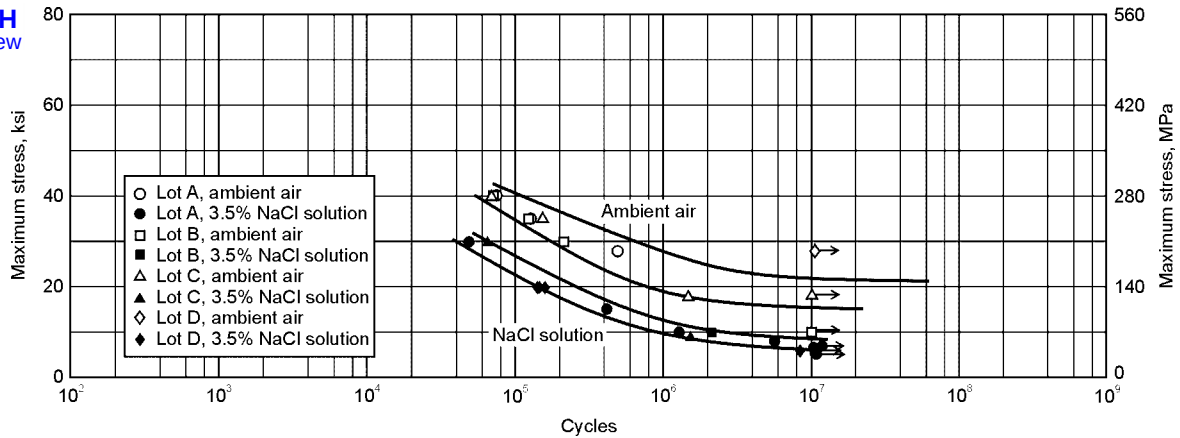


Fig. 2014.AS09 Axial stress fatigue curves for 2014-T652 die forging across parting plane in air and 3.5% NaCl, $R = 0.0$



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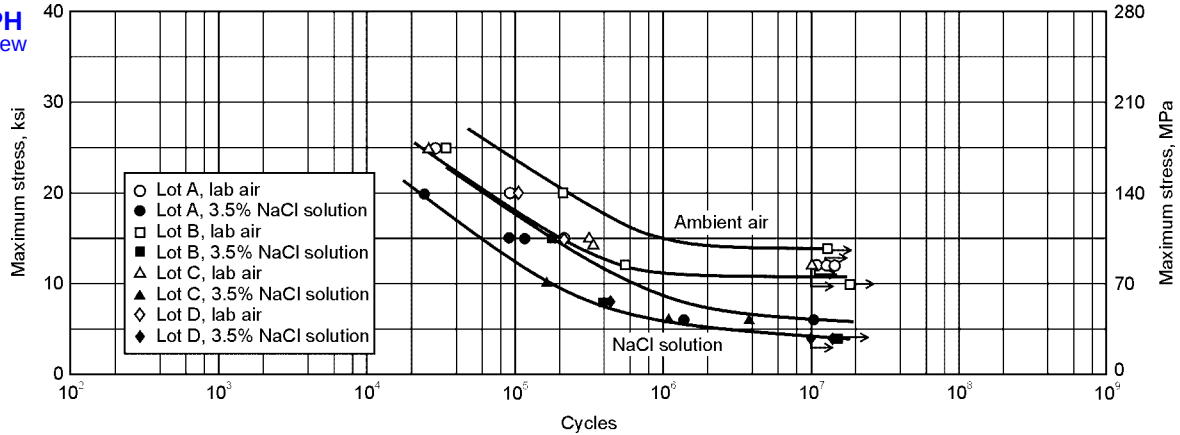


Fig. 2014.AS10 Axial stress fatigue curves for 2014-T652 die forging across parting plane in air and 3.5% NaCl, $R = +0.1$, notched ($K_t = 3$) specimens



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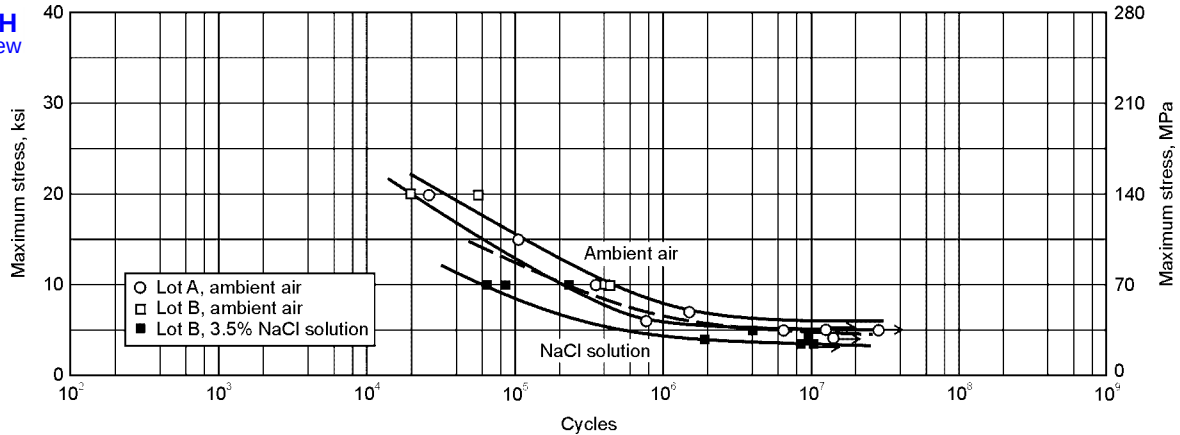


Fig. 2014.AS11 Axial stress fatigue curves for 2014-T652 die forging across parting plane in air and 3.5% NaCl, $R = +0.1$, notched ($K_t = 12$) specimens

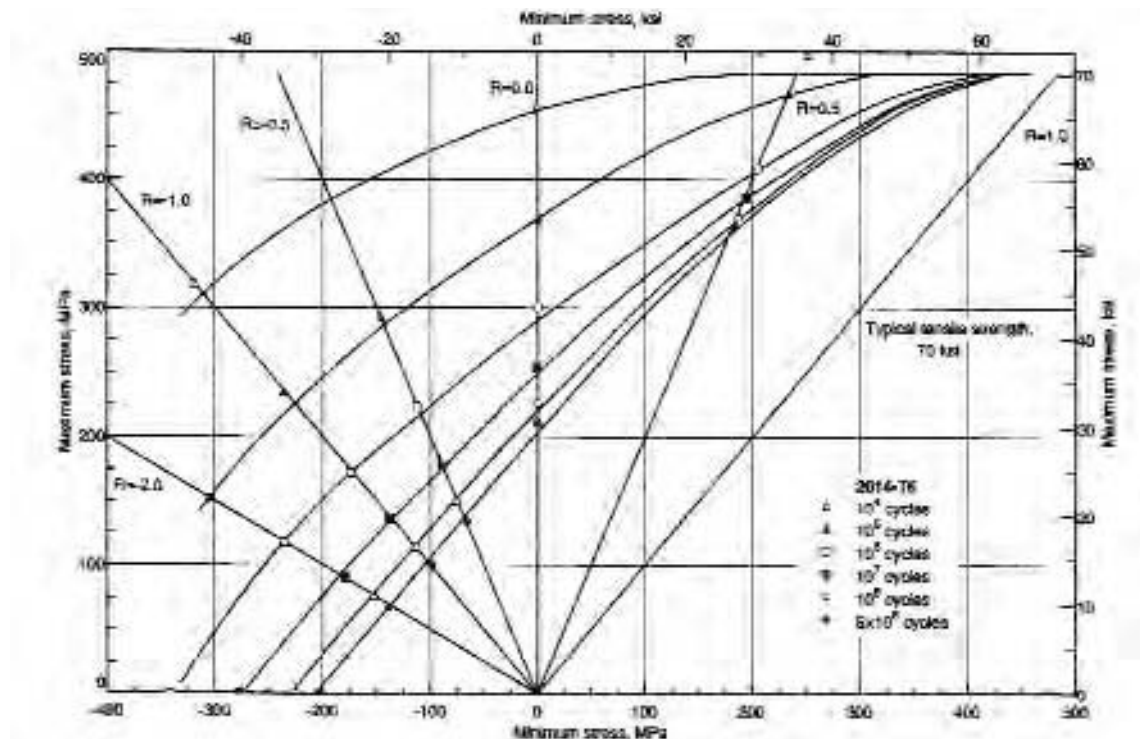


Fig. 2014.GD01 Modified Goodman diagram for 2014-T6 products at room temperature

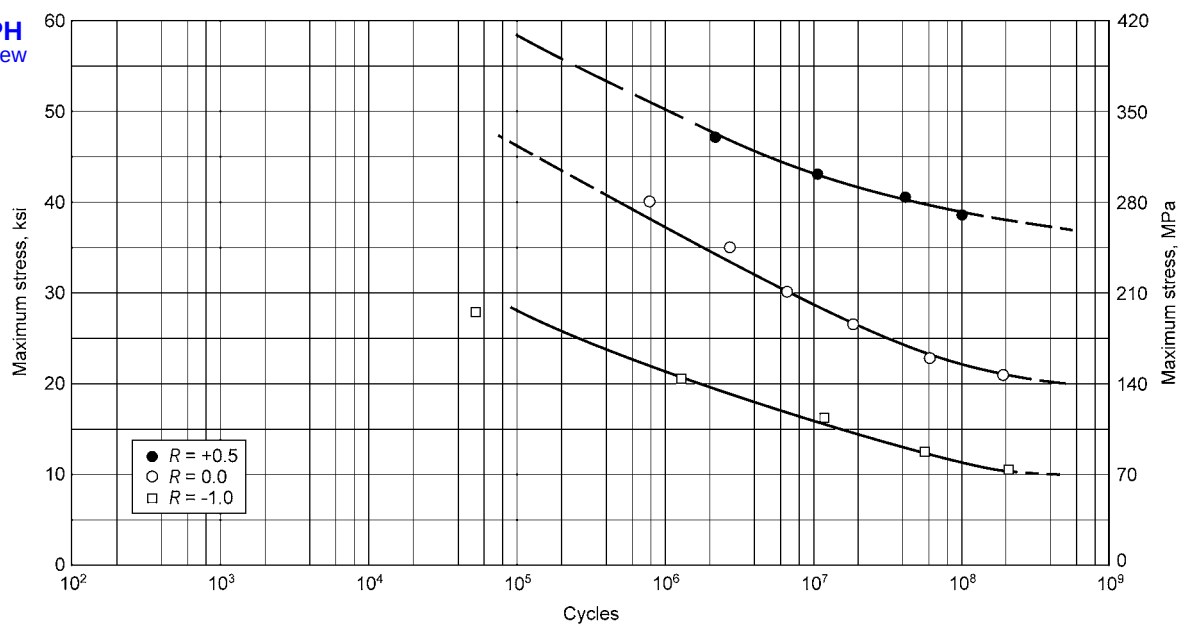


Fig. 2014.TR01 Torsion fatigue curve for 3/4 in. diam 2014-T6 rolled and drawn rod, $R = +0.5, 0.0, -1.0$

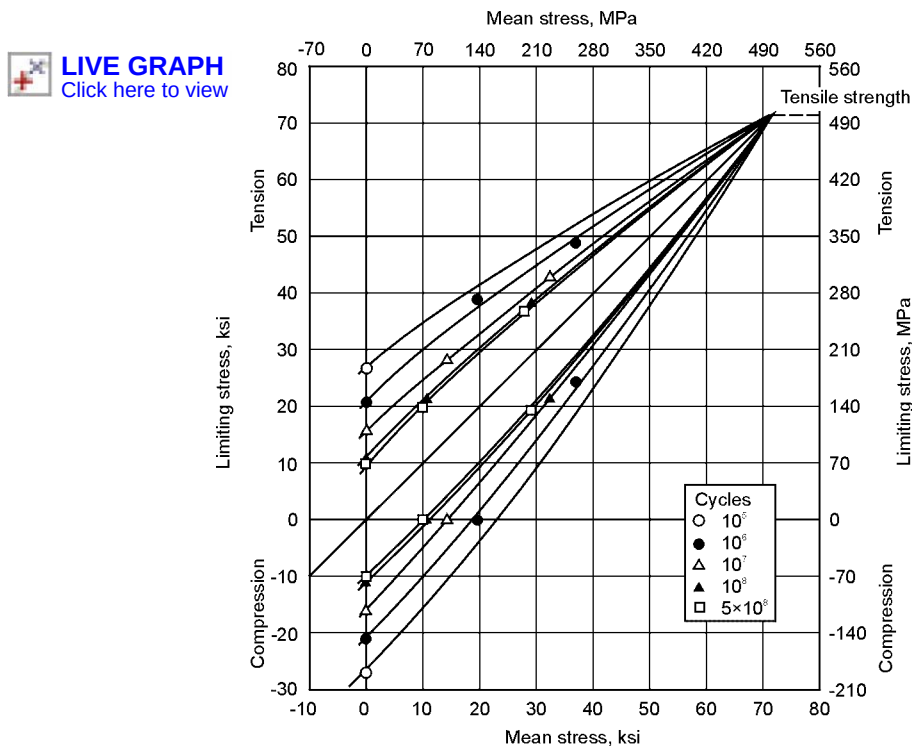


Fig. 2014.GT01 Modified Goodman range of stress diagram in torsion for 2014-T6 products

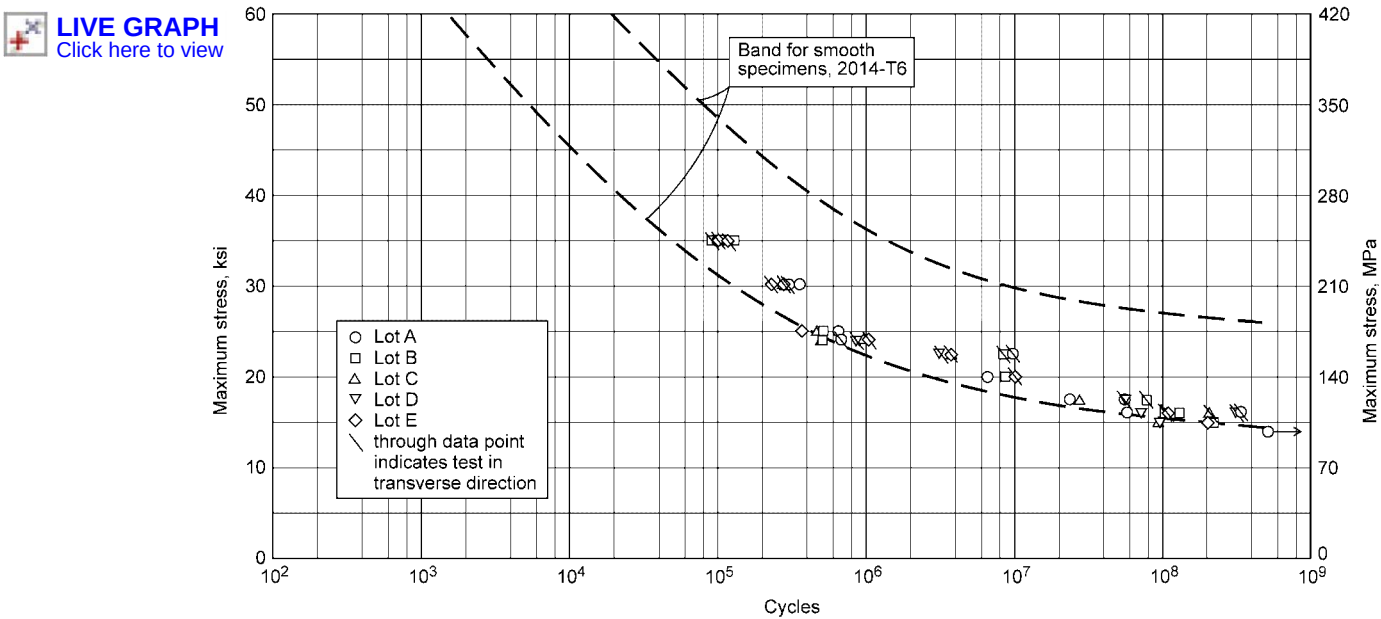


Fig. 2214.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 2214-T651 plate, smooth specimens



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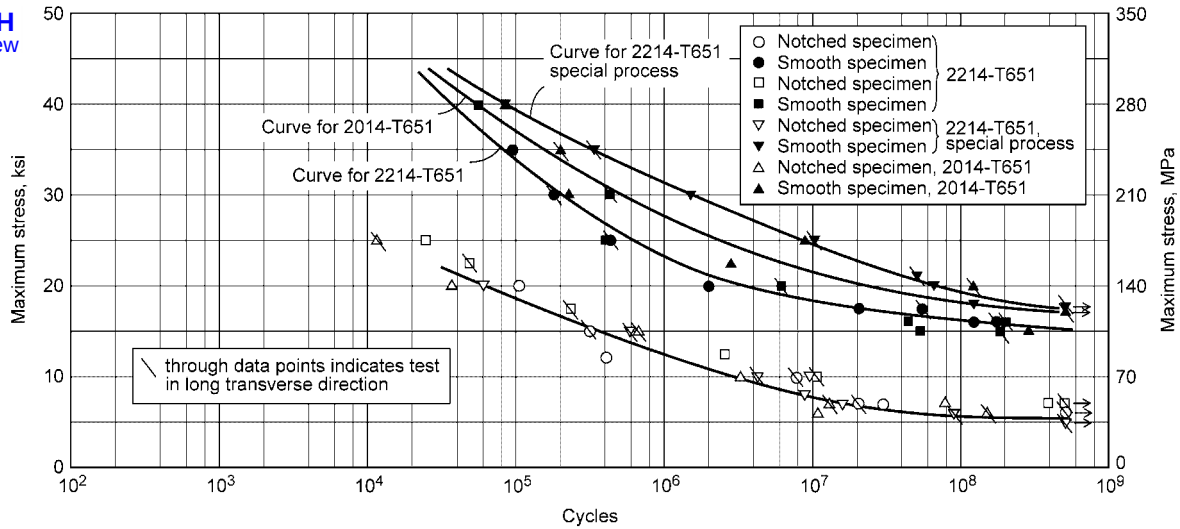


Fig. 2214.RB02 Comparison of rotating-beam ($R = -1.0$) fatigue curves for 2014 and 2214-T651 plate, smooth and sharply notched specimens



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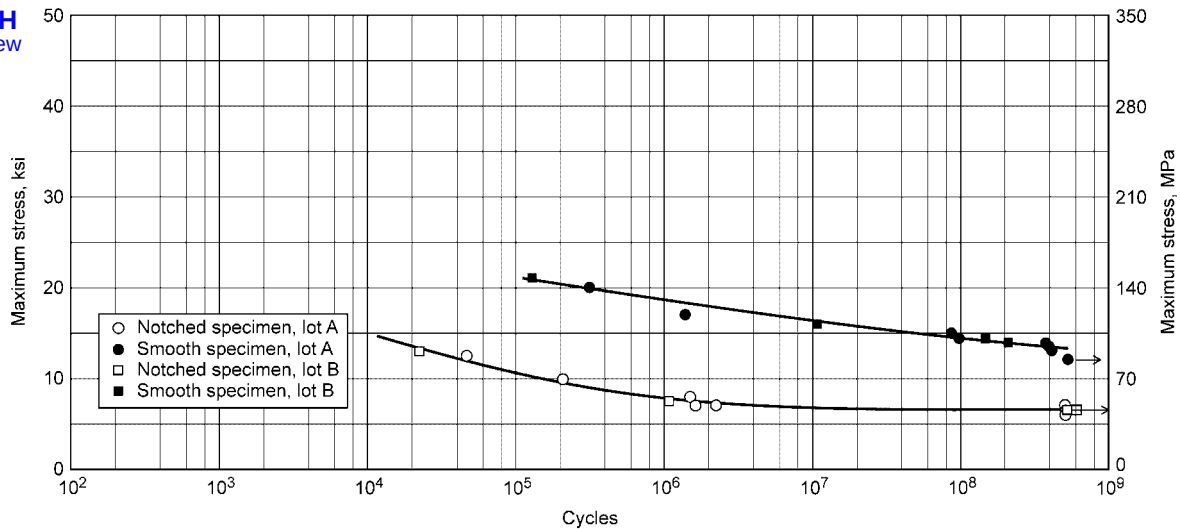


Fig. 2017.RB01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2017-O rolled and drawn rod, smooth and sharply notched specimens

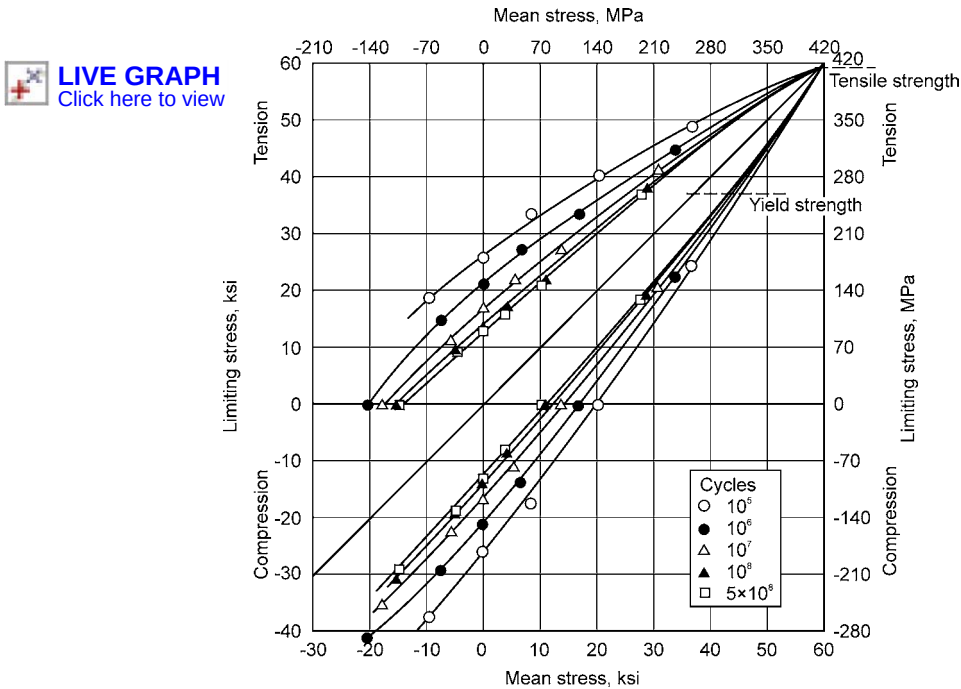


Fig. 2017.GD01 Modified Goodman range of stress diagram for 2024-T3 products at room temperature

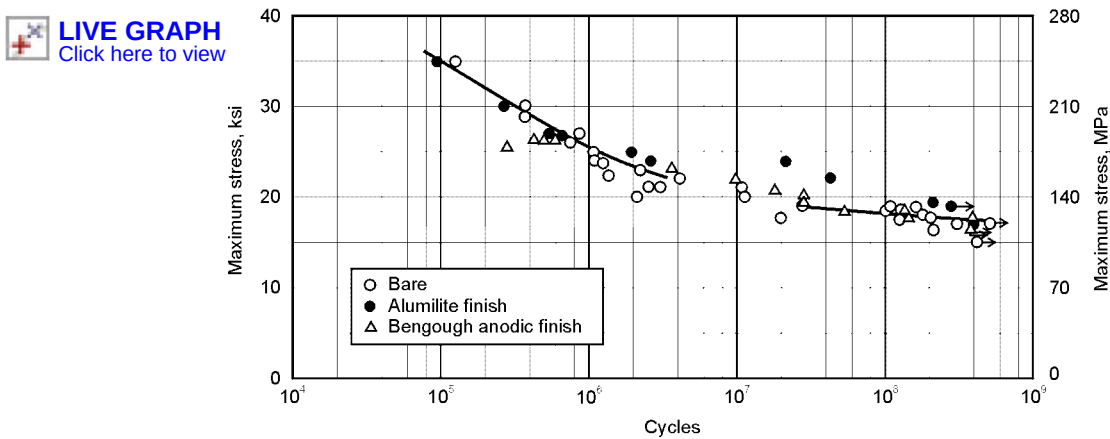


Fig. 2017.FL01 Flexural fatigue ($R = -1.0$) curve for bare and anodic finished 0.064 in. thick 2024-T3 sheet

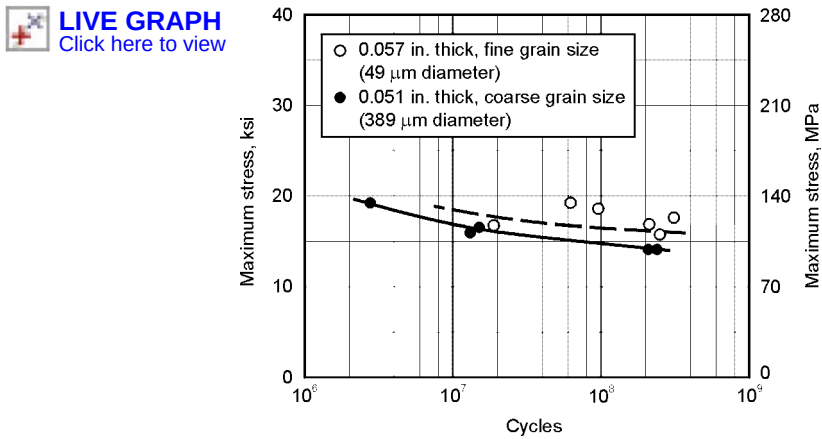


Fig. 2017.FL02 Flexural fatigue ($R = -1.0$) curve for fine and coarse grained 2024-T3 sheet

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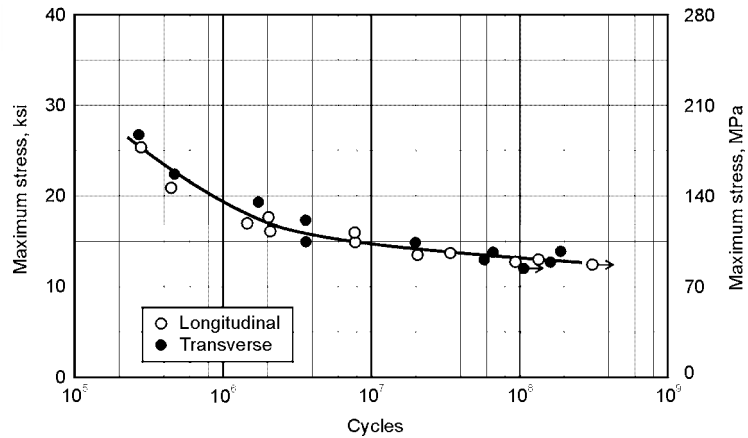


Fig. 2017.FL03 Flexural fatigue ($R = -1.0$) curve for 0.062 in. thick Alclad 2017-T36 sheet

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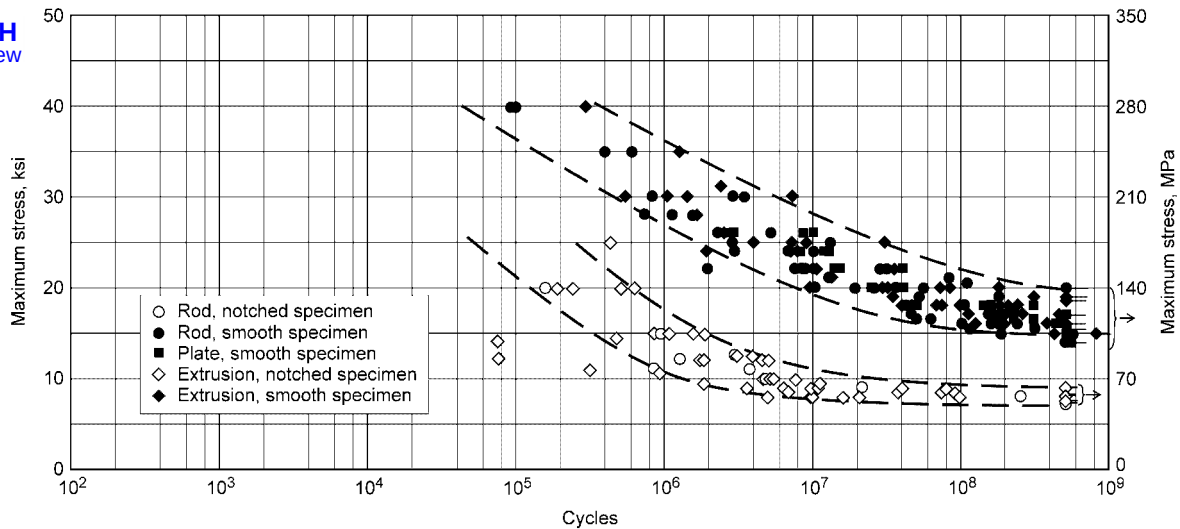


Fig. 2017.RB02 Rotating-beam ($R = -1.0$) fatigue curve for all 2017-T4 products, smooth and sharply notched specimens of rod, plate, and extrusion

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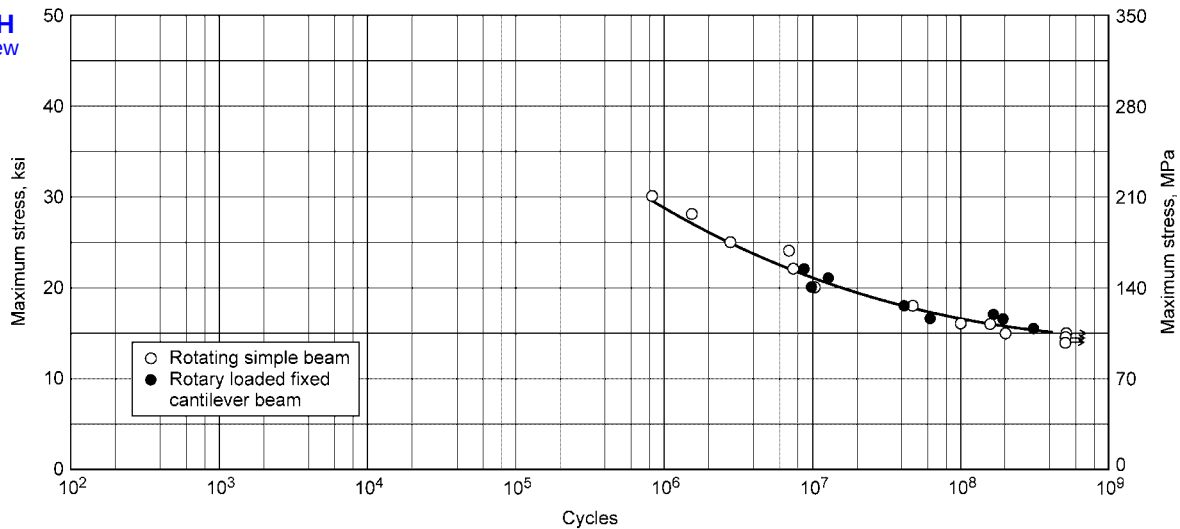


Fig. 2017.RB03 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2017-T4 rolled and drawn rod, smooth specimens, effect of specimen machine type



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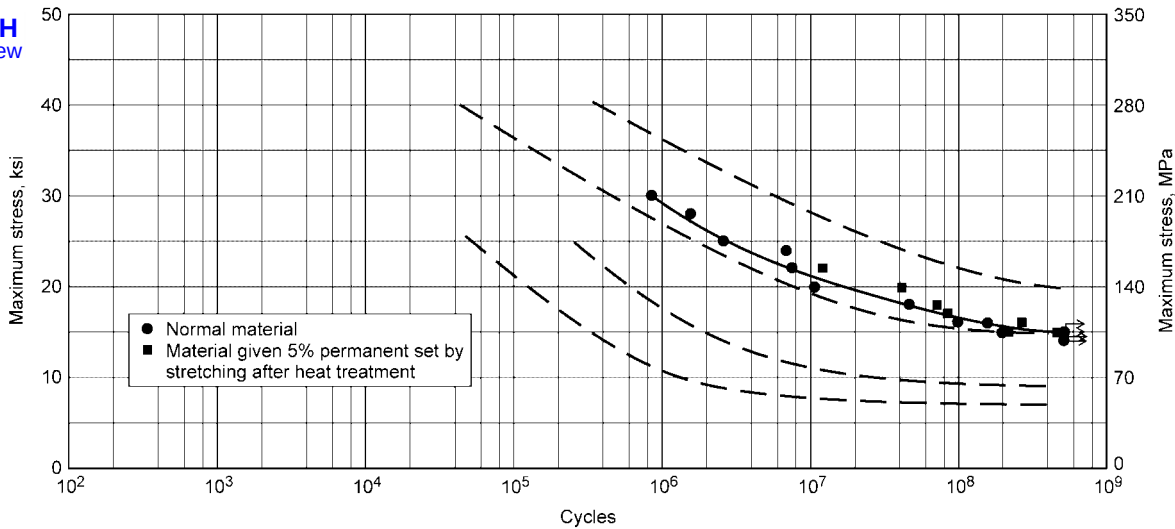


Fig. 2017.RB04 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2017-T4 rolled and drawn rod, smooth specimens, effect of 5% stretching



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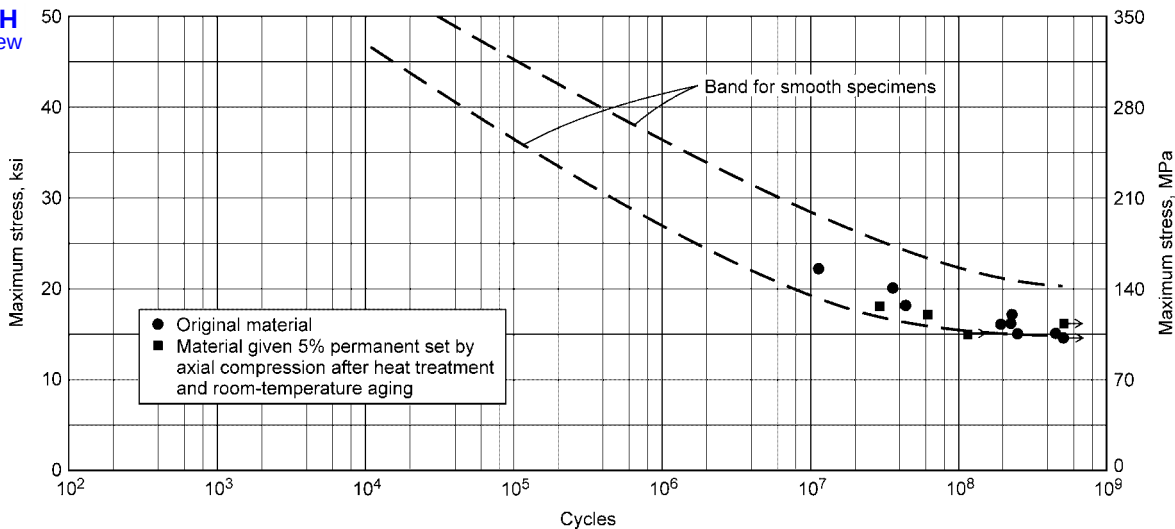


Fig. 2017.RB05 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2017-T4 rolled and drawn rod, smooth specimens, effect of 5% compression



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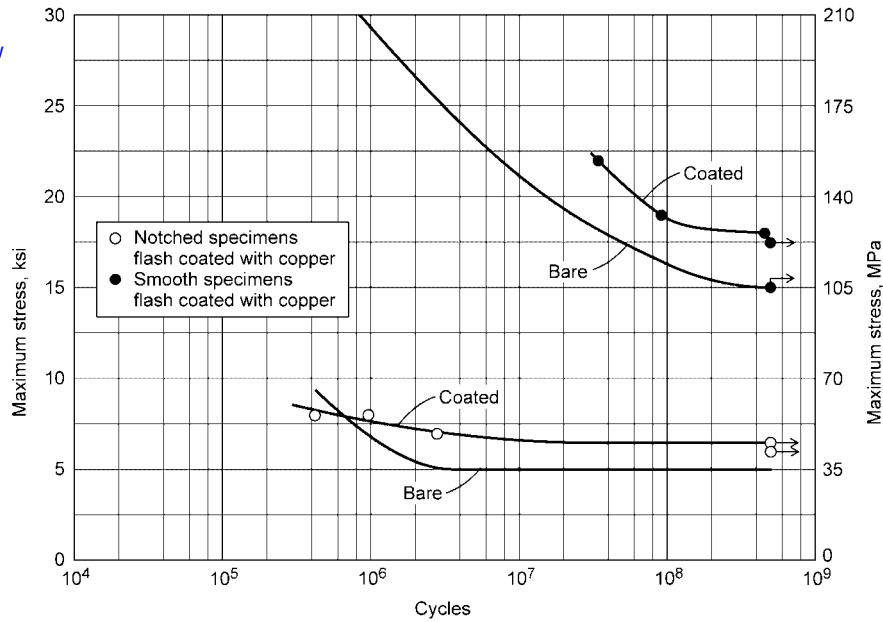


Fig. 2017.RB06 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2017-T4 rolled and drawn rod, smooth and sharply notched specimens, effect of copper flash coating



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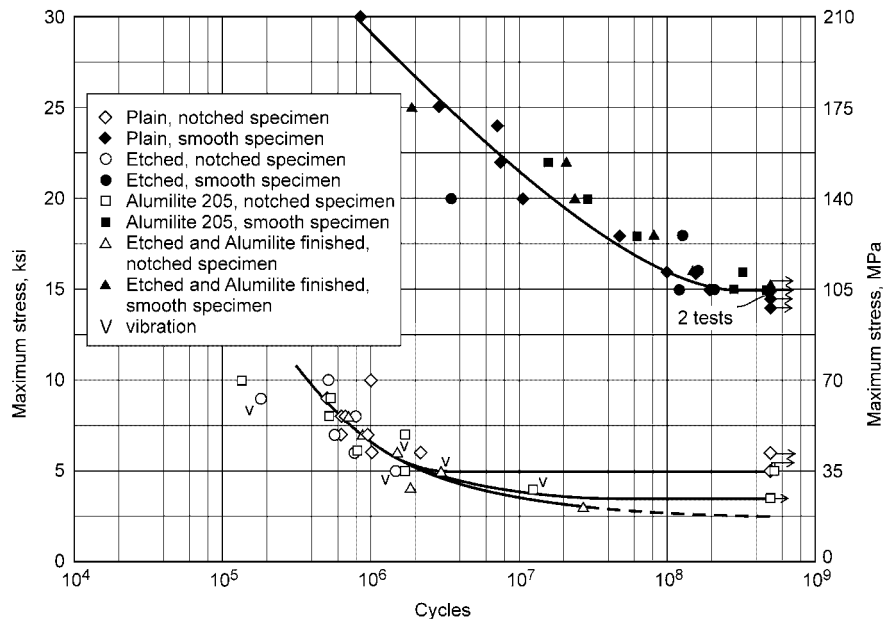


Fig. 2017.RB07 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2017-T4 rolled and drawn rod, smooth and sharply notched specimens, effect of etching and aluminizing

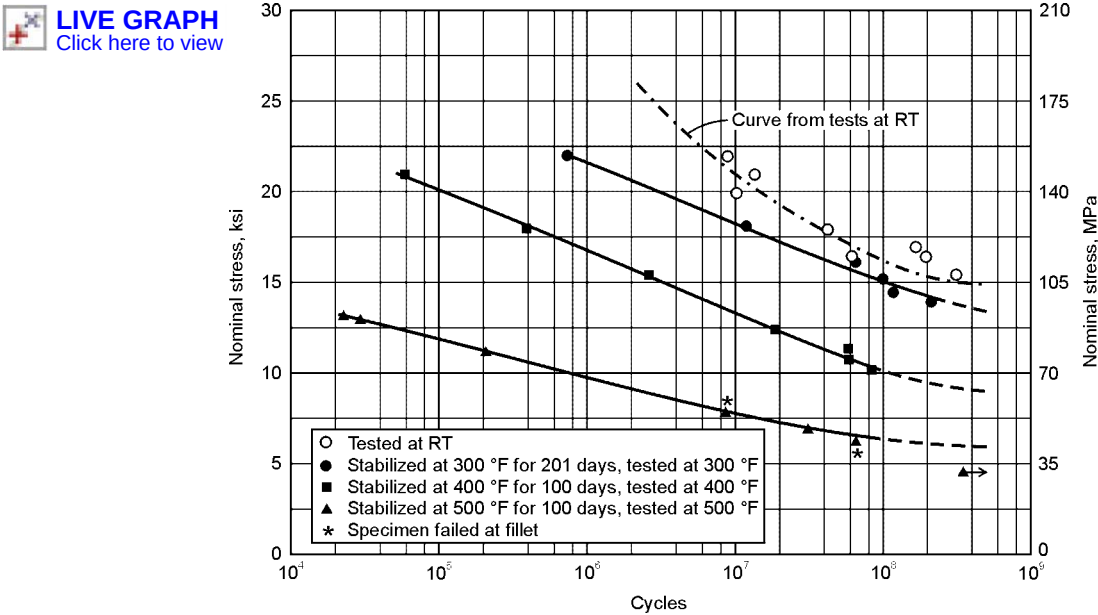


Fig. 2017.HT01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2017-T4 rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)

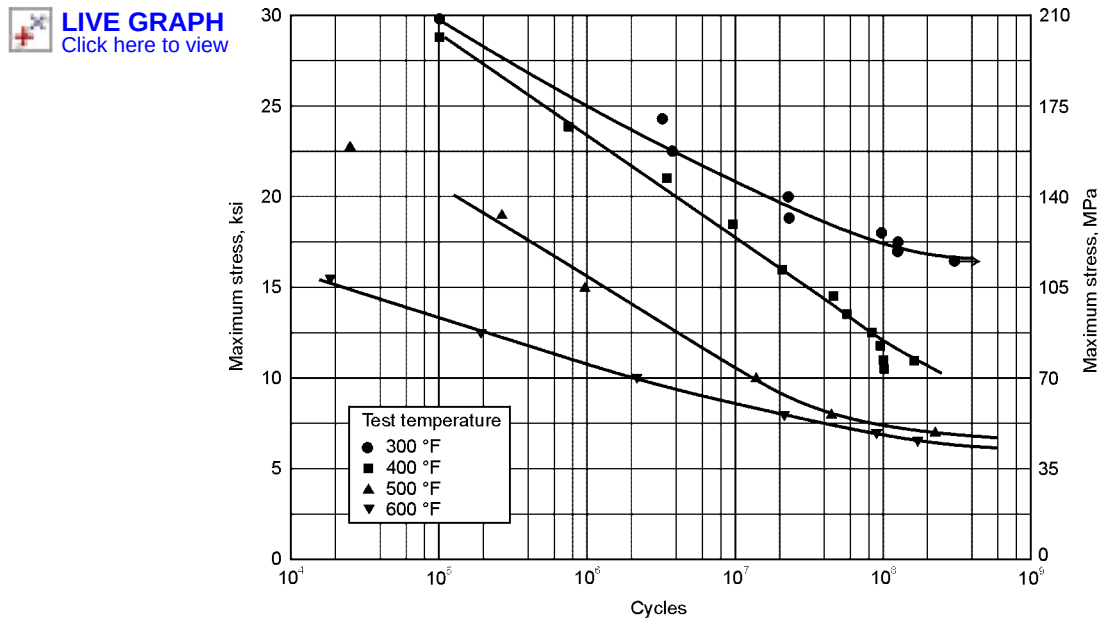


Fig. 2017.HT02 Rotating-beam ($R = -1.0$) fatigue curves for 2017-T4 extruded shape at 300, 400, 500, and 600 °F (150, 205, 260, and 315 °C)

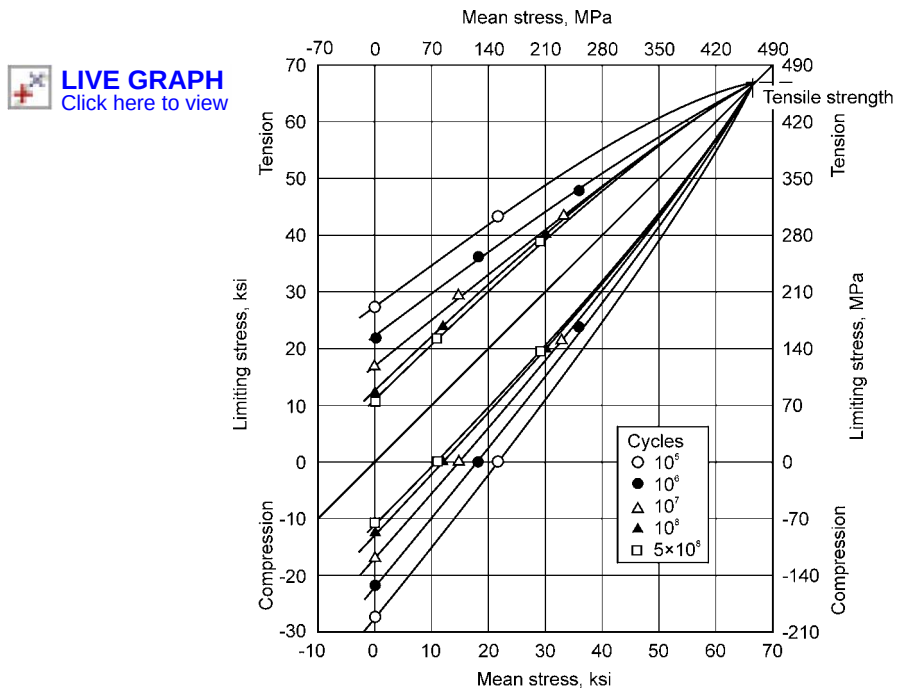


Fig. 2017.GT01 Modified Goodman range of stress diagram in torsion for 2017-T4 products

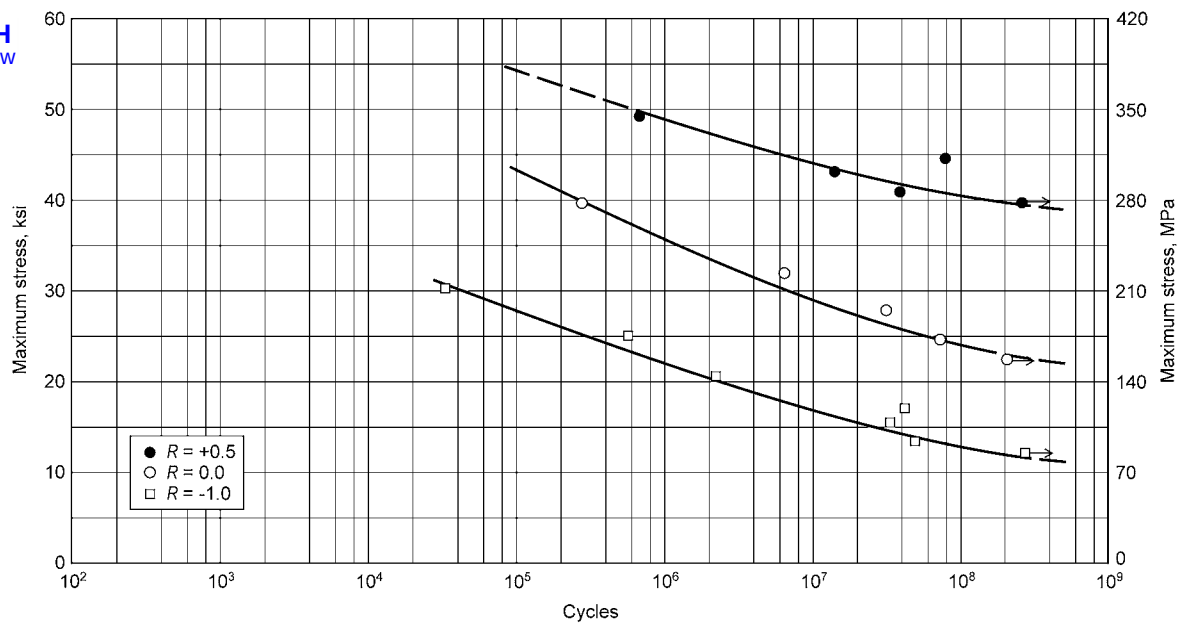


Fig. 2017.TR01 Torsion fatigue curve for 3/4 in. diam 2017-T4 rolled and drawn rod, $R = +0.5, 0.0, -1.0$

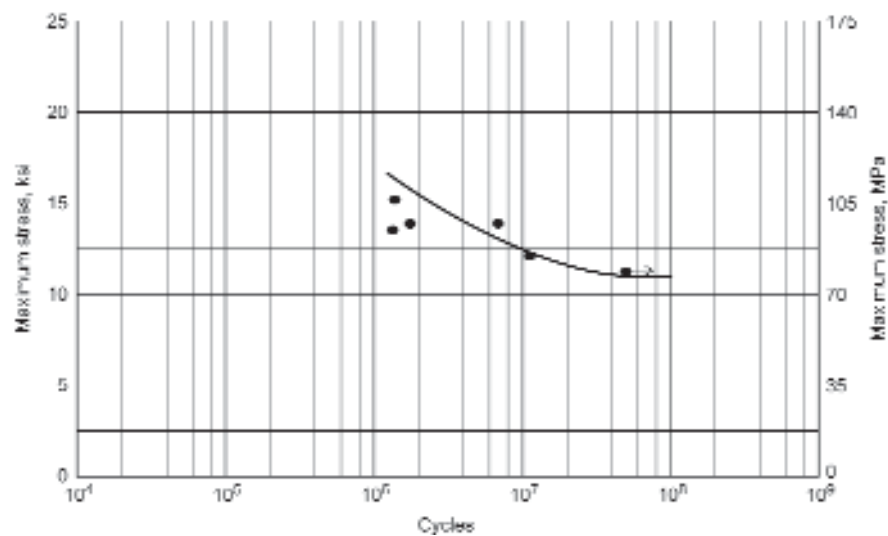


Fig. 2017.RB08 Rotating-beam ($R = -1.0$) fatigue curve for 3/16 in. diam 2017-T4 wire, smooth specimens

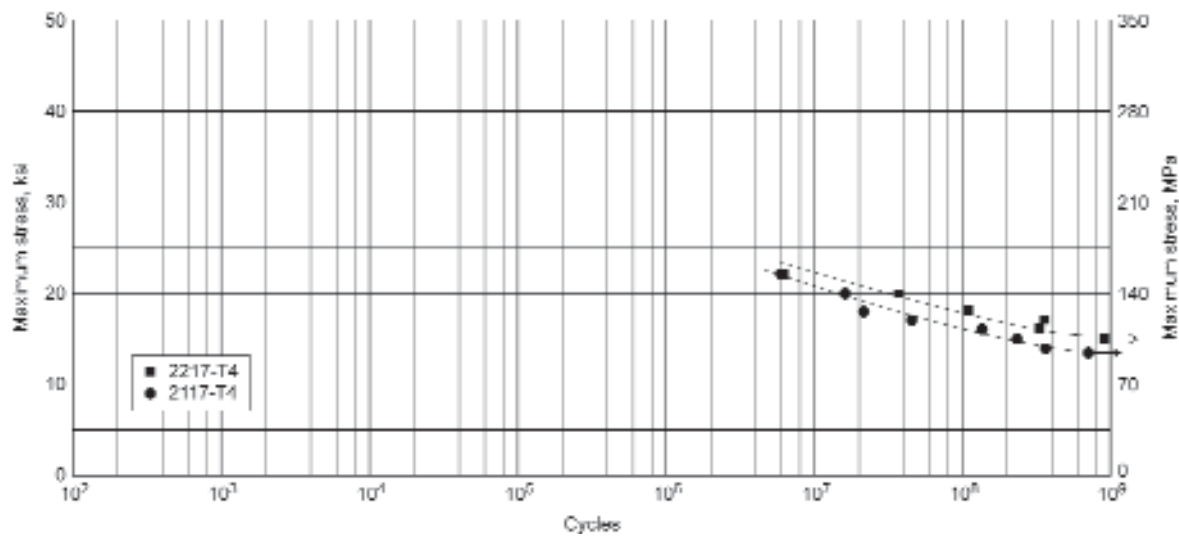


Fig. 2117.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2117-T4 and 2217-T4 rolled and drawn rod, smooth specimens

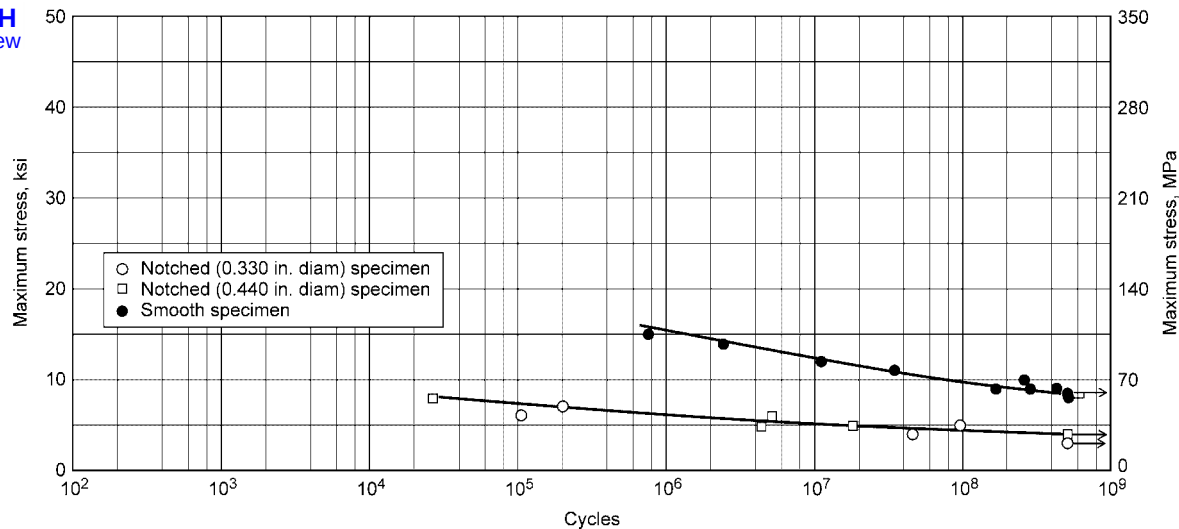


Fig. 2018.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2018-O rolled and drawn rod, smooth and sharply notched specimens

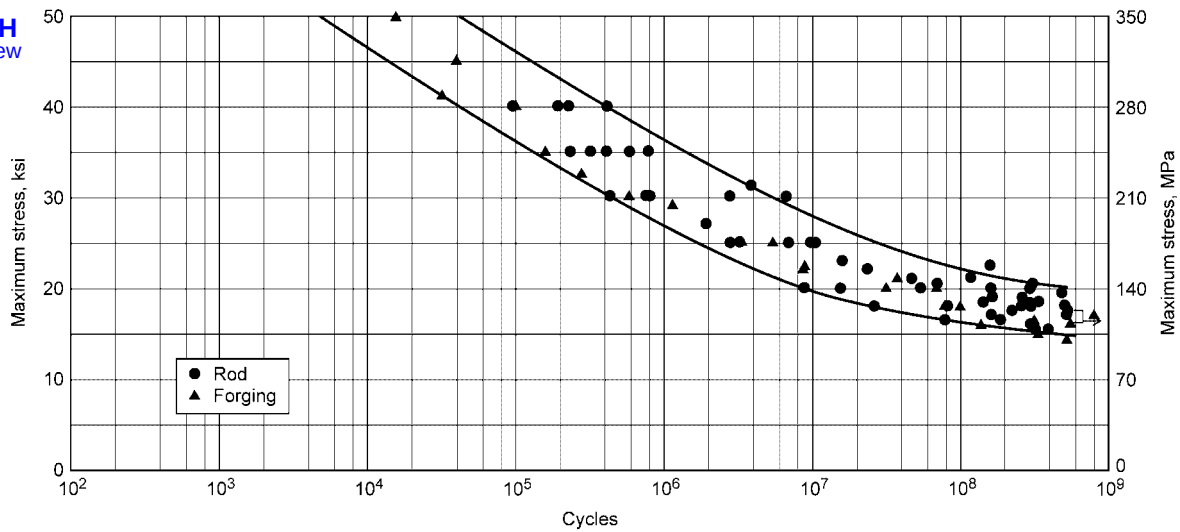


Fig. 2018.RB02 Rotating-beam ($R = -1.0$) fatigue curve for all 2018-T51 products, smooth specimens

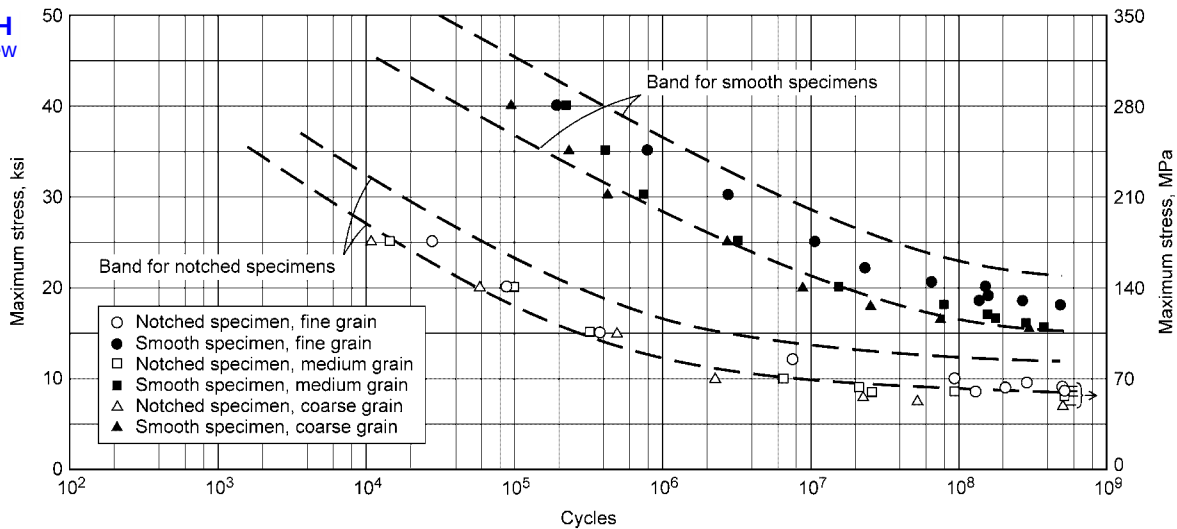


Fig. 2018.RB03 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2018-T61 rolled and drawn rod, smooth and sharply notched specimens, effect of grain size (gr/mm^2 and gr/mm^3)

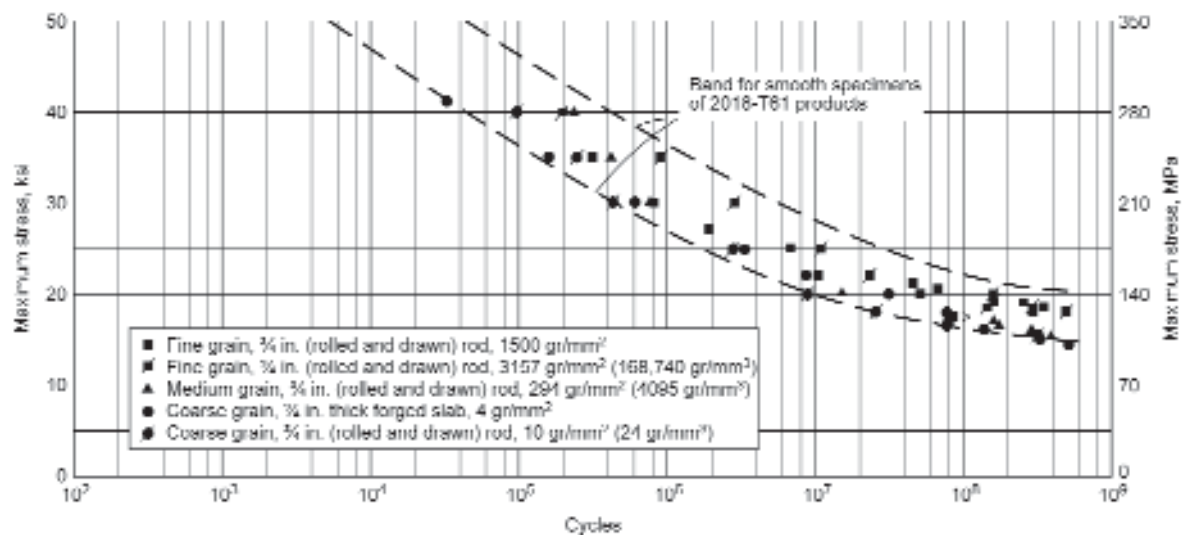


Fig. 2018.RB04 Rotating-beam ($R = -1.0$) fatigue curve for all 2018-T61 products, smooth specimens, effect of grain size

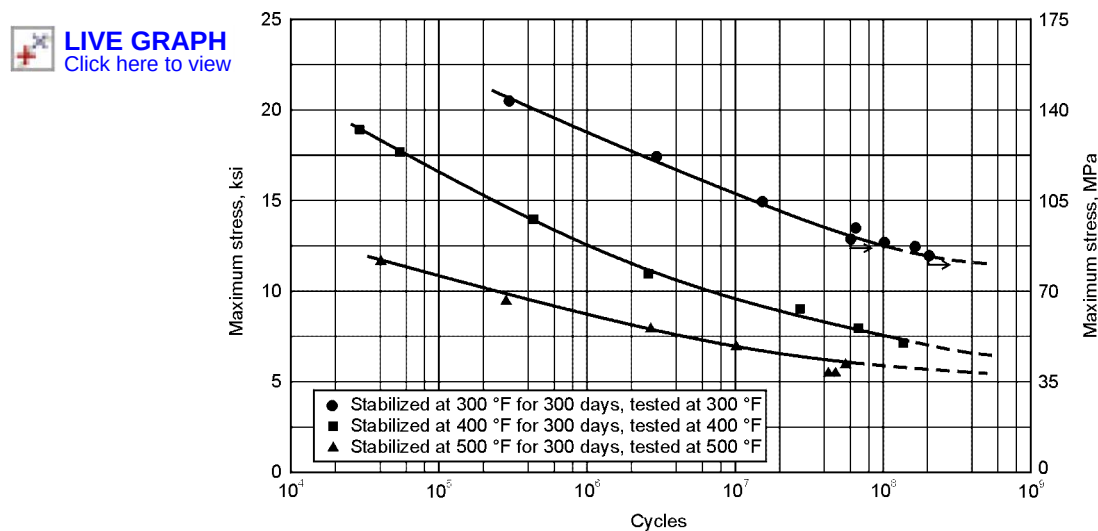


Fig. 2018.HT01 Rotating-beam ($R = -1.0$) fatigue curves for 3/4 in. diam 2018-T6 rolled and drawn rod at 300, 400, and 500 °F (150, 205, and 260 °C)

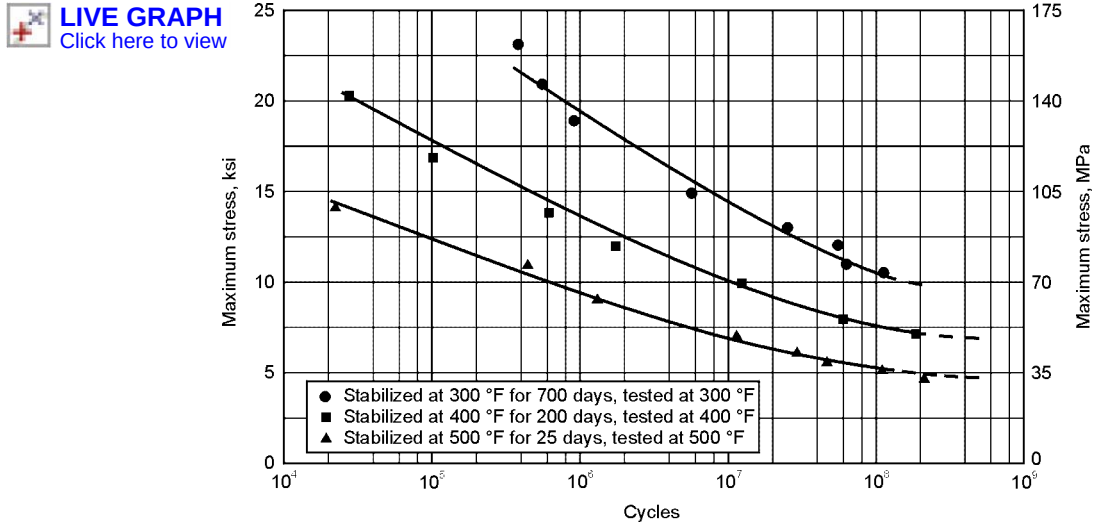


Fig. 2018.HT02 Rotating-beam ($R = -1.0$) fatigue curves for 7/8 in. diam 2018-T6 forged rod at 300, 400, and 500 °F (150, 205, and 260 °C)

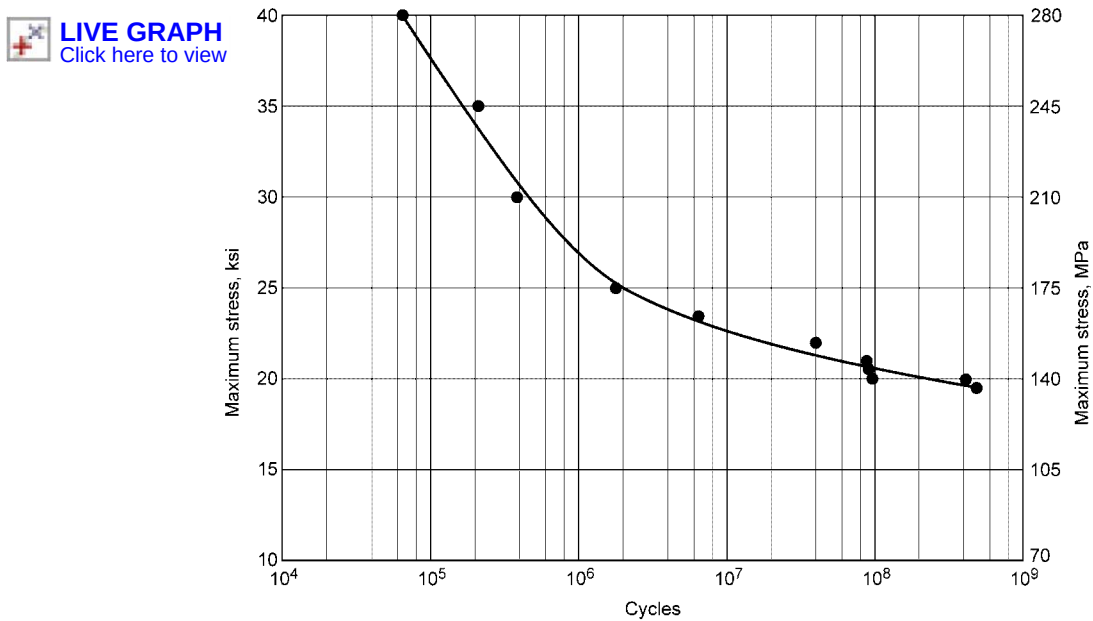


Fig. 2118.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. diam 2118-T61 rolled and drawn rod, smooth specimens

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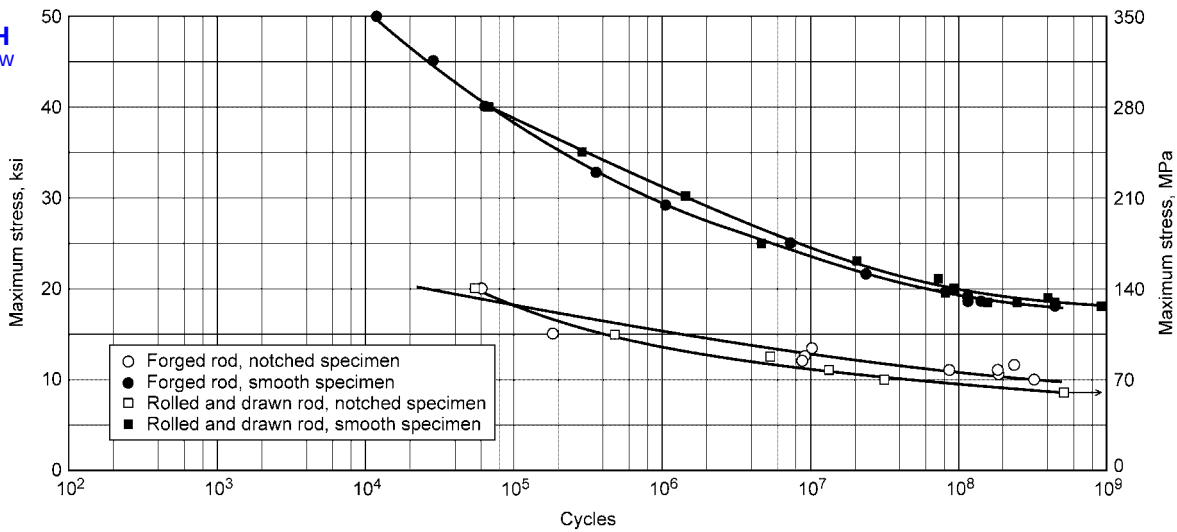


Fig. 2218.RB01 Rotating-beam ($R = -1.0$) fatigue curve for 3/4 in. and 7/8 in. diam 2218-T61 rod, smooth and sharply notched specimens, comparison of rolled and drawn and forged rod

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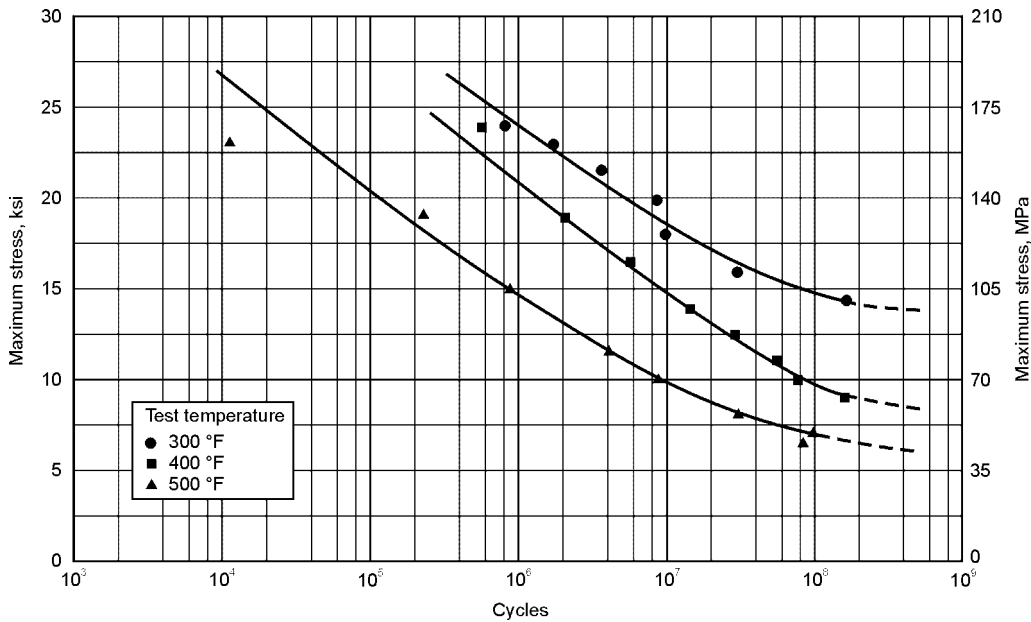


Fig. 2218.HT01 Rotating-beam ($R = -1.0$) fatigue curves for 7/8 in. diam 2218-T6 forged rod at 300, 400, and 500 °F (150, 205, and 260 °C). No preliminary stabilization

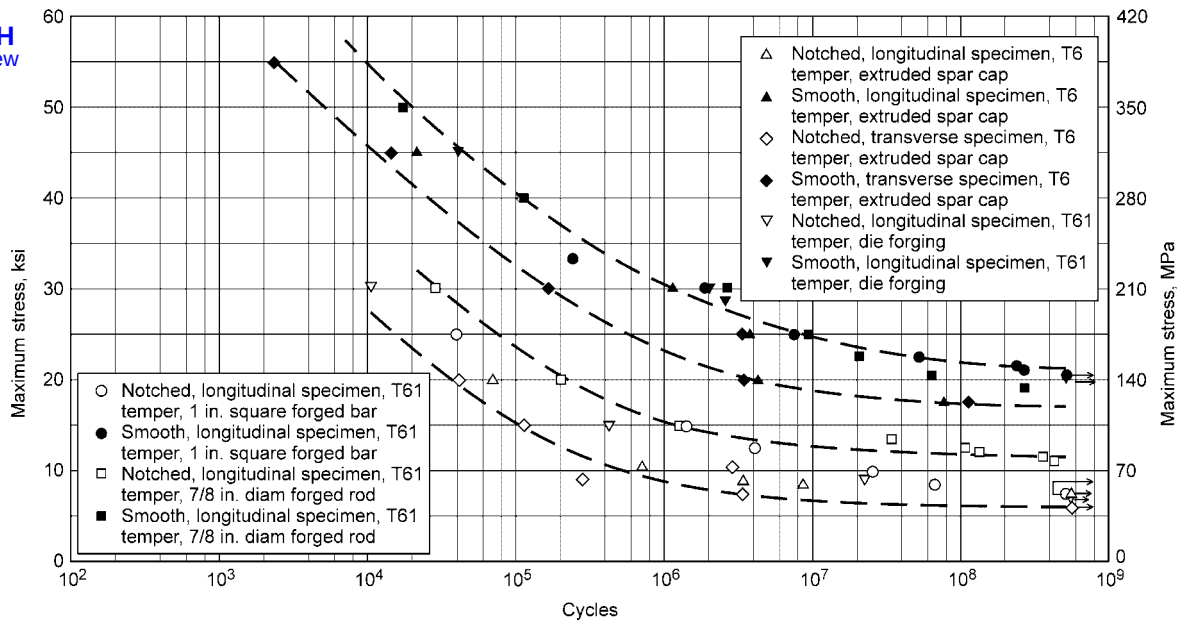


Fig. 2618.RB01 Rotating-beam ($R = -1.0$) fatigue curve for all 2618-T6, T61 products, smooth and sharply notched specimens. Test direction: longitudinal and transverse

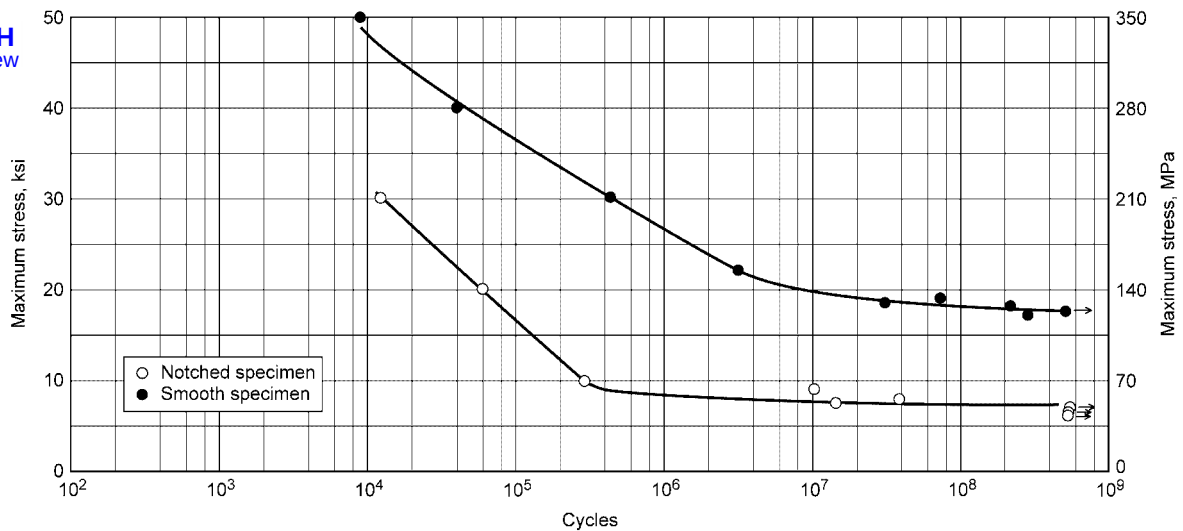


Fig. 2618.RB02 Rotating-beam ($R = -1.0$) fatigue curve for 2618-T651 plate, smooth and sharply notched specimens

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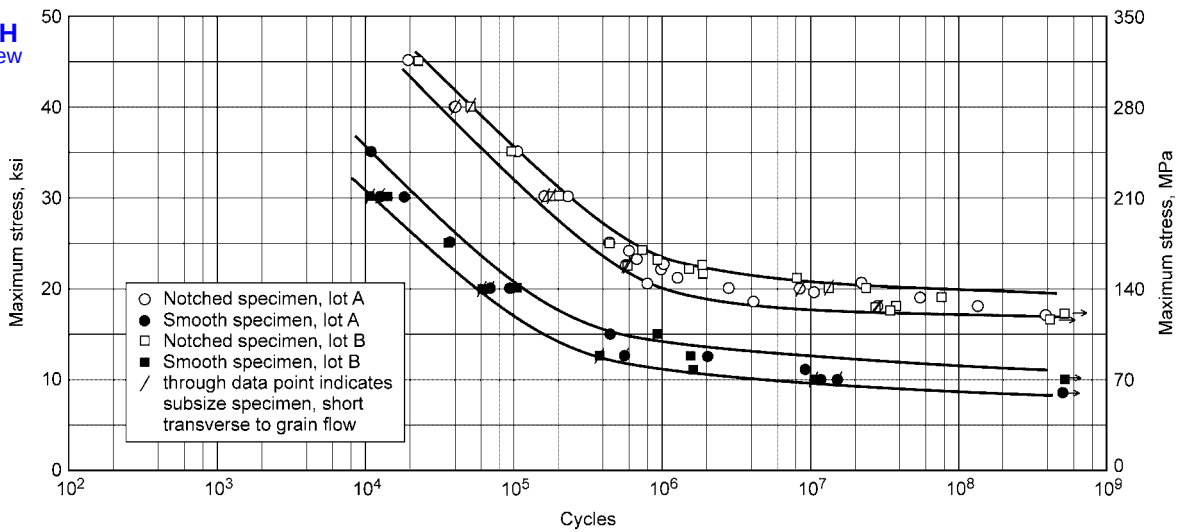


Fig. 2618.RB03 Rotating-beam ($R = -1.0$) fatigue curve for 2618-T61 die forged wheels, smooth and sharply notched specimens. Test direction: longitudinal and short transverse

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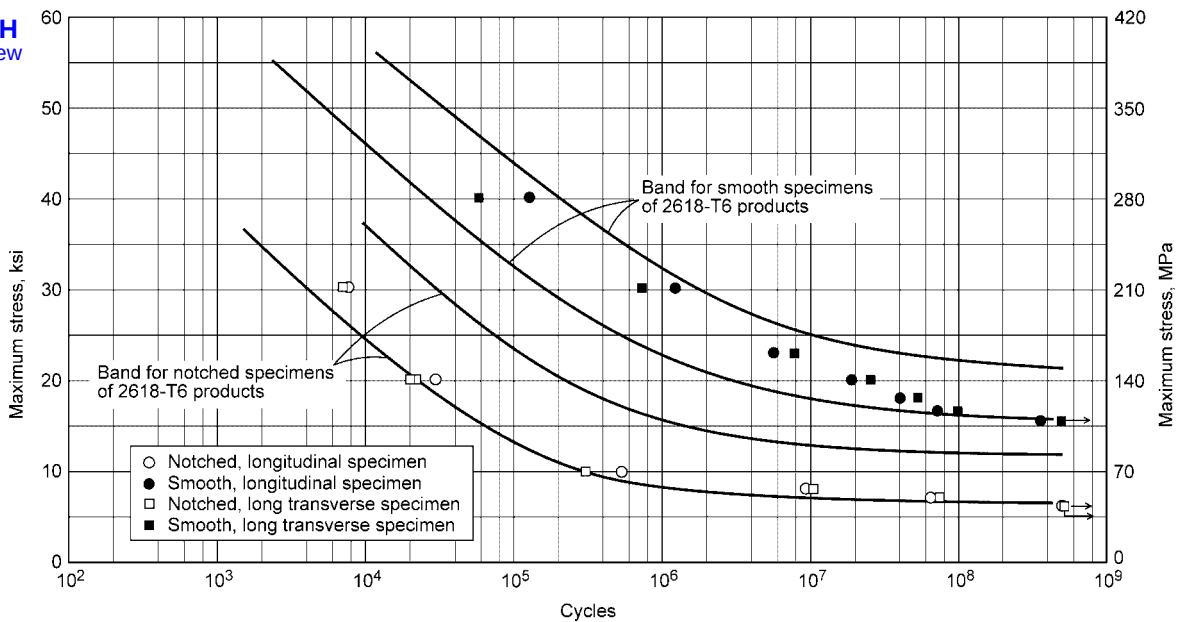


Fig. 2618.RB04 Rotating-beam ($R = -1.0$) fatigue curve for 2618-T6511 extrusions, smooth and sharply notched specimens. Test direction: longitudinal and long transverse



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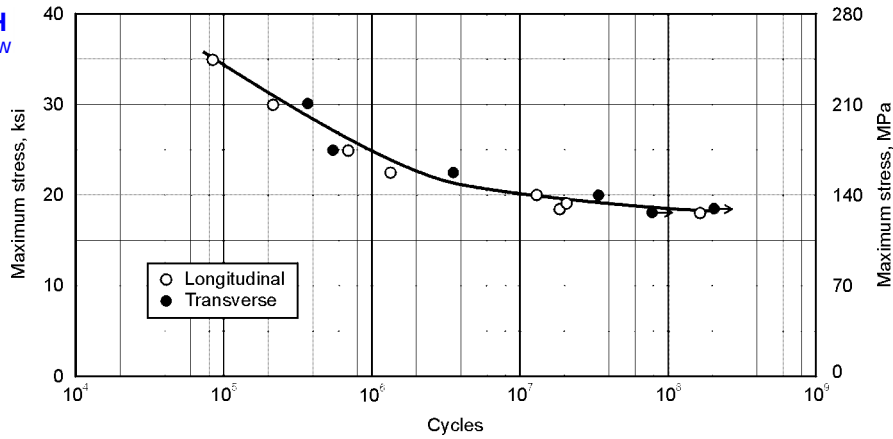


Fig. 2618.FL01 Flexural fatigue ($R = -1.0$) curve for 0.100 in. thick 2618-T6 sheet



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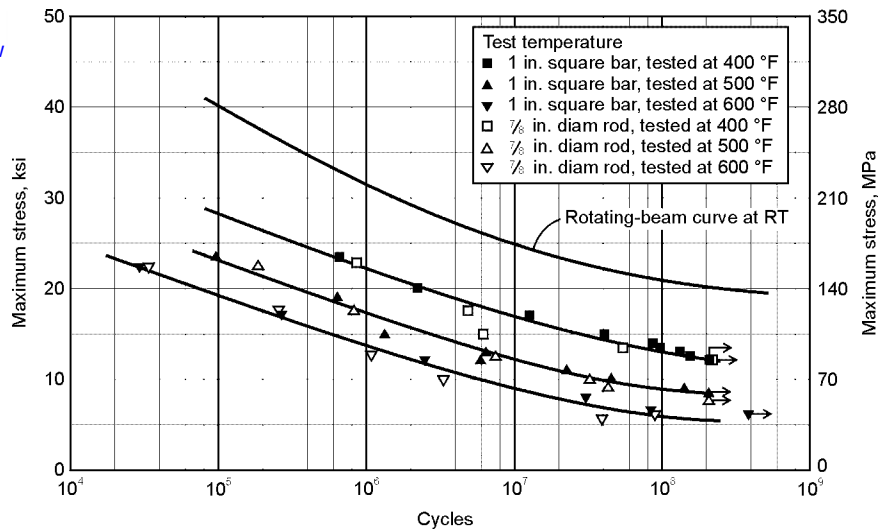


Fig. 2618.HT01 Rotating-beam ($R = -1.0$) fatigue curves for 2618-T6, 7/8 in. diam forged rod and 1 in. square rod at 400, 500, and 600 °F (205, 260, and 315 °C)



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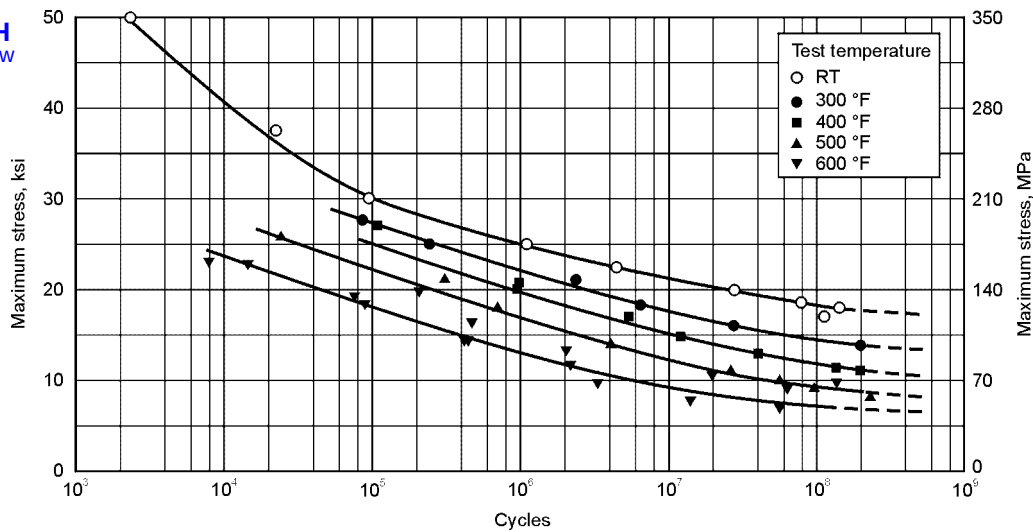


Fig. 2618.HT02 Rotating-beam ($R = -1.0$) fatigue curves for 7/8 in. diam 2618-T6 forged rod at RT, 300, 400, 500, and 600 °F (RT, 150, 205, 260, and 315 °C)

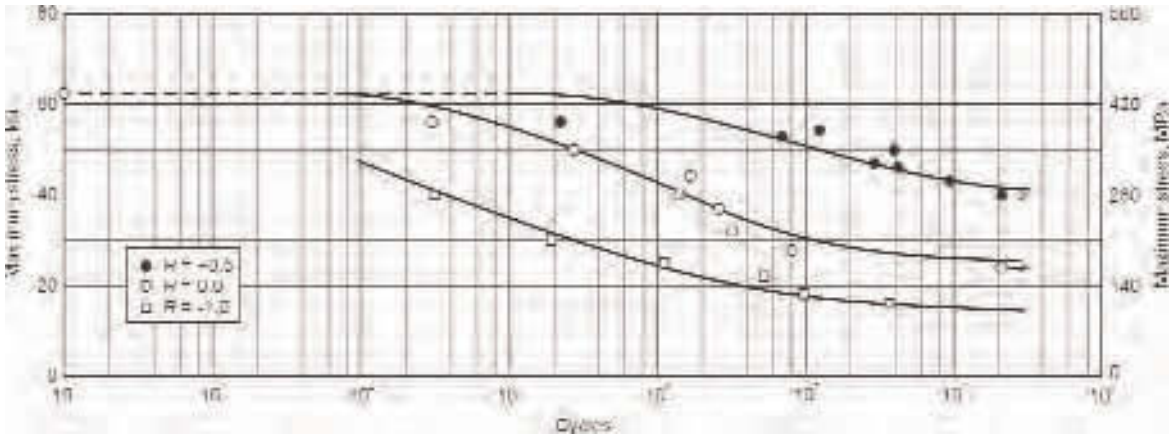


Fig. 2618.AS01 Axial stress fatigue curves for 1.356 in. thick 2618-T651 plate, $R = -1.0, 0.0,$ and $+0.5$. Test direction: longitudinal



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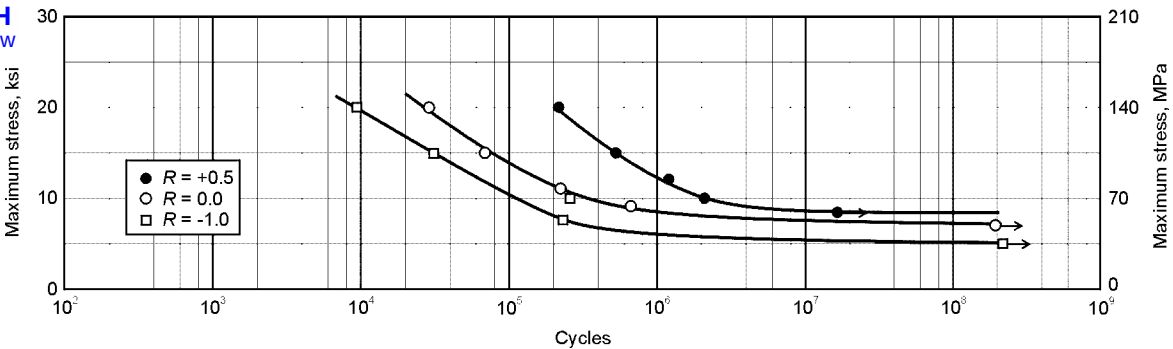


Fig. 2618.AS02 Axial stress fatigue curves for 1.356 in. thick 2618-T651 plate, $R = -1.0, 0.0,$ and $+0.5$, notched ($K_t = 12$) specimens. Test direction: longitudinal



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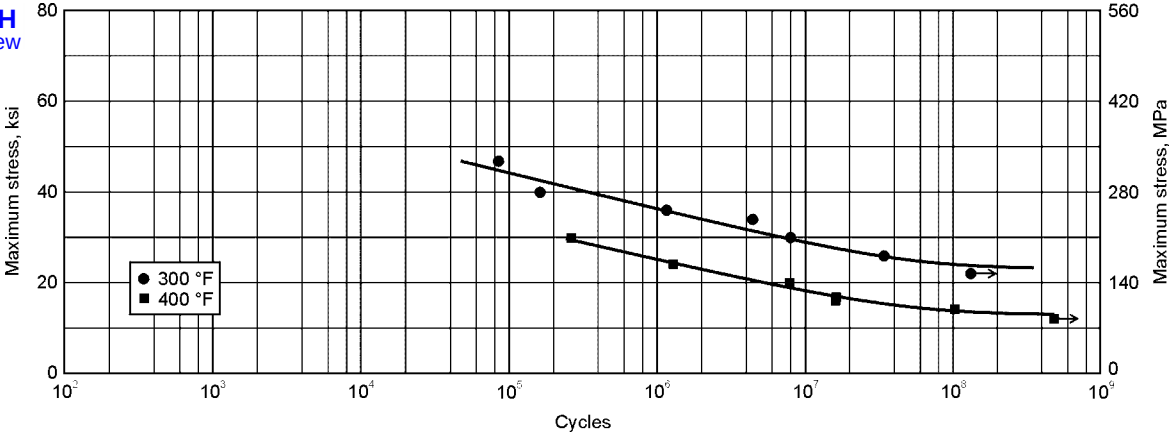


Fig. 2618.AS03 Axial stress fatigue curves for 1.356 in. thick 2618-T651 plate at 300 and 500 °F (150 and 260 °C), $R = 0.0$. Test direction: longitudinal

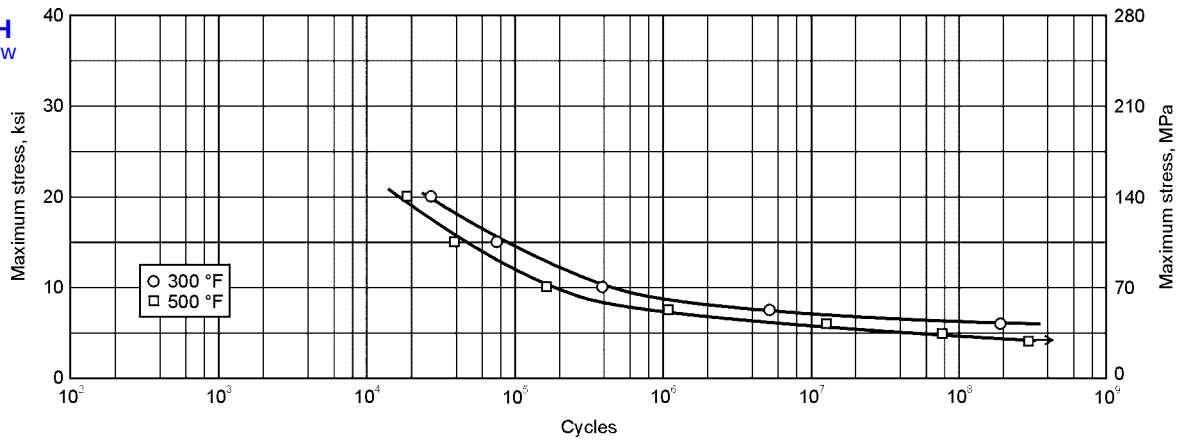


Fig. 2618.AS04 Axial stress fatigue curves for 1.356 in. thick 2618-T651 plate at 300 and 500 °F (150 and 260 °C), $R = 0.0$, notched ($K_t = 12$) specimens. Test direction: longitudinal

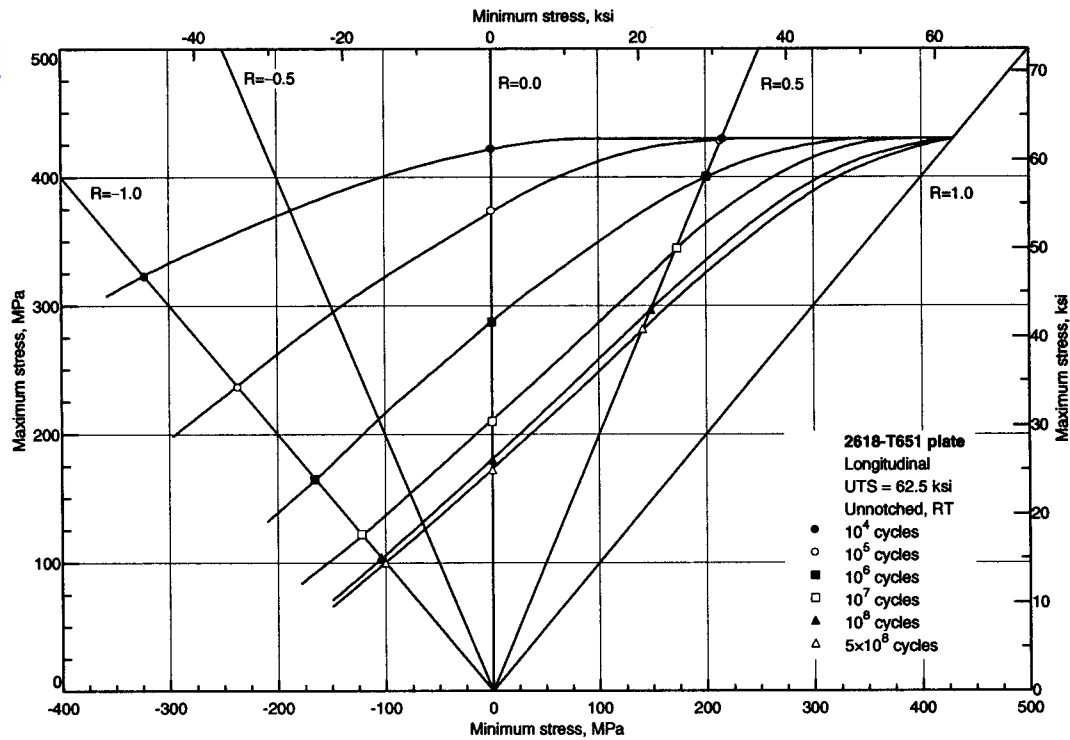


Fig. 2618.GD01 Modified Goodman diagram for 1 3/8 in. thick 2618-T651 plate at room temperature. Test direction: longitudinal



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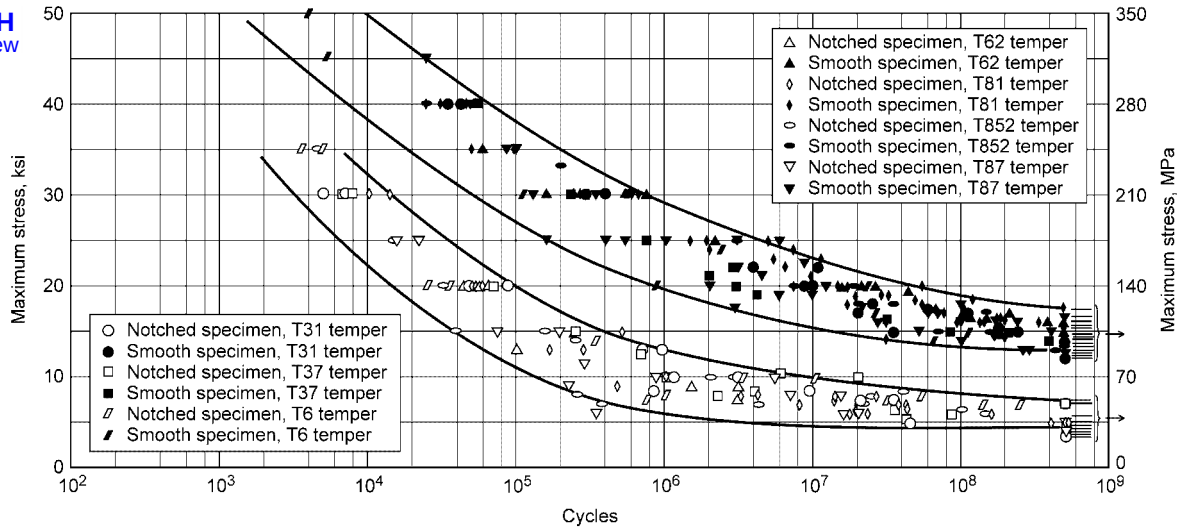


Fig. 2219.RB01 Rotating-beam ($R = -1.0$) fatigue curve for all 2219 products, smooth and sharply notched specimens, comparison of tempers



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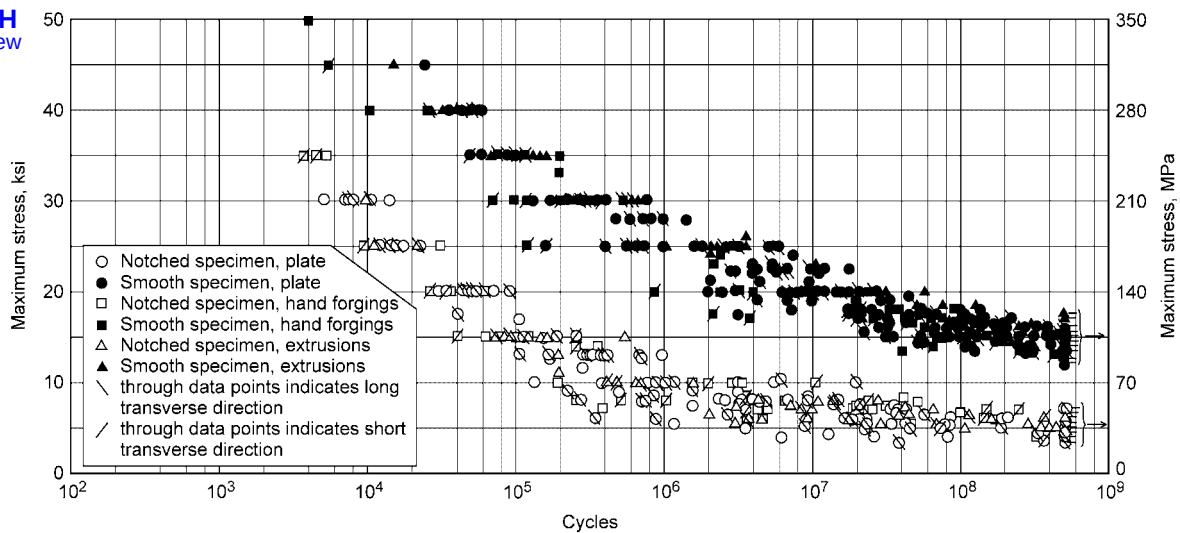


Fig. 2219.RB02 Rotating-beam ($R = -1.0$) fatigue curve for all 2219 products, smooth and sharply notched specimens, comparison of products. Test direction: longitudinal, long transverse, and short transverse



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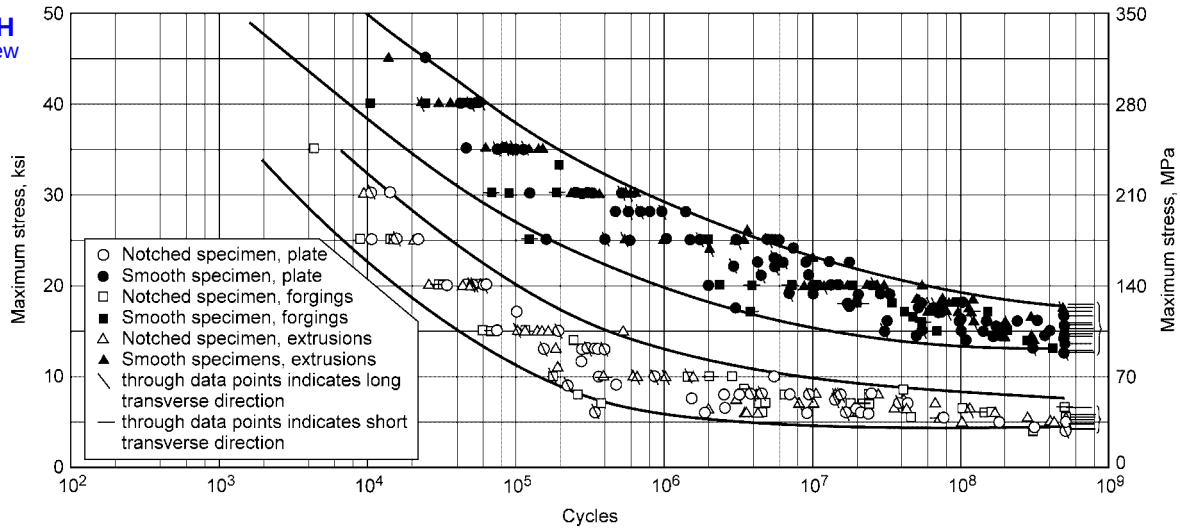


Fig. 2219.RB03 Rotating-beam ($R = -1.0$) fatigue curve for all 2219-T8-type products, smooth and sharply notched specimens, comparison of products. Test direction: longitudinal, long transverse, and short transverse



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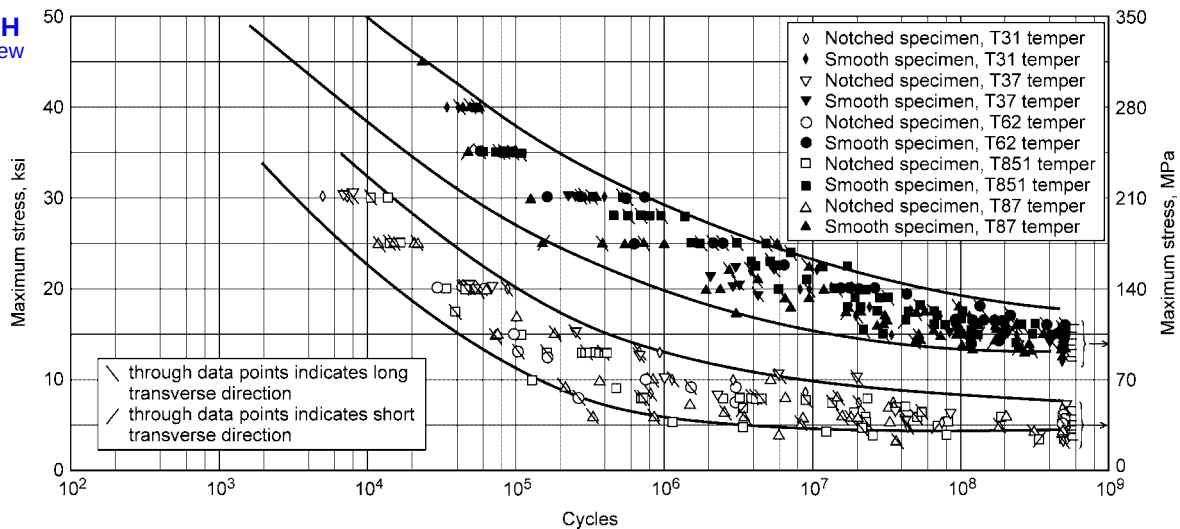


Fig. 2219.RB04 Rotating-beam ($R = -1.0$) fatigue curve for all 2219 plate, smooth and sharply notched specimens, comparison of temps. Test direction: longitudinal, long transverse, and short transverse

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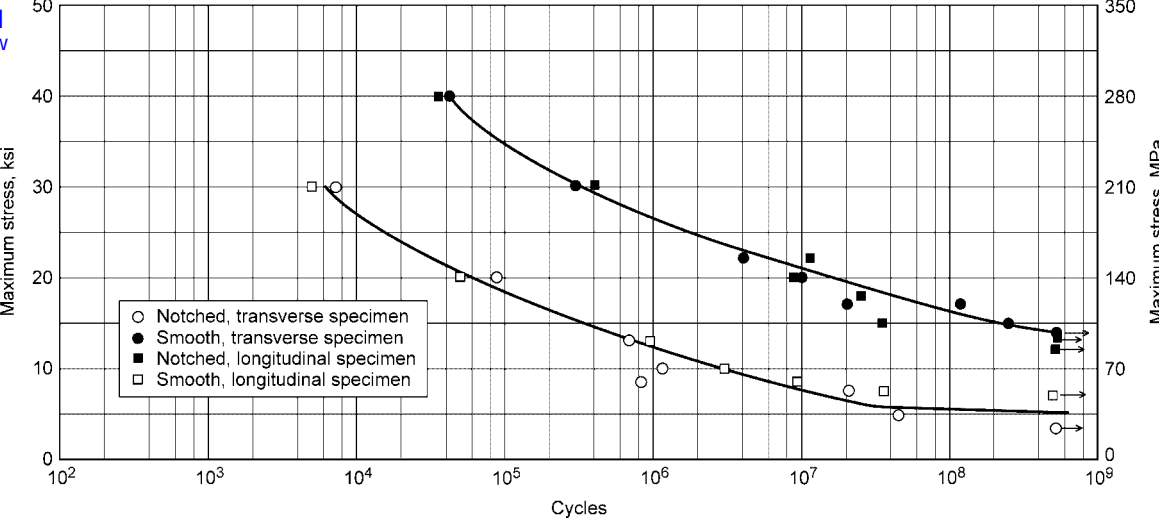


Fig. 2219.RB05 Rotating-beam ($R = -1.0$) fatigue curve for 2219-T31 plate, smooth and sharply notched specimens. Test direction: longitudinal and transverse

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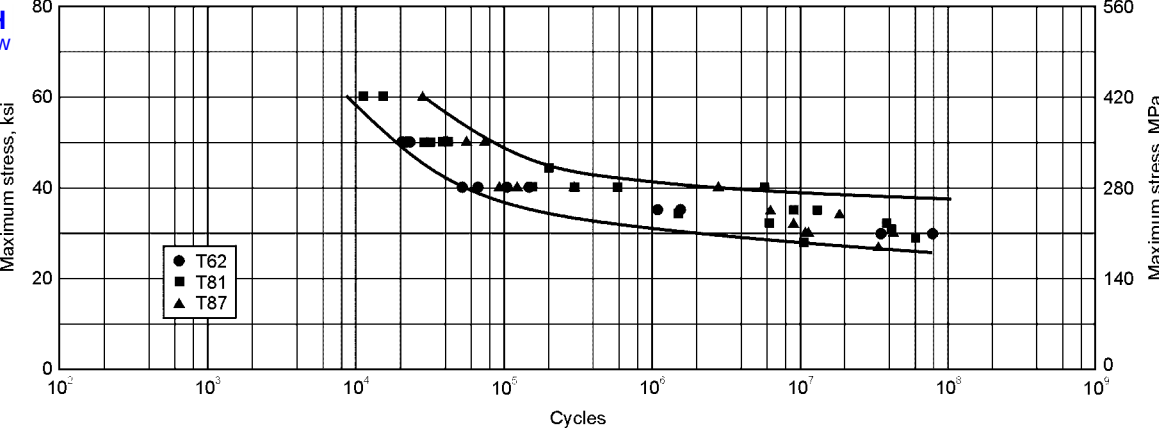


Fig. 2219.AS01 Axial stress fatigue curve for 2219-T62, T81, and T87 products, $R = 0.0$

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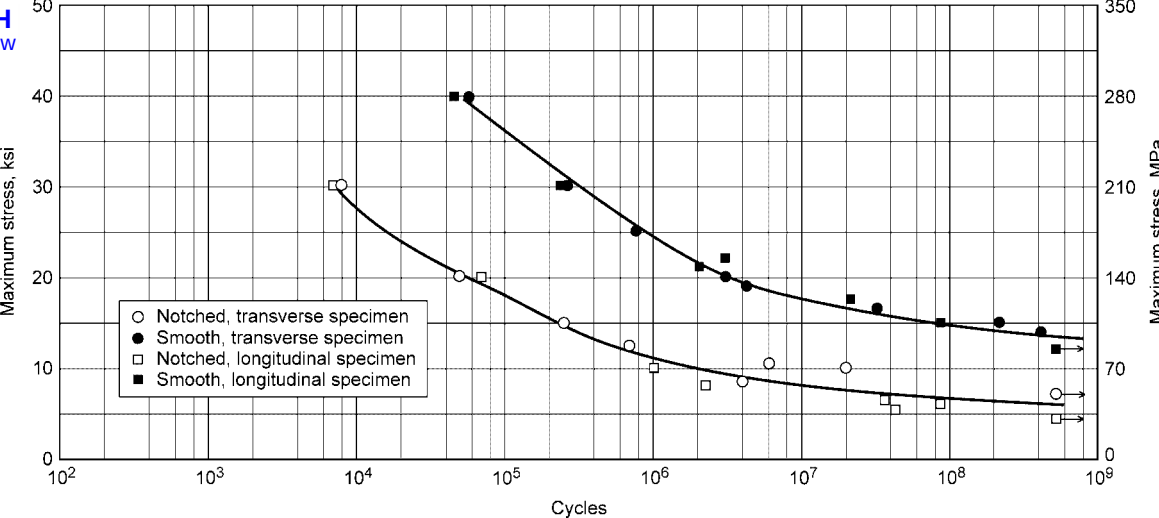


Fig. 2219.RB06 Rotating-beam ($R = -1.0$) fatigue curve for 2219-T37 plate (1 in. thick), smooth and sharply notched specimens. Test direction: longitudinal and transverse

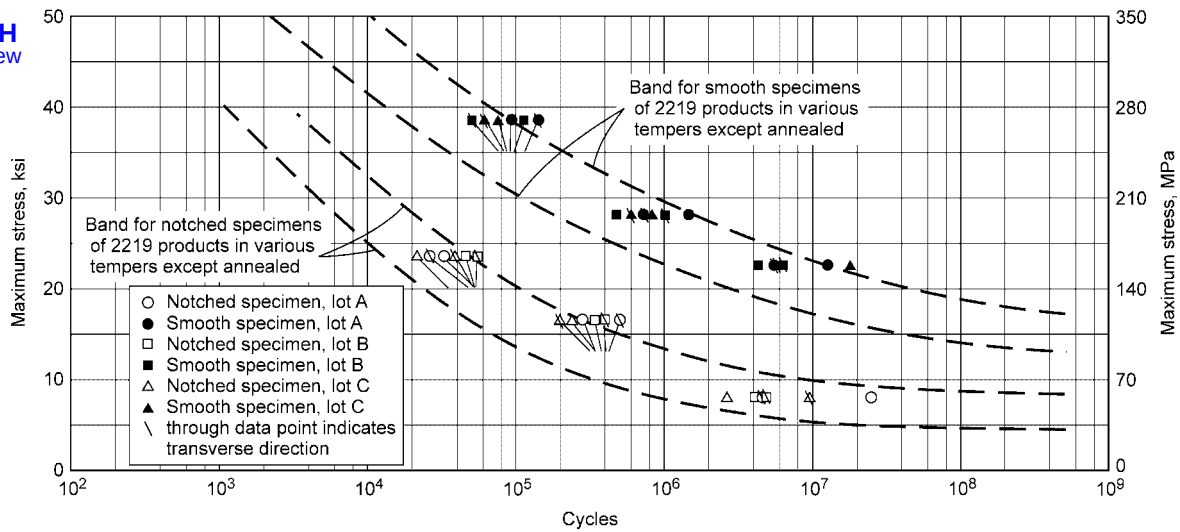


Fig. 2219.RB07 Rotating-beam ($R = -1.0$) fatigue curve for 2219-T851 plate (1.375 in. thick), smooth and sharply notched specimens. Test direction: longitudinal and transverse

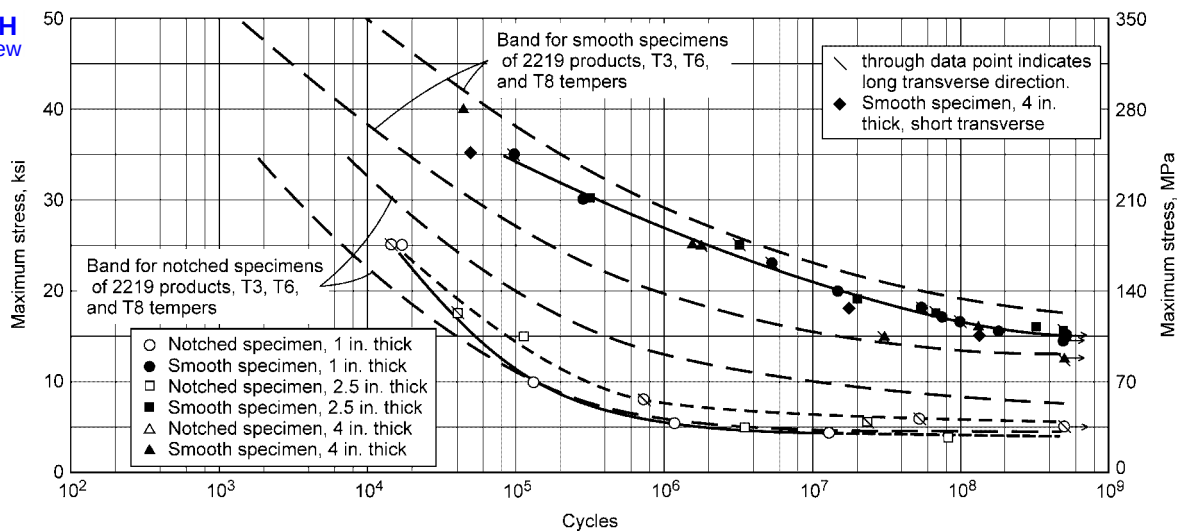


Fig. 2219.RB08 Rotating-beam ($R = -1.0$) fatigue curve for 2219-T87 plate (1–4 in. thick), smooth and sharply notched specimens. Test direction: longitudinal, long transverse, and short transverse

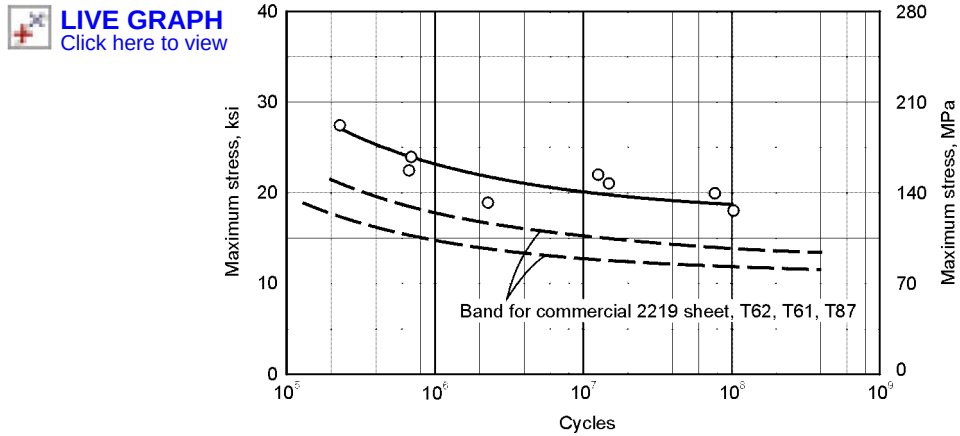


Fig. 2219.FL01 Flexural fatigue ($R = -1.0$) curve for 0.064 in. thick 2219-T6 sheet

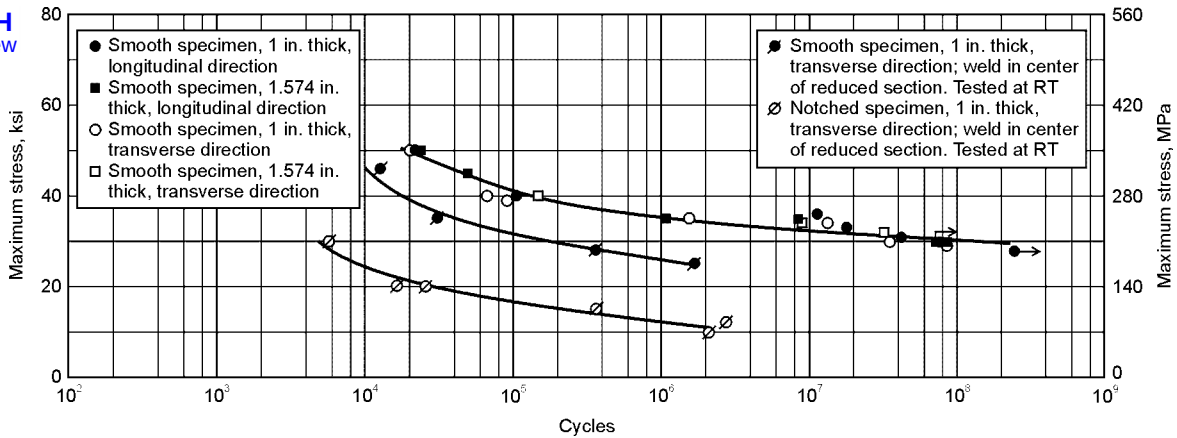


Fig. 2219.AS02 Axial stress fatigue curve for welded and unwelded 2219-T62 plate, $R = 0.0$

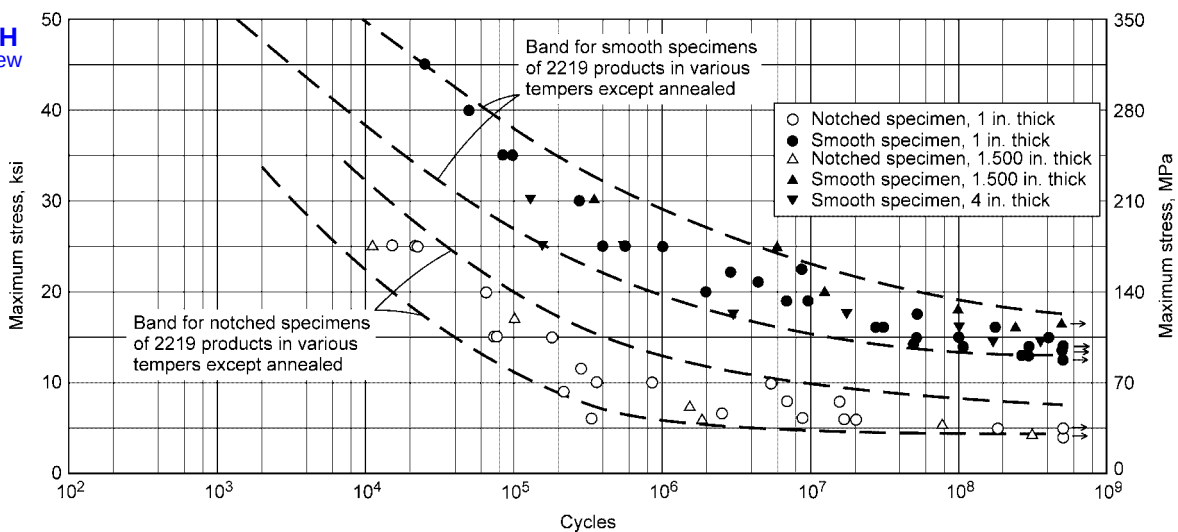


Fig. 2219.RB09 Rotating-beam ($R = -1.0$) fatigue curve for 2219-T87 plate (1–4 in. thick), smooth and sharply notched specimens

CHAPTER 4

General Observations and Comparisons

BEFORE LOOKING AT THE EFFECTS of individual composition, microstructural, process, and fabrication variables, it is useful to note several general observations about the small-specimen fatigue properties of aluminum alloys.

4.1 Total Data Spread among Alloys

One of the major trends rather clearly indicated by the data presented herein is the relatively narrow range of fatigue strengths for all of the alloys and tempers. This is illustrated by the rotating-bending ($R = -1.0$) data in Fig. 4.1, which shows the bands of smooth and sharply notched ($K_t > 12$) specimen data for three of the most widely studied alloys: 2014, 2024, and 7075 (Ref 1). For these three alloys—representing two broad alloy types, Al-Cu and Al-Zn-Mg, and two tempers, T4 and T6—it seems clear that there are not major differences among them. The means of the bands, if plotted, would differ only slightly, with the 7075-T6 showing a slight superiority for smooth specimens and 2024-T4 a slight superiority with notched specimens.

A similar trend is clear from smooth- and notched-specimen rotating-bending ($R = -1.0$) S - N fatigue bands for all cast aluminum alloys, illustrated in Fig. 4.2 (Ref 1). All of the casting alloys and tempers fall into a fairly narrow range. In this case, the

differences between the bands for smooth and notched specimens are much smaller, a possible inference being that the internal imperfections in some aluminum alloy castings may be somewhat effective as notches in lowering smooth-specimen fatigue strengths closer to those resulting from machined notches.

Despite these initial broad observations, there are a number of important differences to be found among alloys (Chapter 9) and resulting from process changes (Chapters 6–8), as will be seen in these later chapters.

4.2 Data Band Width

Looking again at the bands from rotating-beam tests of some of the most broadly used wrought alloys (2014, 2024, and 7075) in Fig. 4.1, there tends to be greater spread in fatigue strengths for smooth specimens than for sharply notched ($K_t > 12$) specimens of the same alloy and temper. This may be taken as evidence that the presence of a severe stress concentration minimizes differences among alloys and tempers, not only within replicate tests of a single alloy and temper but across a variety of alloys and tempers.

While the small-specimen S - N approach does not provide clear distinctions in characterizing the crack initiation and crack propagation stages of fatigue, the differences between band widths for smooth and notched specimens suggest that the larger spread in smooth fatigue life is partly associated with variations in time (cycles of stress) to initiate a crack, whether at surface imperfections or strain localization, whereas with a notch (especially a very sharp notch, as in Fig. 4.1 and 4.2), the crack initiation phase is shorter and the total life bands narrowed.

Bear in mind that the generalizations noted in the previous two paragraphs are just that, generalizations. A closer look later demonstrates that there are indeed significant differences among some alloys and tempers and important effects of some process variations.

4.3 Questions about the Existence of an Endurance Limit

For many years, there has been conjecture as to whether or not aluminum alloys truly exhibit an endurance limit, that is, a stress below which the material would carry an indefinite number of

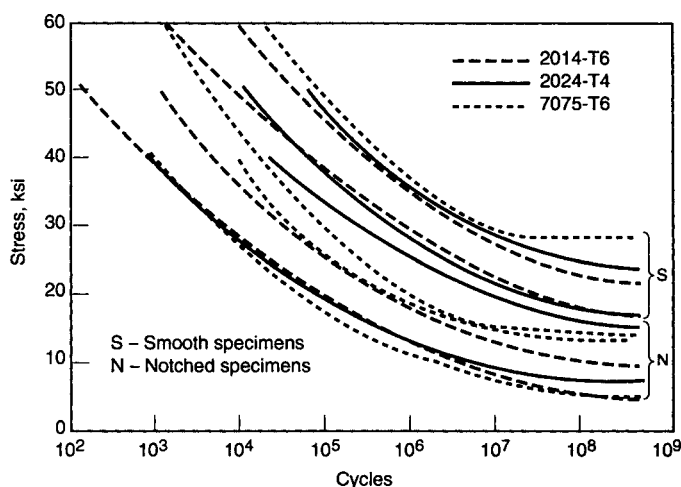
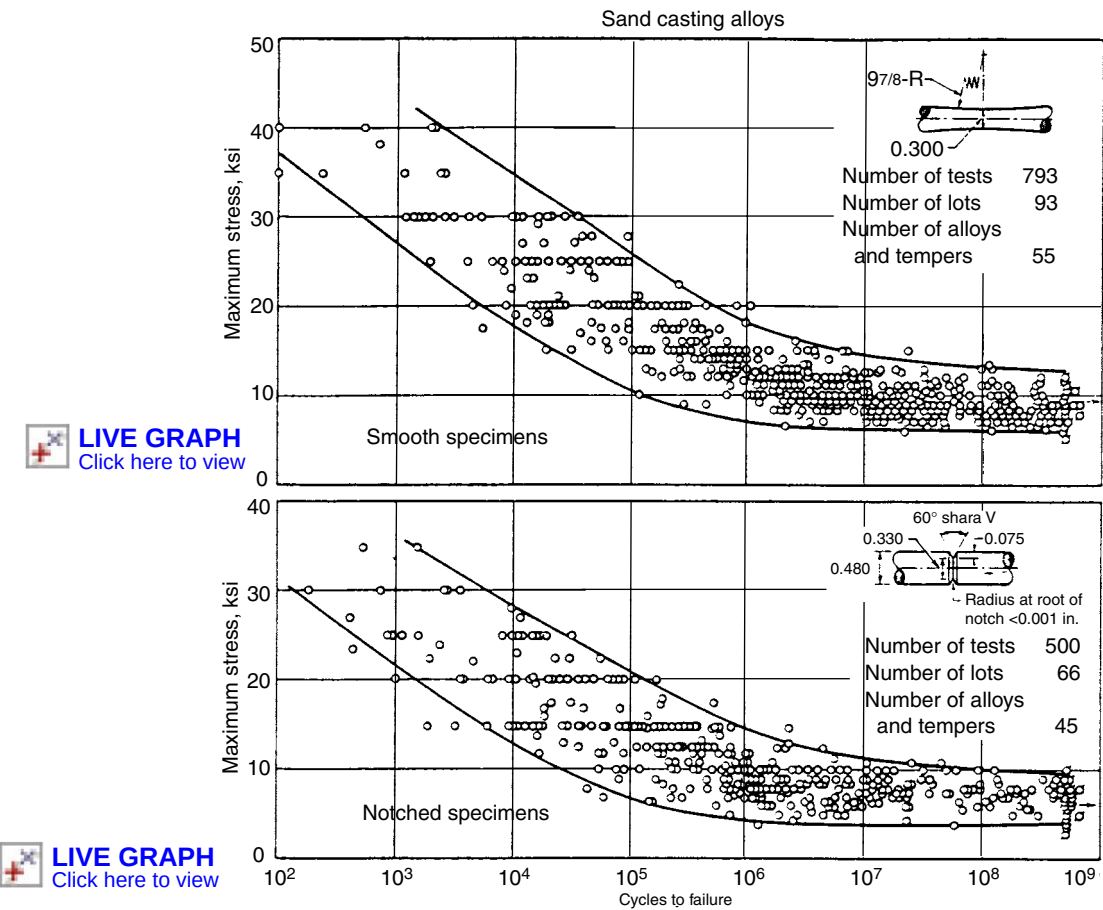


Fig. 4.1 Summary S - N plots of smooth- and notched-specimen rotating-bending ($R = -1.0$) fatigue data for 2014-T6, 2024-T4, and 7075-T6. Source: Ref 1



Specimen				Specimen			
Alloy and temper	Smooth	Notched	Status	Alloy and temper	Smooth	Notched	Status
208.0-F	×	×	...	A334.0-F	×	×	(a)
209.0-F	×	×	(a)	355.0-T4	×	×	...
212.0-F	×	×	(a)	355.0-T51	×	×	...
212.0-T2	...	×	(a)	355.0-T514	×	×	...
213.0-F	×	×	...	355.0-T6	×	×	...
221.0-F	×	...	(a)	355.0-T61	×	×	...
222.0-F	×	...	...	355.0-T7	×	×	...
222.0-T2	×	×	...	355.0-T71	×	×	...
222.0-T61	×	×	...	A355.0-T51	×	×	(a)
242.0-F	×	×	...	A355.0-T59	×	×	(a)
242.0-T2	×	×	...	A355.0-T6	×	...	(a)
242.0-T21	×	×	...	A355.0-T71	×	×	(a)
242.0-T571	×	×	...	B355.0-T6	×	×	(a)
242.0-T61	×	×	...	356.0-T4	...	×	...
242.0-T77	×	×	...	356.0-T51	×	×	...
A242.0-T75	×	×	...	356.0-T59	×	×	...
251.0-F	×	...	(a)	356.0-T6	×	×	...
295.0-T4	×	×	...	356.0-T7	×	×	...
295.0-T59	×	×	...	356.0-T71	×	×	...
295.0-T6	×	×	...	406.0-F	×	...	(a)
295.0-T62	×	×	...	413.0-F	×	×	...
A295.0-T4	×	...	...	B443.0-F	×	×	...
B295.0-T4	×	...	...	C443.0-F	×	...	...
296.0-T62	×	×	(a)	512.0-F	×	×	...
319.0-F	×	...	...	514.0-F	×	×	...
319.0-T21	×	...	...	520.0-T4	×	×	...
319.0-T4	×	×	...	A712.0-T5	×	×	...
319.0-T72	×	×	...	745.0-F	×	...	(a)

(a) Obsolete—no modern commercial alloy

Fig. 4.2 Summary *S-N* plot for smooth and sharply notched ($K_t > 12$) rotating-bending ($R = -1.0$) fatigue data for all aluminum casting alloys. Source: Adapted from Ref 1

cycles of repeated load without failure. When comparing rotating-beam fatigue strengths of smooth and notched specimens of some alloys, as in Fig. 4.1, there clearly seems to be an asymptotic leveling of the S - N curve as the number of applied cycles approaches 100 to 500 million, supporting the long-used industry definition of endurance limit being effectively equivalent to the fatigue strength at 5×10^8 cycles.

Even at that long life, some alloys, tempers, and products still exhibit some gradual reduction in stress with increase in cycles of loading. An illustration is shown in Fig. 5052.FL01 for 5052-O sheet; for the longitudinal direction, fatigue strength seems to continue to decrease in a straight line on this semi-log plot, even beyond 10^8 cycles. However, such cases are relatively few, and the small decreases illustrated are sufficiently small to allow the adoption of a fatigue endurance limit at 5×10^8 cycles. As noted earlier, that has been the basis of the fatigue endurance limits tabulated and published for over 50 years for commercial aluminum alloys by the Aluminum Association (Ref 2) and by the various casting organizations (Ref 3–7).

Clear endurance limits should not necessarily be expected in aggressive environments, because corrosion may continue to occur indefinitely, and S - N curves may not always tend to level out when corrosion fatigue occurs (Section 9.2 in Chapter 9).

4.4 Specimen Directional Effects

For most aluminum alloy products, fatigue strengths determined in the long-transverse (LT) direction are generally not significantly different from test results in the longitudinal (L) direction, although there are some exceptions. The scatter band limits for 2014-T6 products in Fig. 4.3 (Ref 1) show relatively small overall effects in rotating-bending ($R = -1.0$) fatigue strengths attributable to working direction, particularly for the notched-specimen data.

One exception to that generalization that is evidenced rather regularly is the higher LT flexural-fatigue strengths of cold-

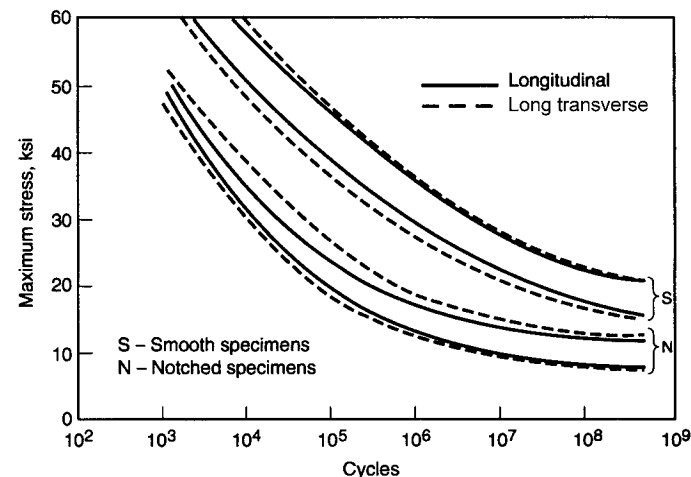


Fig. 4.3 Summary rotating-bending ($R = -1.0$) S - N plots for 2014-T6 by specimen direction. Source: Ref 1

worked tempers of some non-heat-treatable alloys, for example, 5154-H34 and H38 (Fig. 5154.FL02 and FL03, respectively). In most cases, such differences are relatively small.

A more pronounced exception is found in 7049-T73 hand forgings, data for which are shown in Fig. 7049.AS01. For this alloy and product, a pronounced difference between fatigue lives of L and LT specimens was observed; the fatigue lives of L specimens were sometimes an order of magnitude longer than those of LT specimens. This seems an exception, not the rule, and regrettably, there are no metallographic studies to determine whether or not quality issues resulted in these differences. Such differences do not typically show up in data for forgings (or other products) of other high-strength alloys.

For the short-transverse (ST) direction, however, especially of relatively thick aluminum alloy products, it can be expected that fatigue strengths may be significantly lower than in the L and LT directions. An example is thick 5083-H113 plate, for which rotating-bending ($R = -1.0$) data for all three major specimen directions (L, LT, and ST) are presented in Fig. 5083.RB04. These data illustrate that in the L and LT directions, the fatigue strengths of smooth specimens are comparable to those of thinner plate (Fig. 5083.RB03). However, in the ST direction of thicker plate, fatigue strengths are significantly lower, the difference increasing with increase in life; the ST endurance limit is approximately 11 ksi (76 MPa) compared with approximately 19.5 ksi (134 MPa) for the L and LT directions.

Other illustrations of the lower ST fatigue strengths include the data for 2024-T852 die forgings in Fig. 2024.AS24, 7050-T7351 plate in Fig. 7050.AS01, and 7075-T65 plate in Fig. 7075.AS11. In these cases, the ST fatigue strengths are approximately 10 ksi (69 MPa) lower than for the other two test directions.

More detailed studies of ST fatigue strengths were carried out for 7075-T6 and T7351 plate. Data for ST axial-stress ($R = +0.5$) specimens from 2.5 in. (6.4 cm) thick 7075-T6 plate are shown in Fig. 7075.AS10 and AS11. While the results vary with ultrasonically measured “hash level,” the lower ST fatigue strengths are apparent, especially in the higher-hash-level, that is, lower-quality, samples (Section 7.3 in Chapter 7).

A similar case of lower ST fatigue properties is found in $R = -1.0$ data for 7075-T7351 plate by comparing the data in Fig. 7075.RB15 and RB16 for the ST direction in 3 in. (7.6 cm) plate with the normal bands for 7075-T73 products in Fig. 7075.RB14. While once again this comparison is complicated by the presence of various quality levels as defined by ultrasonic hash levels, almost all of the ST smooth-specimen data fall below the 7075-T73 bands that represent L and LT specimens. There is much less difference for the notched specimens, because the severe ($K_t > 12$) notches override the directional and hash-level variables.

4.5 Correlations with Static Strength

Attempts have been made from time to time to correlate the fatigue properties of aluminum alloys with their static tensile properties. One approach is shown in Fig. 4.4 (Ref 1), a plot of endurance limits (at 5×10^8 cycles) as a function of ultimate tensile strength. From this presentation, there does indeed appear to

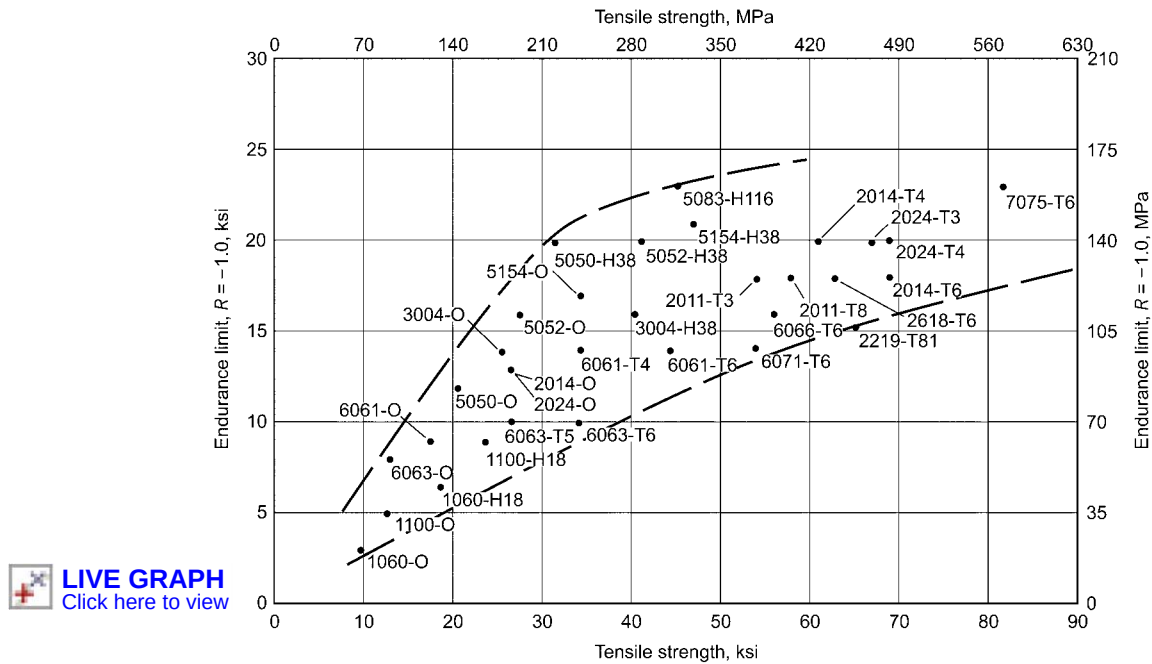


Fig. 4.4 Endurance limit (5×10^8) versus tensile strength for a number of aluminum alloys ($R = -1.0$). Source: Adapted from Ref 1

be a broad relationship in which fatigue strength increases with increasing tensile strength. However, the relationship is so broad as to not be very useful for predictive purposes at a detailed level. At a tensile strength of 40 ksi (276 MPa), the endurance limit may range from approximately 11 to almost 20 ksi (76 to almost 138 MPa), about half the total observed range for all aluminum alloys.

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CHAPTER 5

Comparisons of Fatigue Properties of Various Alloys, Tempers, and Products

5.1 Wrought Alloys

As noted in Section 4.1 in Chapter 4, there is not a great total spread in small-specimen fatigue strength among aluminum alloys and tempers; however, there are some general trends that may be noted. These can be illustrated by the S - N plots in Fig. 5.1 to 5.5, which show bands of data for the 2xxx, 4xxx, 5xxx, 6xxx, and 7xxx series of aluminum alloys, each with both smooth and sharply notched ($K_t > 12$) specimens.

From these S - N plots, it can be seen that for smooth specimens, the 2xxx (Fig. 5.1), 5xxx (Fig. 5.3), and 7xxx (Fig. 5.5) series trend higher than the 4xxx (Fig. 5.2) and 6xxx (Fig. 5.4) series; the latter, the 6xxx series (Fig. 5.4), clearly trends lowest. The reason for this is not entirely clear, but it may be related to the fact that many of the tested 6xxx products are extruded shapes, many of which are press air quenched rather than cold water quenched, the former resulting in less fully developed precipitate structures. More is said about this subject in Chapter 6, which discusses processing variables.

For the sharply notched specimens, there are no apparent clear alloy-specific trends. The very sharp stress raiser used in these tests seemingly reduces all alloy classes to a common denominator. Some differences are observed when data are examined in more detail later.

Some specific observations on the individual series are worth noting. These arise not only from the summary plots in Fig. 5.1 to 5.5 but also from review of the data sets herein.

5.1.1 1xxx Pure Aluminum

Pure aluminum compositions, such as 1100 (99% Al) and 1350 (99.5% Al), have lower fatigue strengths than any of the intentionally alloyed compositions, especially in the annealed (O) temper. However, their exceptional corrosion resistance, ductility and formability, and electrical conductivity make them very useful for many purposes, including packaging and as an electrical conductor.

5.1.2 2xxx Alloys

Some alloys of the 2xxx series, notably 2024 and 2124 in the T8-type tempers, have relatively high smooth-specimen fatigue strengths, approximately comparable to the best of the 5xxx and 7xxx series. They are generally more sensitive to severe stress

raisers, however. The T3- and T4-type tempers of these alloys fare better with notched specimens, however, and generally fall higher in the notch data bands.

5.1.3 3xxx Alloys

Lightly alloyed 3xxx alloys, such as 3003 and 3004, have very low fatigue strengths but other exceptional properties, such as formability and corrosion resistance, that make them ideal for applications in heat exchangers and beverage containers.

5.1.4 4xxx Alloys

This is the least-used wrought alloy system, and data are included herein only for 4032-T6 and 4043 weld wire. Their fatigue strengths are unremarkable, but their flow characteristics make 4032 useful for intricate forgings and 4043 for filler alloy for gas metal arc (GMA) welding.

5.1.5 5xxx Alloys

From the smooth-specimen fatigue-endurance-limit perspective, the Al-Mg-Mn of the 5xxx series seem to have among the highest strengths, especially considering their modest static tensile and yield strengths. Added to this are their relative notch resistance and corrosion fatigue resistance plus their weldability. They are versatile alloys for a variety of critical applications, such as automotive body components, marine vessels and structures, and highway bridges, although their static strength is not great enough for most aerospace applications.

Figures 5.6 and 5.7 provide a direct comparison at room temperature and -320°F (-195°C), respectively, of the four most widely used Al-Mg-Mn alloys, including specimens from GMA groove welds in the four. As would be anticipated, data for alloy 5456 and for welds in 5456 with 5556 filler alloy often appear near the upper parts of the bands at both temperatures. Weld fatigue strengths are approximately 50 to 75% of parent metal strengths, little different from those for the annealed (O) temper of the four alloys; this is also to be expected, since gas metal arc welding leaves an annealed cast metal weld zone.

The limited notched-specimen testing suggests sharp notch ($K_t > 12$) fatigue strengths 50 to 70% below smooth-specimen strengths. It is interesting to note in comparing Fig. 5.6 and 5.7 that the effects of both the welding and the notches seem less at

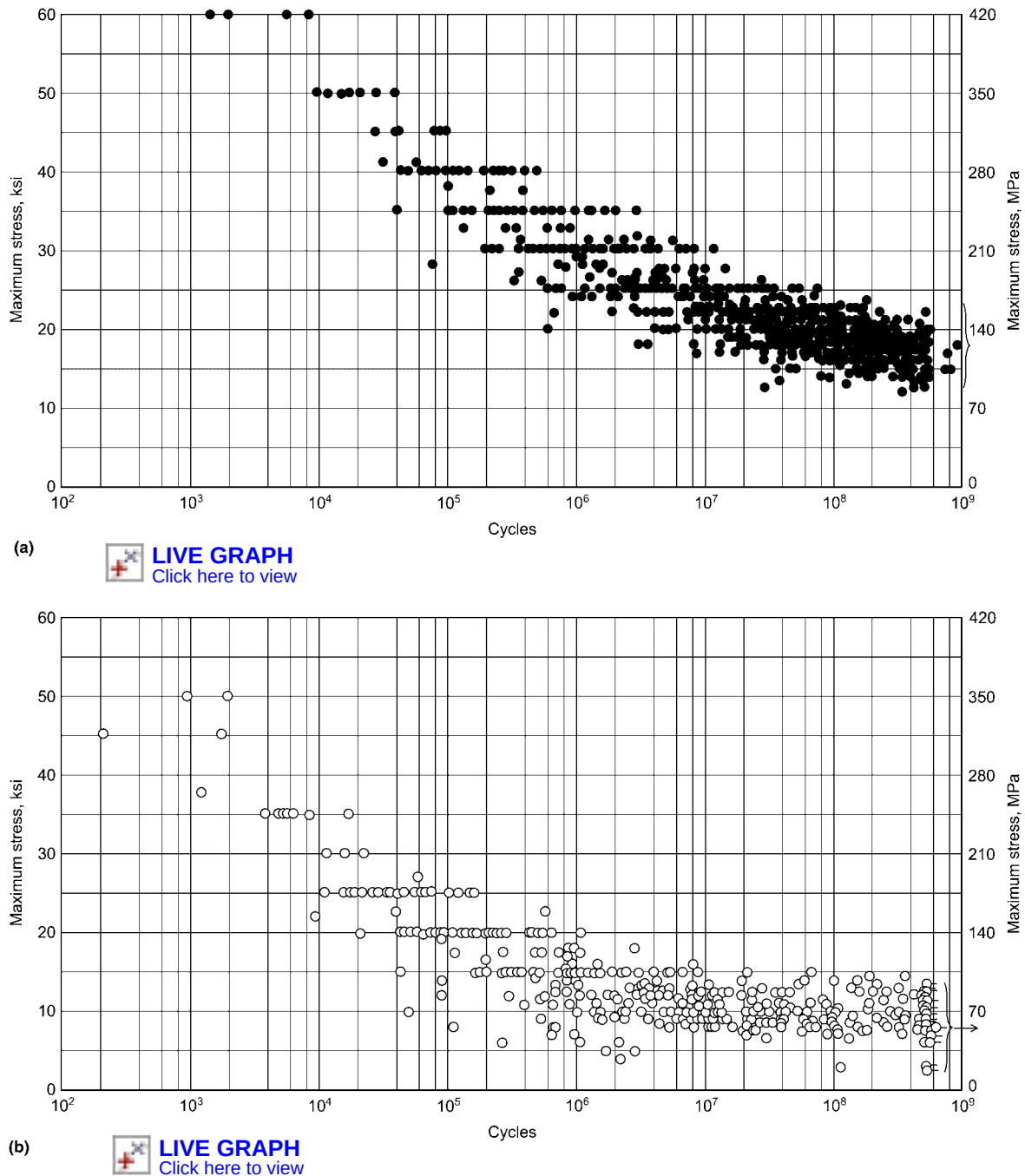


Fig. 5.1 Rotating-beam ($R = -1.0$) fatigue curve for all 2xxx alloy products. (a) Smooth specimens. (b) Sharply notched specimens

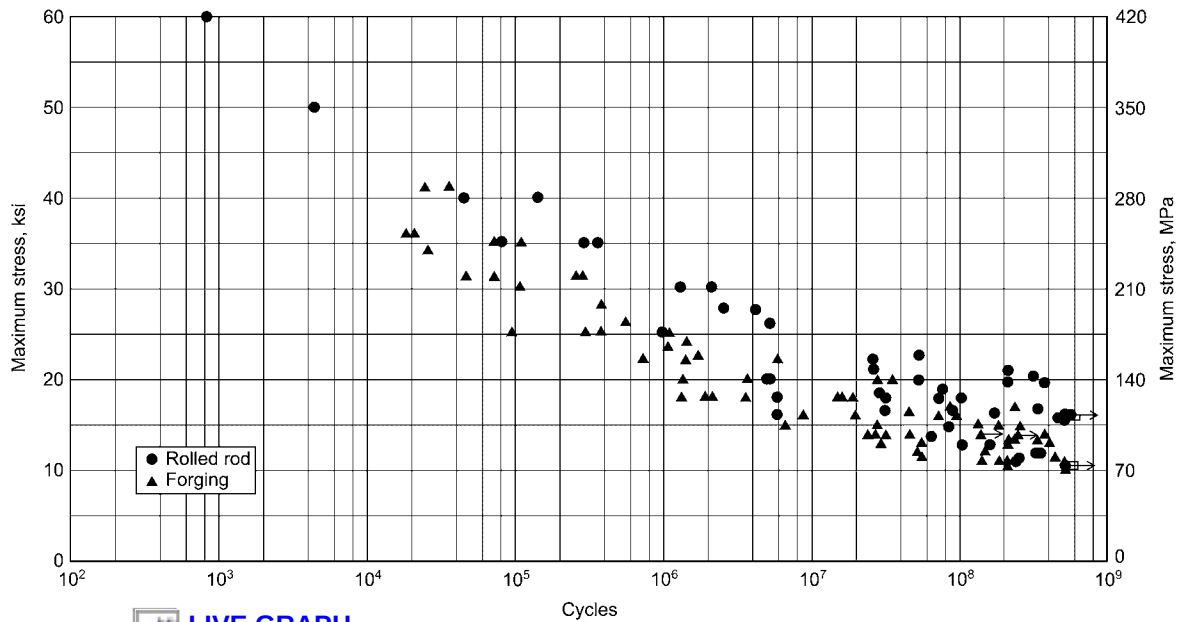
-320°F (-195°C) than at room temperature. A most important feature, perhaps, is that fatigue strengths at -320°F (-195°C) are as high as or higher than at room temperature (Section 9.1.3 in Chapter 9).

5.1.6 6xxx Alloys

A widely used group of alloys, especially in applications calling for weldable extruded shapes, is the 6xxx series and especially the workhorse alloys 6061 and 6063. While fatigue strengths of these alloys are not as high as those of some 2xxx,

5xxx, and 7xxx alloys, when optimized fabrication practices are used, they perform very well.

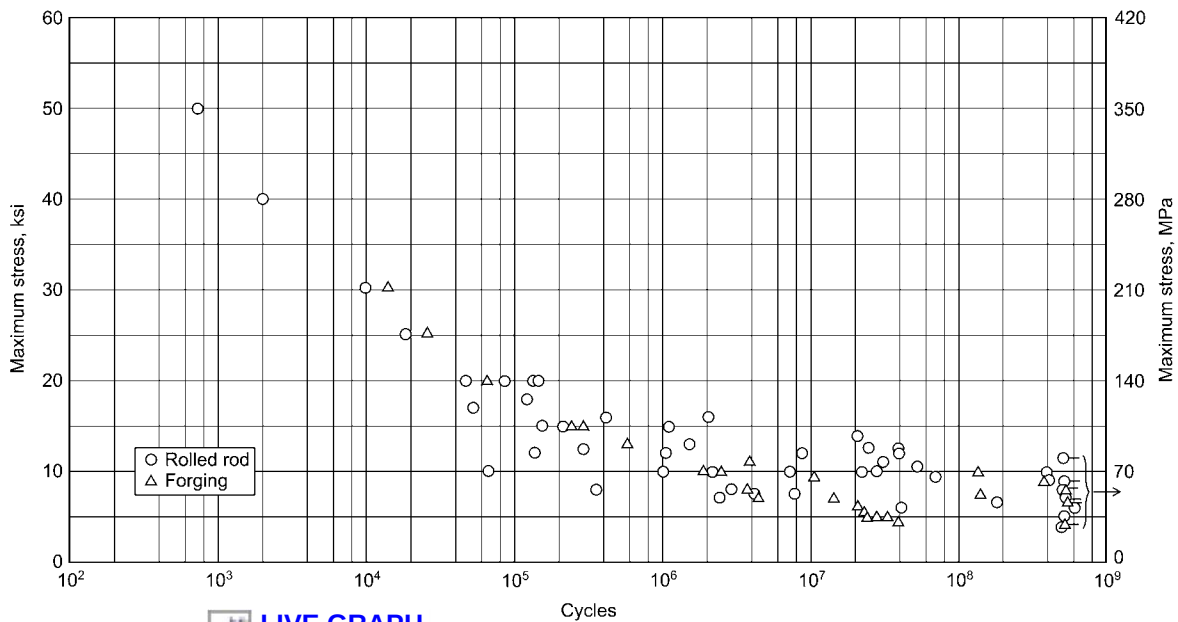
In considering these 6xxx alloys for fairly critical structural applications, it is important to recognize the importance of a high-quality solution heat treatment and cold water quench, as also noted in the discussion in Chapter 6. Direct comparisons of the four 6xxx alloys (6005, 6061, 6063, and 6351) referred to in Chapter 6 are presented in Fig. 5.8, flexural fatigue ($R = -1.0$) for all four alloys solution heat treated and quenched, and in Fig. 5.9, axial stress for all forced-air quenched. In both cases, where



(a)



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(b)



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Fig. 5.2 Rotating-beam ($R = -1.0$) fatigue curve for all 4xxx alloy products. (a) Smooth specimens. (b) Sharply notched specimens

fatigue strength is important, alloys 6061 and 6351 are the better choices.

Considering that, and broadening the comparison of 6061 and 6351 with various types of quench as the metal leaves the extrusion press, as in the axial-stress data in Fig. 5.10, the relative importance of a press water quench instead of a forced-air quench is reinforced. In the press water quench method, the extruded length moves quickly into the cold water tank as it leaves the extrusion

press. Forced-air quench uses fans to blow cold air on the extruded length as it leaves the extrusion press.

5.1.7 7xxx Alloys

The Al-Zn-Mg alloys containing copper have the highest static strengths of commercial aluminum alloys. This tends to be reflected in their relatively high room-temperature fatigue strengths as well. Data for alloys such as 7050, 7075, and 7178 typically

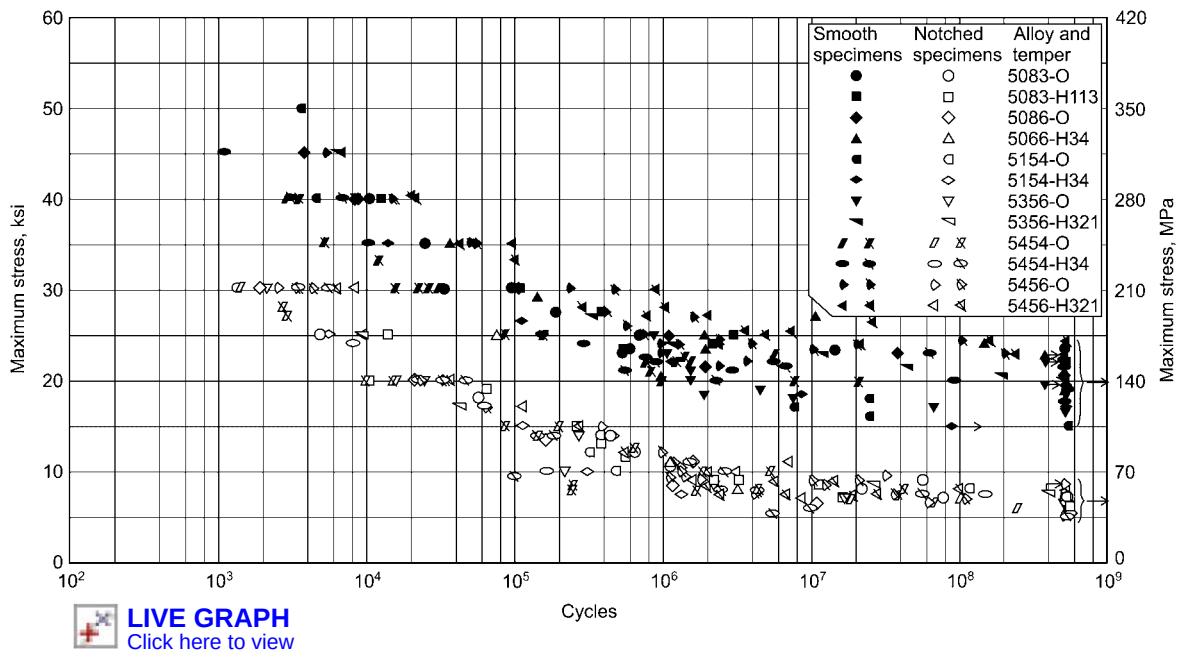


Fig. 5.3 Rotating-beam ($R = -1.0$) fatigue curve for all 5xxx alloy products, smooth specimens and sharply notched specimens. Symbols with \ are long transverse, all others are longitudinal.

fall into the upper part of the 7xxx-series band at room temperature, although they drop off at high temperatures, especially above 300 °F (150 °C). These alloys lack the better toughness and notch resistance as well as corrosion resistance of the Al-Mg-Mn alloys and thus are not the usual choices for nonmilitary structural applications.

5.2 Comparison of Different Wrought Products

Wrought aluminum alloys are produced as a number of different products, including rolled sheet and plate; rolled and drawn rod, bar, and shapes; extruded shapes; and forgings. There are not great differences to be noted among these products, with two exceptions.

5.2.1 Extruded Shapes

Relatively thick extruded shapes (i.e., greater than approximately 3/8 in., or 9.5 mm, in thickness) that, through processing, remain largely unrecrystallized generally have higher fatigue strengths than do thinner extruded shapes that are fully recrystallized and most other products that tend to be partly or entirely recrystallized. This is discussed in more detail in Section 7.1 in Chapter 7.

Even thick extrusions usually have a thin layer of fully recrystallized structure around the outer boundary of the shape, where the work of extrusion was the greatest. This outer surface region would also be expected to have lower fatigue strengths than the unrecrystallized interior of the shape, and, for this reason, that surface is sometimes machined off.

5.2.2 Thick Plate, Forgings, and Extruded Shapes

Those products thick enough to be tested in a short-transverse (ST) specimen orientation, that is, through the thickness, perpen-

dicular to the principal plane of the product, generally exhibit lower fatigue strengths in the ST orientation than in the long and long-transverse directions. This is discussed in detail in Section 4.4 in Chapter 4.

5.3 Wrought Product Temper

In general, for any specific alloy there are only minor differences in fatigue strength associated with differences within a type of temper, that is, within the H-type (strain-hardened) or T-type (i.e., heat treated) tempers.

5.3.1 Annealed (O) Temper

The fully annealed (O) temper of all alloys consistently has the lowest strength in fatigue as in static loading. The fatigue strengths of O-temper products are less affected by high-temperature exposure than strain-hardened or heat treated products, simply because in production they have already been exposed to temperatures high enough to fully recrystallize them.

5.3.2 Strain-Hardening Tempers, H-Type

For the strain-hardenable alloys, as noted in Section 6.1.2 in Chapter 6, while there may be a gradual increase in fatigue strength with significant increases in the amount of cold work, there is no apparent difference with other variations in the combination of cold work and thermal treatment given the alloys. This is illustrated in Fig. 5083.AS05, containing axial-stress ($R = 0.0$) data for four tempers of 5083 (H112, H113, H115, and H131); all data for the four tempers fall within a relatively narrow band over the whole life-cycle range, with endurance limits in the 28 to 32 ksi (195 to 220 MPa) range. That compares with an endurance limit of approximately 10 ksi (70 MPa) for the O temper (Fig. 5083.AS04).

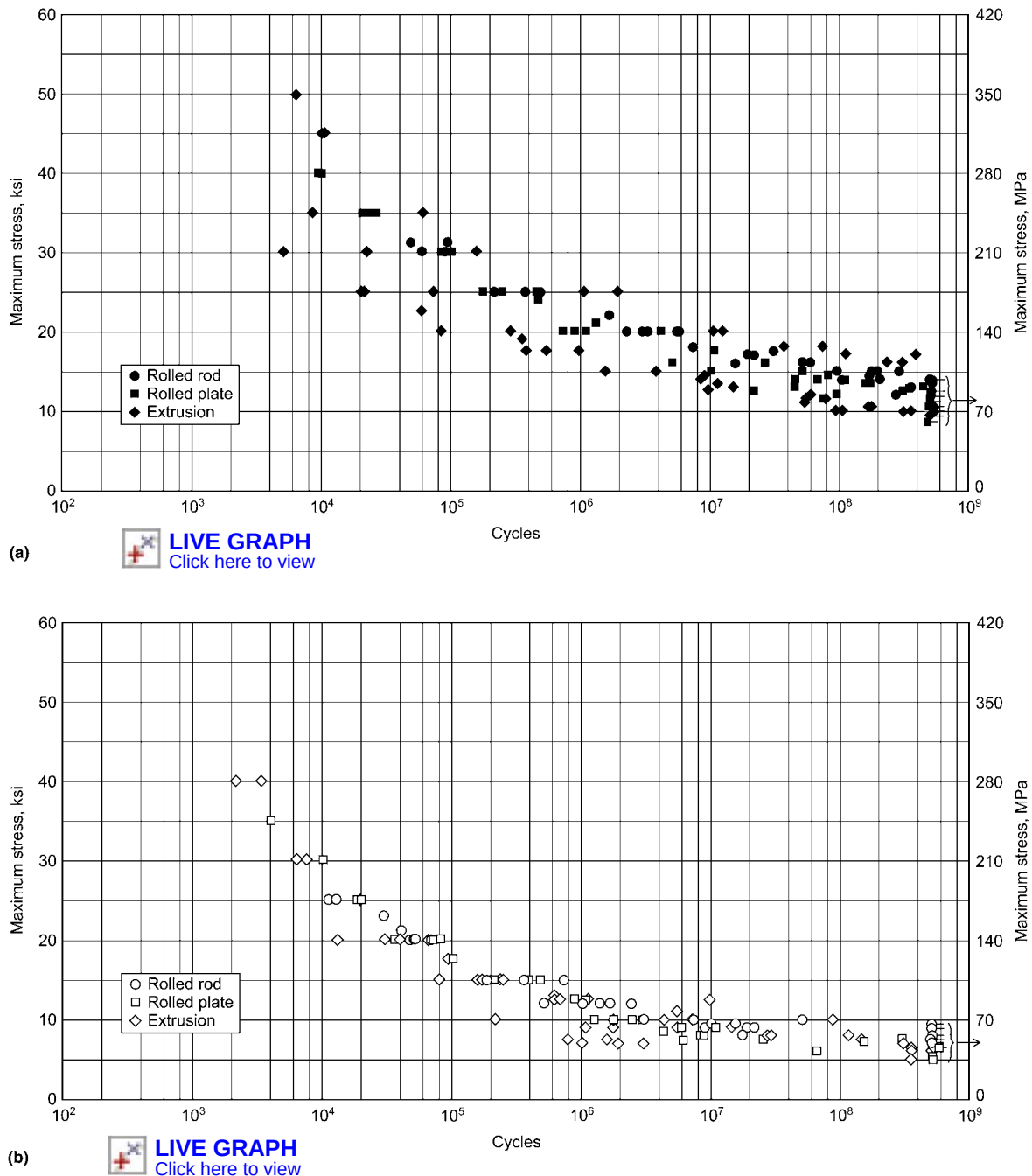


Fig. 5.4 Rotating-beam ($R = -1.0$) fatigue curve for all 6xxx alloy products. (a) Smooth specimens. (b) Sharply notched specimens

5.3.3 Heat Treat Tempers, T-Type

Similarly, for the solution heat treatable alloys such as 2024 and 7075, there are generally only minor differences in fatigue strength, whether they are naturally or artificially precipitation aged (e.g., 2024-T3 type versus T8 type) or whether they are peak aged or overaged (e.g., 7075-T6 type versus T73 type or T76 type). Figures 2024.FL09 and 7075.FL12 provide examples of this trend for sheet-flexural tests ($R = -1.0$); data for the differing tempers are essentially indistinguishable.

5.4 Comparison of Wrought versus Cast Alloys

A summary $S-N$ plot for all cast products was shown in Fig. 4.2 in Chapter 4. By comparing this with the bands in Fig. 4.1 or those in Fig. 5.1 through 5.5, it is clear that smooth-specimen casting data trend significantly lower than all of the wrought groups, including the 6xxx series. This is not surprising, because many aluminum alloy castings produced by commercial high-volume

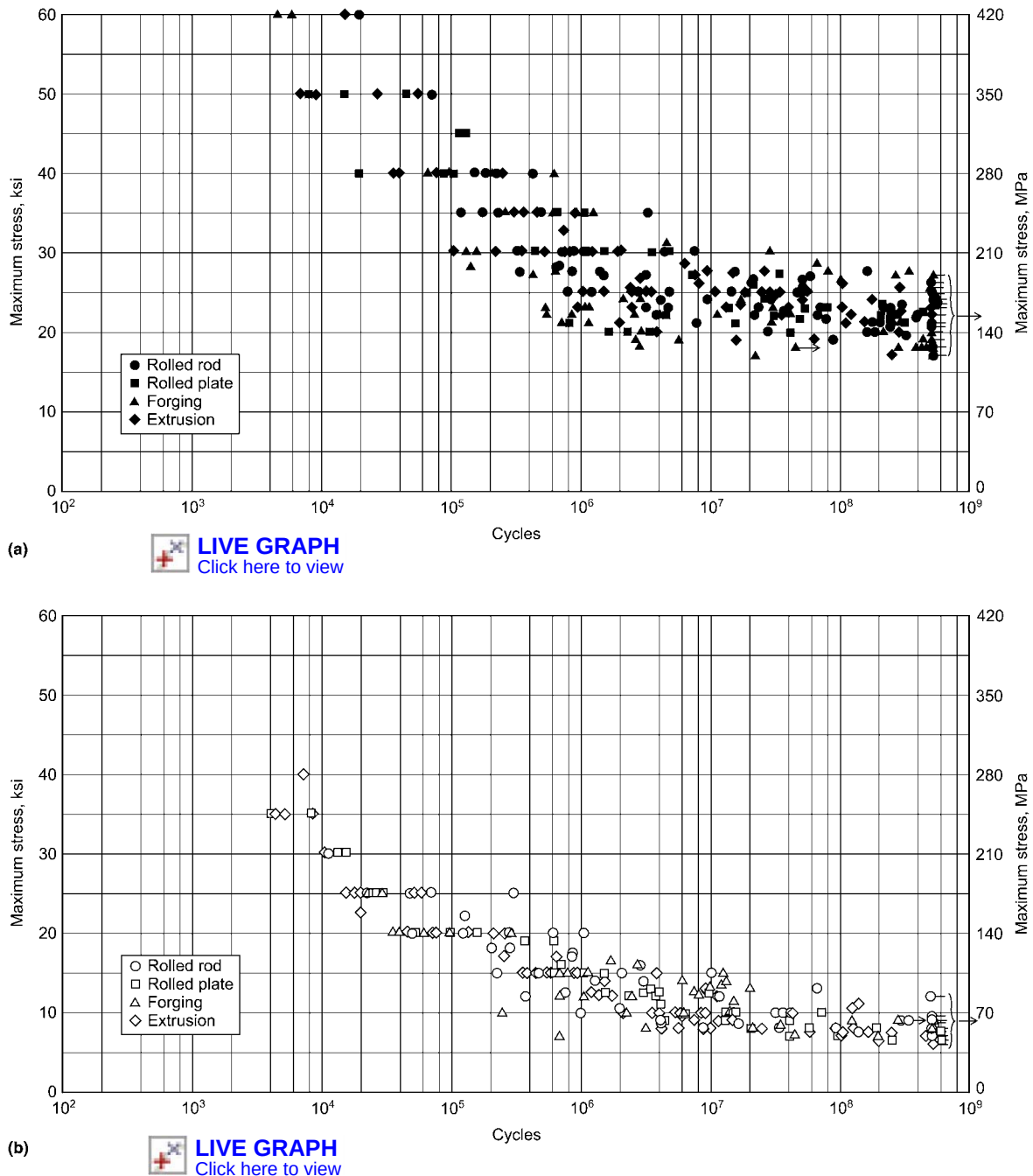


Fig. 5.5 Rotating-beam ($R = -1.0$) fatigue curve for all 7xxx alloy products. (a) Smooth specimens. (b) Sharply notched specimens

sand- and die-cast processes contain measurable porosity and would not be expected to perform as well as wrought products.

On the other hand, fatigue strengths of castings can be significantly affected by casting process technology, as discussed in more detail in Sections 5.5 of this chapter and 6.2 in Chapter 6.

It is appropriate to note that data from other sources, such as those from Juvinall (Ref 1) as reproduced in Fig. 5.11 (Ref 2), also 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 indication that the fatigue strengths of cast aluminum components may be expected to be inferior to those of wrought

aluminum products is 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, shown in Fig. 5.12 (Ref 2). The band of data for the cast beams falls consistently below the curve for 6061-T6 beams.

5.5 Comparisons of Some Cast Aluminum Alloys

Ignoring potential residual-stress influences on scatter and results for the moment, of the casting alloys and tempers for which data are available herein, those exhibiting the highest rotating-beam

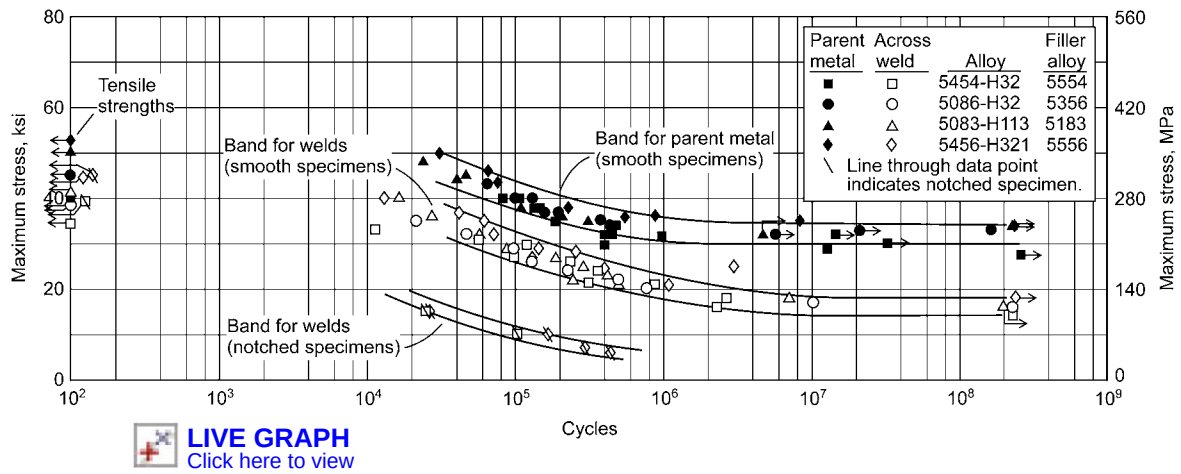


Fig. 5.6 Comparison of axial-stress fatigue curves for 22mm (7/8 in.) thick 5083-H113, 5086-H32, 5454-H32, and 5456-H321 plain and welded plate at room temperature. $R = 0$; smooth and notched ($K_t = 12$) specimens. Transverse specimens from parent metal and across weld

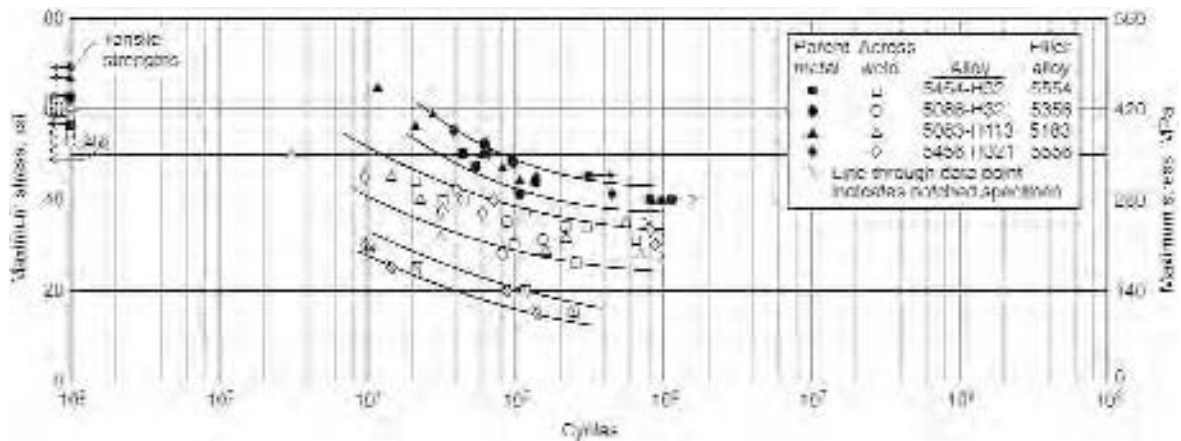


Fig. 5.7 Comparison of axial-stress fatigue curves for 22mm (7/8 in.) thick 5083-H113, 5086-H32, 5454-H32, and 5456-H321 plain and welded plate at -320°C (-195°C). $R = 0$; smooth and notched ($K_t = 12$) specimens. Transverse specimens from parent metal and across weld

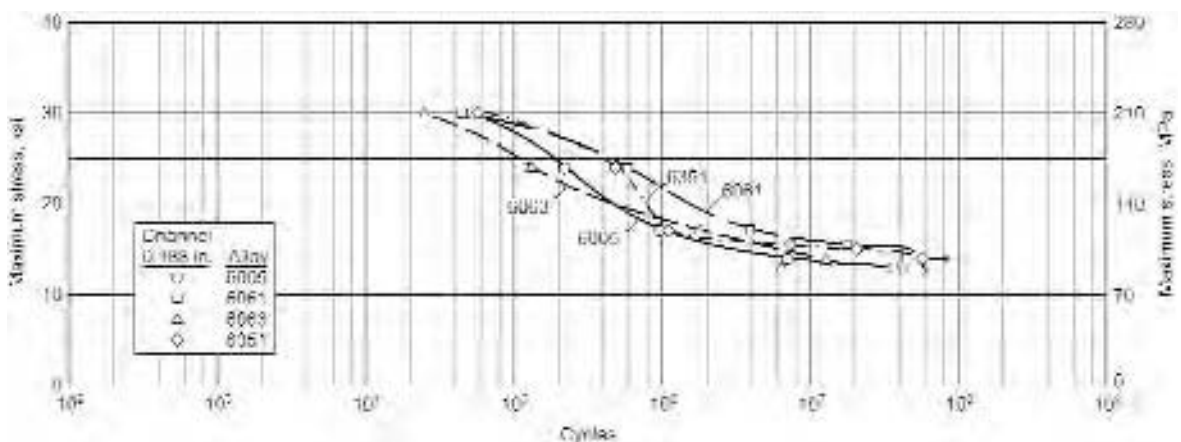


Fig. 5.8 Flexural fatigue ($R = -1.0$) curve for 6005-T6, 6061-T6, 6063-T6, and T6351-T6 extruded shapes, furnace heat treated and water quenched. Longitudinal specimens

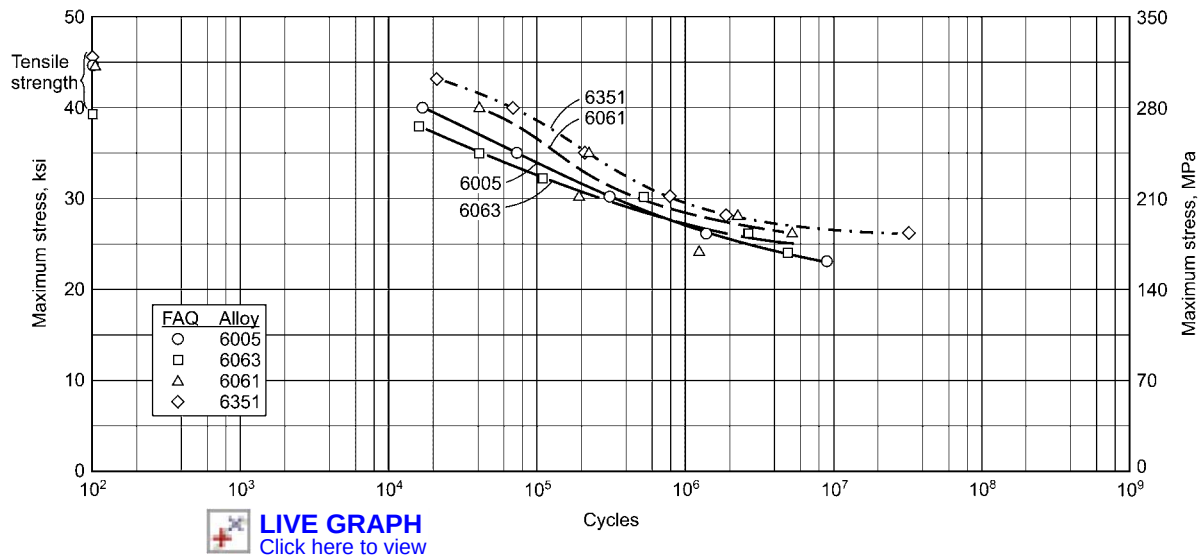


Fig. 5.9 Comparison of axial-stress fatigue curves ($R = 0$) curve for 6005, 6061, 6063, and 6351 extruded bar, forced-air quenched (FAQ). Longitudinal specimens

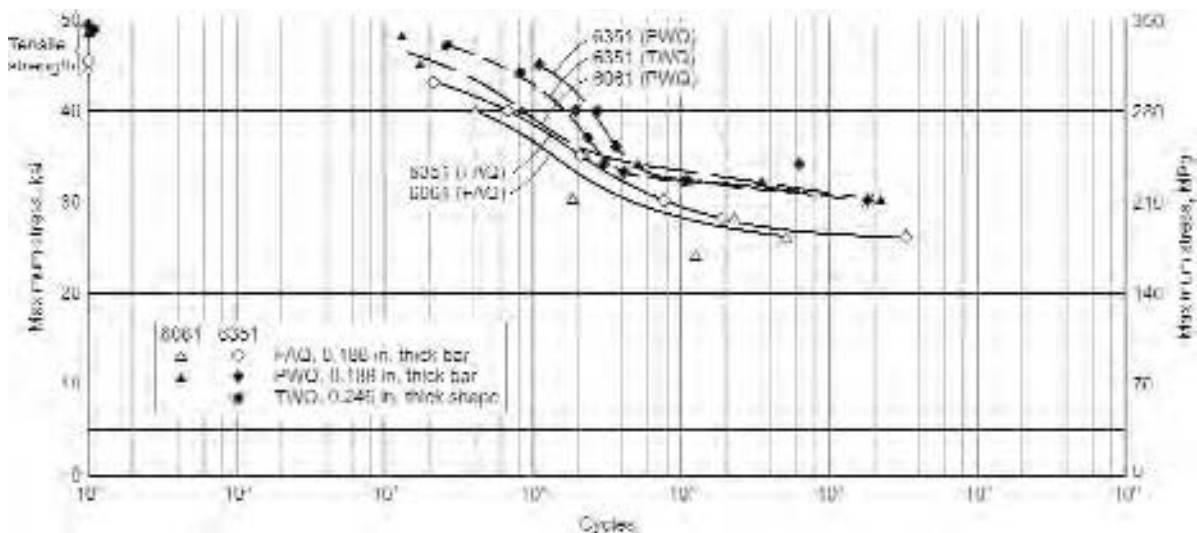


Fig. 5.10 Comparison of axial-stress fatigue curves ($R = 0$) curve for 6061 and 6351 extruded bar, forced-air quenched (FAQ), press-water quenched (PWQ), and tank-water quenched (TWQ). Effect of method of quench. Longitudinal specimens

($R = -1.0$) fatigue strengths (Table A5.2 in Appendix 5) include sand-cast A206.0-T71 and A240.0-F and 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 may be noted that all of the specimens for the die castings had as-cast surfaces, perhaps accounting for their generally 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 various casting alloys, for either smooth or notched specimens or for room or elevated temperatures (Chapter 9). The principal conclu-

sion to be reached is that choice of detailed casting practices for any of the major casting technologies and adherence to premium casting practices may be as or more important in determining fatigue performance as choice of alloy. More is presented about casting practices in Section 6.2 of Chapter 6.

5.5.1 Premium-Strength Casting Alloys

Alloys considered premium strength by specification are those covered by AMS-A-21180 (Ref 3), including A201.0, A206, 224.0, 249.0, 354.0, A through D356.0, 358.0, and 359.0. Others sometimes considered to display premium-strength characteristics include 204.0, 206.0, C355.0, and 365.0. Focusing on available room-temperature data for those alloys included herein and

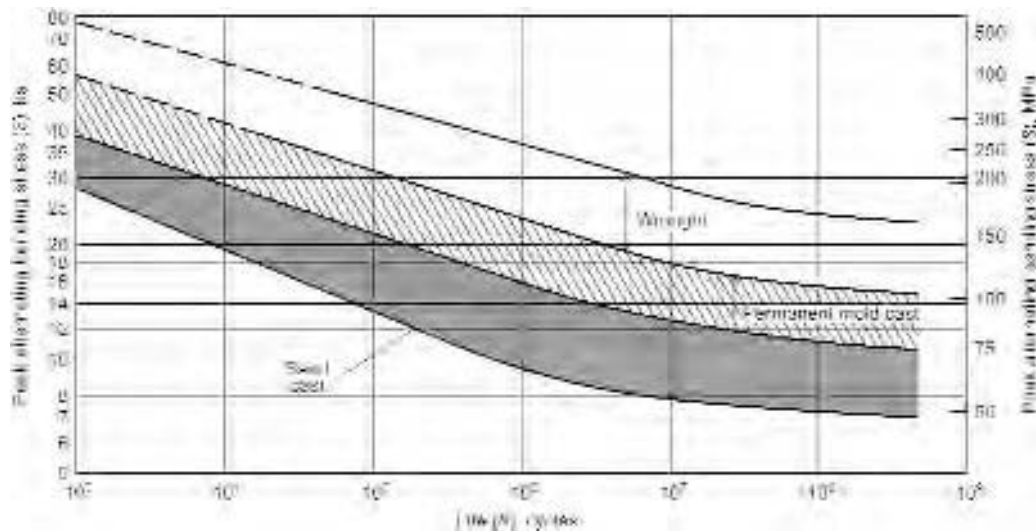


Fig. 5.11 Alternating bending stress fatigue curves for wrought and cast aluminum alloys. Source: Ref 2 as adapted from Ref 1

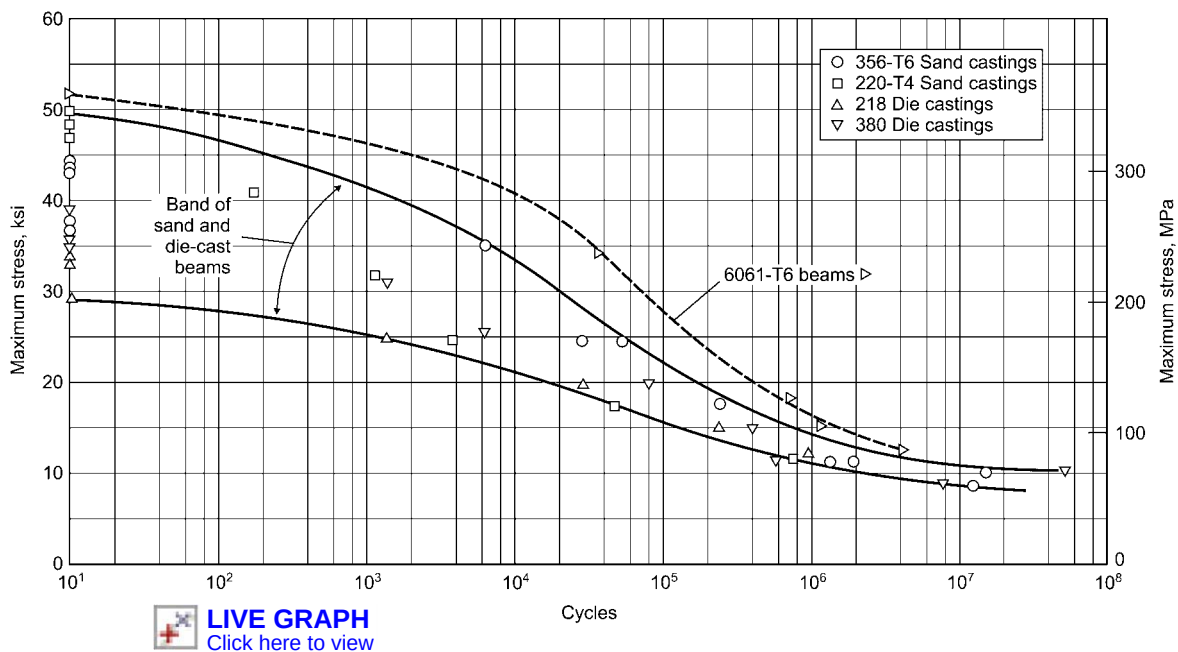


Fig. 5.12 Flexural fatigue properties ($R = 0$) of aluminum alloy beams produced from wrought and cast aluminum alloys. Source: Ref 2 as adapted from Ref 1

recognizing that all may not have been produced by what today would be called premium practices leads to the summary provided in Table 5.1.

Of the alloys covered in Table 5.1, alloys 354.0-T61 and 359.0-T61 seem to provide higher-than-average strengths for the group, especially for the notched ($K_t > 12$) specimens. As a result of the high notch strengths, these alloys also exhibit the lowest fatigue strength reduction factors. None of the other alloys in this group display notable room-temperature fatigue characteristics.

5.6 Effect of Surface Cladding

A number of aluminum alloys and tempers are produced as clad products, that is, a sandwich of the core alloy layered with a relatively thin coating (2.5%) of highly corrosion-resistant pure or lightly alloyed aluminum to increase the corrosion resistance of the product. The most common of these products and simplest to evaluate in small-specimen tests is clad sheet, usually designated as Alclad. The cladding adds greatly to the appearance as well as

Table 5.1 Endurance limits (EL) at 5×10^8 cycles for some high-strength (AMS-A-21180) aluminum casting alloys ($R = -1.0$)

Alloy and temper	Casting process(a)	Figure No.	Endurance limit(b)		FSRF(c), %
			Smooth $K_t = 1$	Notched $K_t > 12$	
224.0-T62	SC	224.RB01	12.5	7.5	-40
249.0-T63	SC	249.RB01	10.0	6.0	-40
354.0-T61	PM	354.RB01, RB02	17.0	11.0	-35
A356.0-T6	PM	A356.RB01	13.5	7.5	-44
A356.0-T61	PC	A356.RB03, RB04	12.0	8.0	-33
A356.0-T6	PMP	A356.RB02	10.0	8.0	-20
A357.0-T61	PMP	A357.RB01	13.0	7.0	-46
A357.0-T62	PM	A357.RB02	12.0	6.0	-50
359.0-T61	PM	359.RB01	15.5	11.0	-29
359.0-T62	PM	359.RB02	<u>15.0</u>	<u>9.0</u>	<u>-40</u>
Average			13.1	8.1	-38

(a) SC, sand cast; PM, permanent mold cast; PC, plaster cast; PMP, premium-quality permanent mold. (b) Room temperature. (c) FSRF, fatigue strength reduction factor; percent difference from smooth

the corrosion resistance of the sheet, making it suitable for unpainted use on the surface of vehicles such as aircraft and railroad cars.

There is some penalty in fatigue life, however, especially in reversed bending. Flexural fatigue ($R = -1.0$) tests have been made of bare and Alclad high-strength alloy sheet of a number of alloys to determine the difference in performance. The summary in Table 5.2 provides direct comparisons for bare and clad aluminum sheet of comparable alloys and tempers. The flexural ($R = -1.0$) endurance limits of clad aluminum alloy sheet are expected to be approximately 20 to 40% lower than those of comparable bare, that is, not clad, sheet of the same thickness. The principal reason for this effect is the lower fatigue strength of the relatively unalloyed cladding alloy, which is usually 1100 or 7003, at the highly stressed surface in reversed bending. As illustrated in Fig. 1100.RB01 through RB05, such materials have only approximately one-quarter the fatigue strength of high-strength heat treatable alloys that make up the core of clad sheet.

One additional study of Alclad 2024-T81 is worth noting; data in Fig. 2024.FL16 show the fatigue lives of sheet with both 2.5% (the standard) and 5% cladding on each side of the 2024-T81 core.

Table 5.2 Effect of cladding on flexural fatigue endurance limit (EL) at 5×10^8 cycles

Alloy and Temper	Figure No.	Endurance limit				Endurance limit difference, %
		Bare		Alclad		
		ksi	MPa	ksi	MPa	
2020-T6	2020.FL02 and FL03	17.5	121	10.5	72	−40
2024-T3	2024.FL01 and FL03	16.5	114	13.5	93	−18
2024-T3(a)	2024.FL04 and FL05	23.0	159	14.5	100	−37
2024-T36	2024.FL07 and FL08	18.5	128	14.0	97	−24
2024-T81	2024.FL09 and FL16	17.5	121	13.0	90	−26
6061-T6	6061.FL01 and FL02	14.0	97	8.5	59	−39
7075-T6	7075.FL01 and FL06	19.5	134	13.5	93	−31
7079-T6	7079.FL01 and FL02	18.5	128	13.5	93	−27

(a) Continuous heat treated; others were batch heat treated.

The fatigue properties of the two versions of Alclad 2024-T81 were indistinguishable, so cladding thickness is not an important variable.

The effect of cladding is not as noticeable in axial-stress tests, where surface characteristics are not quite so important. This is evident from a comparison of Fig. 7050.AS19 and AS22 for bare and Alclad 7050-T6 sheet, respectively; there is relatively little difference between the fatigue lives of the bare and Alclad 7050 sheet.

As noted earlier, differences in small-specimen flexural fatigue life do not necessarily translate to a design limitation for clad aluminum alloy sheet. The presence of rivet holes for joints and other structural details may easily completely override the differences noted previously.

REFERENCES

1. R.C. Juvinall, *Fundamentals of Machine Component Design*, John Wiley & Sons, New York, NY, 1983, p 207
2. J.G. Kaufman and E.L. Rooy, *Aluminum Alloy Castings — Properties, Processes, and Applications*, ASM International, 2004
3. "High-Strength Aluminum Alloy Castings," AMS-A-21180 (previously MIL-A-21180), Aeronautic Materials Specification, updated periodically

CHAPTER 6

Influence of Production Process Variables on Fatigue Properties

IN THE SUBSEQUENT SECTIONS, the following variables are addressed for wrought and casting processes. For wrought alloy processing practices, the variables include:

- Starting stock for forgings
- Strain hardening
- Heat treatment
- Coiled versus flat sheet
- Continuous versus batch heat treating
- Type of quench following heat treatment
- Precipitation (artificial) aging
- Stress relief following heat treatment
- Additional cold work following heat treatment
- Variation in properties in large cross-sectional products
- Variations in properties in long extruded lengths
- Effect of pressure welds in hollow extrusions

For casting alloy processing practices, the variables include:

- Comparison of casting processes (sand, permanent mold, and die casting differences)
- Improvements in casting procedures over time
- Effects of porosity
- Premium casting practices
- Squeeze casting

6.1 Wrought Alloy Processing Practices

6.1.1 Effect of Type of Starting Stock for Forgings

Forgings, either die forgings or hand forgings, may be produced by using cast stock, rolled stock, or extruded stock. Direct comparisons of the fatigue properties of the same compositions of 2014-T6 die forgings produced from several types of stock are presented in Fig. 2014.RB13 and RB14. No consistent or significant differences are apparent for either smooth or notched specimens among any of the two or three types of stock represented, although in Fig. 2014.RB14, the cast stock data are most often near the lower side of the band for notched specimens.

6.1.2 Effect of Strain Hardening on Fatigue Strength

Strain hardening by cold rolling has a positive effect on the fatigue strength of aluminum alloys under all stress ratios. This may be illustrated by a few representative endurance limits in Table 6.1,

using the annealed (O) temper as the basis of comparison with the strain-hardened (HXX) tempers.

Strain hardening by rolling increases the rotating-beam ($R = -1.0$) endurance limit of strain-hardenable alloys by a significant amount, the effect generally decreasing as the strength of the alloy increases. The effect of rolling to the H18 temper (nominally 60 to 80% cold reduction) increases the strength of pure aluminum (1100) by approximately 100%, but for higher-strength alloys (3004 and 5052), approximately 30%.

Another comparison (Table 6.2) to be made involves strain hardening given non-heat-treatable alloys before they are stabilized to an H3X temper. These are produced by cold rolling to tempers comparable to H14 and H38 and then stabilizing back with an intermediate temperature to produce the H34 and H38 tempers, respectively.

The effect of the cold work on the fatigue performance of stabilized tempers is similar to that of unstabilized tempers, including the smaller-percentage improvement in fatigue strength from cold working higher-strength alloys.

6.1.3 Effect of Solution Heat Treatment on Fatigue Strength

Once again, a few comparisons (Table 6.3) illustrate the very great importance of solution heat treatment in increasing the

Table 6.1 Effect of strain hardening on endurance limit (EL) at 5×10^8 cycles

Alloy and temper	Stress ratio	Figure No.	Endurance limit		Endurance limit difference, %
			ksi	MPa	
1100-O	-1.0	1100.RB01	5.0	34.5	...
1100-H14	-1.0	1100.RB02	7.0	48.3	+40
1100-H16	-1.0	1100.RB03	8.0	55.2	+60
1100-H18	-1.0	1100.RB04	10.0	68.9	+100
3003-O	-1.0	3003.RB01	6.0	41.4	...
3003-H14	-1.0	3003.RB02	8.0	55.2	+33
3003-H16	-1.0	3003.RB03	9.5	65.5	+58
		and RB06			
3003-H18	-1.0	3003.RB04	10.0	68.9	+66
		and RB06			
3004-O	-1.0	3004.RB01	15.0	103	...
3004-H14	-1.0	3004.RB02	16.5	114	+10
3004-H18	-1.0	3004.RB03	19.5	134	+30
3004-H19	-1.0	3004.RB04	18.5	128	+23
5052-O	-1.0	5052.RB01	15.5	107	...
5052-H14	-1.0	5052.RB02	18.5	128	+19
5052-H16	-1.0	5052.RB03	18.5	128	+19
5052-H18	-1.0	5052.RB04	20.5	141	+32

Table 6.2 Effect of strain hardening and stabilization on endurance limit (EL) at 5×10^8 cycles

Alloy and temper	Stress ratio	Figure No.	Endurance limit		Endurance limit difference, %
			ksi	MPa	
5050-O	-1.0	5050.FL01	10.5	72.4	...
5050-H34	-1.0	5050.FL01	13.0	89.6	+24
5050-H38	-1.0	5050.FL01	15.5	107	+48
5052-O(L)	-1.0	5052.FL01	12.5	86.2	...
5052-H34	-1.0	5052.FL02	17.0	117	+36
5154-O	-1.0	5154.FL01	14.0	96.5	...
5154-H34	-1.0	5154.FL02	16.0	110	+14
5154-H38	-1.0	5154.FL03	18.0	124	+29
5056-O	-1.0	5056.RB01	20.5	141	...
5056-H32	-1.0	5056.RB01	22.0	152	+7
5056-H34	-1.0	5056.RB01	23.5	162	+15

Table 6.3 Effect of solution heat treatment on endurance limit (EL) at 5×10^8 cycles

Alloy and temper	Stress ratio	Figure No.	Endurance limit		Endurance limit difference, %
			ksi	MPa	
2014-O	-1.0	2014.RB01	10.5	72.4	...
2014-T4	-1.0	2014.RB02	17.5	121	+67
2017-O	-1.0	2017.RB01	13.0	89.6	...
2017-T4	-1.0	2017.RB02	17.0	117	+30
2024-O	-1.0	2024.RB01	12.0	82.7	...
2024-T4	-1.0	2024.RB05	20.0	138	+67
6053-O	-1.0	6053.RB01	7.0	48.3	...
6053-T4	-1.0	6053.RB02	13.5	93.1	+92
6062-O	-1.0	6062.FL01	8.5	58.6	...
6062-T4	-1.0	6062.FL02	13.0	89.6	+53

fatigue strength of some aluminum alloys, using the comparison of T4 versus the annealed (O) temper.

These representative values illustrate that solution heat treatment and natural aging (i.e., with no subsequent precipitation-hardening aging treatments) increases the endurance limits from 30 to nearly 100%, depending on the alloy. There are not too many such comparisons available, simply because the properties of high-strength heat treatable alloys are seldom measured for the annealed temper in which they are rarely used.

6.1.4 Coiled Sheet versus Flat Sheet

Figure 2024.FL03 shows a direct comparison of the flexural fatigue ($R = -1.0$) properties of Alclad 2024-T3 sheet heat treated both in coils or as flat sheet. No significant difference appears to result from heat treating the sheet in coiled or flat form. Several flat sheet specimens fell just below the band for Alclad 2024-T3 sheet, but most data points were in the usual range.

A similar direct comparison is illustrated for 7075-T73 in Fig. 7075.FL13. While there is a considerable amount of scatter in the data, no consistent difference stands out dependent on whether the 7075-T73 was heat treated and aged as flat sheet or in a coil.

6.1.5 Effect of Continuous versus Batch Heat Treating of Sheet

Continuous heat treatment (CHT) and artificial aging are very effective in the production of relatively thin sheet on many aluminum alloys. The CHT is accomplished without any degradation in fatigue strength, as shown by the comparison listed in Table 6.4.

Table 6.4 Comparison of endurance limits (EL) at 5×10^8 cycles for batch or continuous heat treated (CHT) sheet

Alloy and temper	Stress ratio	Figure No.	Endurance limit, batch		Endurance limit, CHT		Endurance limit difference, %
			ksi	MPa	ksi	MPa	
Alclad 2024-T3	-1.0	2024.FL02 to FL05	13.0	89.6	13.5	93.1	+4
7075-T6	-1.0	7075.FL01 and FL02	19.5	134	20.0	138	+3
Alclad 7075-T6	-1.0	7075.FL06 and FL07	13.5	93.1	13.0	89.6	-4

There is, in fact, some indication from the fatigue curves in the figures cited that there may be a modest improvement in fatigue life as a result of CHT, but this effect, if real, is obscured by a seemingly larger amount of scatter in the data for CHT lots.

Studies have also been made of the effect of CHT speed through the furnace, quench, and aging system. Figure 7075.FL02 shows the results for two basic speeds, approximately 25 to 35 ft/min (13 to 18 cm/s) and approximately 80 ft/min (41 cm/s). While there is a fair amount of scatter in the data, there is no indication of any significant difference in fatigue strengths related to CHT speed.

6.1.6 Effect of Type of Quench Following Heat Treatment

For a variety of reasons, including economics, there are several acceptable procedures for heat treating and quenching 6xxx aluminum alloy extrusions before aging them for precipitation hardening. These include quenching extruded shapes as they exit the extrusion press with a still air or forced-air quench or with a water quench as the shape comes out of the extrusion press, as well as a conventional furnace heat treatment, water quench, and artificial aging. Technically, the press-quenched products should be defined as being in the T5 temper and the furnace heat treated products defined as T6, but there are various interpretations of this rule (Ref 1).

In order to determine the degree to which fatigue properties are affected by the different procedures for heat treating and quenching 6xxx alloys, studies were carried out on extruded shapes of alloys 6005, 6351, 6061, and 6063, respectively, given four types of heat treatment and quench sequences and subsequently evaluated using sheet-flexural fatigue tests. The four sequences were:

- Still air quenched from the extrusion press and precipitation aged
- Forced-air quench from the press and precipitation aged
- Tank water quenched from the press and precipitation aged
- Furnace solution heat treated and precipitation aged

The precipitation aging was the same with all four sequences.

The results may be summarized as follows for the individual alloys:

- 6005—Fig. 6005.FL01: There was only a minimal and probably insignificant difference among the various types of heat treatment; all four seem to lead to fatigue lives within ± 1 ksi (7 MPa).
- 6351—Fig. 6351.FL01: Press water quench and furnace solution heat treatment generally provided somewhat superior

fatigue strength to those from press still air or forced-air quenches.

- 6061—Fig. 6061.FL03: Furnace heat treatment generally provided the longest fatigue lives, with press air quenches providing the shortest; the spread in endurance limits was approximately 3 to 4 ksi (21 to 28 MPa).
- 6063—Fig. 6063.FL01: As for 6005, the various quenches had little consistent effect on fatigue life.

In summary, for extrusions of the higher-strength 6xxx alloys, such as 6351 and 6061, there is a modest but apparently significant improvement in fatigue strength if they are given a furnace heat treatment and water quench before precipitation aging, with press water quenching being the second choice. For these alloys, the press air quench, whether still air or forced air, provided the lowest fatigue strengths. For alloys 6005 and 6063, lower in total solute, the effect was negligible; but, regardless of quench sequence, the fatigue strengths were lower than for water-quenched 6351 and 6061.

The quench rate effects noted for some 6xxx alloys in flexural tests are consistent with those in 2xxx alloys, judging by the rotating bending ($R = -1.0$) for 2014-T4 forging stock in Fig. 2014.RB04. The fatigue strengths of cold-water-quenched 2014-T4 forging stock are consistently higher than those of air-quenched material, with the difference narrowing to approximately 2 ksi (14 MPa) (10 %) at the endurance limit. The effect for sharply notched ($K_t > 12$) specimens is quite similar.

In contrast to these results for 2xxx and 6xxx alloys, data for 7005-T63 extrusions in Fig. 7005.RB04 suggest there is little, if any, difference in fatigue strengths between cold-water-quenched and forced-air-quenched shapes of that alloy.

In general, furnace solution heat treating and cold water quenching are standard for high-strength 2xxx and 7xxx alloys.

6.1.7 Effect of Precipitation Age Hardening

Many high-strength heat treatable alloys are subsequently aged for some time at moderately elevated temperatures for precipitation hardening, sometimes referred to as artificial aging (as contrasted to natural or room-temperature aging). This treatment usually has a very beneficial effect on static strengths, but a lesser effect on fatigue strengths.

There are two bases for judgment of the magnitude of the effect of precipitation hardening: the additional benefit beyond solution heat treatment itself (i.e., between T4- and T6-type tempers) and the combined effect as compared to the annealed (O) temper. For some representative alloys tested in all three tempers, both comparisons are given in Table 6.5.

These illustrations suggest that there is a relatively small, if any, gain in fatigue strength from precipitation aging following solution heat treatment, at least for 2xxx and 6xxx alloys. While another 12% was gained for 2014, there was no significant gain at all for 2024 or 6053 (less than ± 1 ksi, or 7 MPa, being within the range of discernable error).

A comparison of the fatigue properties of 2024-T351 and T851 (i.e., before and after artificial aging) is available in Fig. 2024.RB04. This comparison, while involving relatively few data points, also suggests little difference in fatigue life as a result of

Table 6.5 Effect of precipitation aging on endurance limit (EL) at 5×10^8 cycles

Alloy and temper	Stress ratio	Figure No.	Endurance limit		Endurance limit difference, %
			ksi	MPa	
2014-O	-1.0	2014.RB01	10.5	72.4	...
2014-T4	-1.0	2014.RB02	17.5	121	+67
2014-T6	-1.0	2014.RB07	19.0	131	+81
2024-O	-1.0	2024.RB01	12.0	82.7	...
2024-T4	-1.0	2024.RB05	20.0	138	+67
2024-T6	-1.0	2024.RB12 to RB15	20.0	138	+67
6053-O	-1.0	6053.RB01	7.0	48	...
6053-T4	-1.0	6053.RB02	13.5	93.1	+92
6053-T6	-1.0	6053.RB03	12.5	86.2	+79
6062-O	-1.0	6062.FL01	8.5	58.6	...
6062-T4	-1.0	6062.FL02	13.0	89.6	+53
6062-T6	-1.0	6062.FL03	13.5	93.1	+59

precipitation aging. A similar result is found in comparisons of comparable tempers of 2024 sheet in Fig. 2024.FL09 and FL14; in both cases, the fatigue lives of T4 and T6 and of T3 and T81 are essentially the same.

Similarly, for 2219 products, the interest would be in differences from precipitation aging of material without cold work after solution heat treatment and aging (T6) and the aging of material that has been strain hardened, for either stress relief (T851, T852) or for added static strengthening (T87). A comparison of those tempers of 2219 is illustrated in Fig. 2219.AS01. Data for all three tempers fall pretty well throughout the band illustrated, once again indicating no significant difference.

For the high-strength 7xxx series of alloys, the question about precipitation aging focuses more on whether or not an alloy such as 7075 is peak strength aged (the usual T6 temper) or is overaged to improve either exfoliation corrosion resistance (T76) or resistance to stress-corrosion cracking (T73). Figure 7075.FL12 shows the result of a study to address that specific question, since data are presented for all three tempers (T6, T76, T73) produced from the same original lot of 0.063 in. (1.6 mm) thick. At all stress levels, the data points are thoroughly mixed together, and no measurable effect is seen. The fatigue properties of the T6, T76, and T73 tempers appear essentially the same.

The primary conclusion to be taken from these comparisons is that, in general, the principal gain in fatigue strength for heat treatable alloys comes from the solution heat treatment itself; little additional benefit to fatigue strength results from the subsequent precipitation aging.

6.1.8 Effect of Stress Relief

Many aluminum alloy products are given a small amount of cold work following solution heat treatment and quenching in order to minimize the internal residual stresses resulting from the combination of working, holding at high temperatures, and quenching rapidly (Ref 1). The amount of cold work given for stress relief treatment is generally in the range of 1 to 3% stretching for plate, rolled, or extruded shapes and 3 to 5% compression for forgings. Products that have been stress relieved by stretching are recognizable by the designation “-51” added to the temper (e.g., T651 or T7351), and those stress relieved by compression are given an added “-52” designation (e.g., T652 or T7352).

Figures 2024.RB14 and RB15 show plots of fatigue data for 2024-T6 forgings (not stress relieved) along with those for 2024-T852 forgings (stress relieved), the former figure for block hand forgings and the latter plot for stepped hand forgings (i.e., containing steps of two different thicknesses, 3 and 6 in., or 7.6 and 15 cm). In both plots, the scatter suggests a small, perhaps insignificant, difference between the performance of stress-relieved and non-stress-relieved forgings, since throughout much of the bands of data, the T6 data points tend to fall in the upper portion of the spread. At large number of cycles, however, there seems to be no consistent difference, with the exception that data points for the one hand forging in Fig. 2024.RB14 that was stretched (T851) rather than compressed for stress relief are below most of the others for both T6 and T852. There are insufficient data to consider this a significant trend, and it may not be important, because hand forgings are rarely stretched for stress relief.

Data for 6061-T6 and T652 hand forgings in Fig. 6061.RB07 also suggest little or no difference between the fatigue strengths of the two tempers; in this case, it is the data points for the T6 that tend to have the slightly shorter lives for both smooth and notched specimens, but once again, the scatter is such that the trend does not appear to be considered significant.

An interesting study of the effects of stretching and compressing 6061-T6 rod samples by 50, 70, and 90% prior to fatigue testing with sharply notched ($K_t > 12$) specimens is illustrated in Fig. 6061.RB08. Stretching resulted in improved notch fatigue strengths, and compressing significantly lowered the notch fatigue strengths, roughly in proportion to the amount of stretching or compressing. No measurements were reported to determine whether the resulting changes were because of the induced residual stresses (positive compressive residuals from stretching and detrimental tensile residuals from compressing) or from changes in notch acuity (and therefore notch severity) resulting from the mechanical working.

6.1.9 Effect of Additional Cold Work Following Solution Heat Treatment

Several studies were carried out in which 2024, 6061, and 7075 sheet were given additional stretching following heat treatment in order to judge the effects on fatigue properties, among others.

Data for 2024 stretched various amounts in the T3, T4, T6, T81, and T86 tempers are shown in Fig. 2024.FL08, FL11, FL15, FL17, and FL19, respectively. In almost all cases, the differences are small and inconsistent, but in no case does the additional stretching appear to provide any benefit in fatigue life; there are some suggestions that it may be harmful.

Data for 6061 are shown in Fig. 6061.FL06 and FL07 for sheet stretched in the W-temper (between heat treating and aging) and in the T6 temper (after solution heat treatment and aging), respectively. For 6061, like 2024, most differences are small and inconsistent and again show no benefit of the additional stretching.

The same pair of comparisons is available for 7075 stretched in the W and T6 tempers in Fig. 7075.FL04 and FL05, with the same findings. There are no benefits to additional stretching of 7075 in either temper; if anything, there may be small negatives, although the differences are generally small and likely insignificant.

Studies were also made of the effect of additional stretching and compression cold work on 2017-T4 rolled and drawn rod, the results of which are shown in Fig. 2017.RB04 and RB05, respectively. Neither 5% additional stretching nor 5% additional compressive cold work had any measurable effect on the fatigue strength of this alloy and temper.

Twisting may be involved as a straightening step for some aluminum alloy products, primarily extruded shapes; it is carried out to straighten sections that have warped as a result of working or thermal processing. To study the impact, if any, on fatigue strength, lengths of 2025-T6 rolled and drawn rod were twisted in torsion to 10° of permanent set and then fatigue tested; the results are shown in Fig. 2025.RB05. Although the differences are small and may not be statistically significant, there was a tendency for the torsional cold work to have a positive effect at shorter lives and a detrimental effect at longer lives, with perhaps a 1 to 2 ksi (7 to 14 MPa) lower endurance limit.

6.1.10 Variation in Fatigue Properties in Thick versus Thin Plate and Forgings

There are several opportunities to illustrate the effect of increasing product thickness on fatigue strengths; several are illustrated here.

2014-T6 Hand Forgings. Figure 2014.AS06 includes the results of axial-stress ($R = 0.0$) tests at three stress levels of 2014-T6 hand forgings of increasing thickness from 2 through 6 in. (5 through 15 cm), with cross-sectional areas from 16 through 72 in.² (103 through 465 cm²). At the two stresses where runouts were not observed, 60 and 40 ksi (414 and 276 MPa), fatigue life generally decreased with increasing thickness. Regrettably, no microstructural comparisons are available to establish the degree to which this variation is associated with microstructural differences or if it is simply the effect of less mechanical working of the material in larger forgings.

2219-T852 Hand Forgings. Much more extensive tests of 2219-T852 hand forgings are shown in Fig. 2219.AS16 and AS17. Very little, if any, detrimental effect of increasing hand forging thickness from 2 through 7.5 in. (5 through 19 cm) is indicated for smooth longitudinal (L) or long-transverse (LT) specimens; data points for the thickest forging are among those for the thinner ones. In the short-transverse (ST) direction, there is some indication that the 7.5 in. (19 cm) thick forging had the shortest smooth-specimen lives. For notched specimens, there were no discernible trends.

2048-T851 Plate. Figures 2048.AS01 and AS02 include fatigue smooth- and notched- ($K_t = 3$) specimen data, respectively, for four thicknesses of 2048-T851 plate from 1.0 to 4.0 in. (2.5 to 10 cm). In each case, for the L and LT directions, it is difficult to discern any consistent trends in fatigue strength as a function of thickness. What is most apparent is that the ST fatigue strengths of the 4 in. (10 cm) thick 2048-T851 for both smooth specimens are significantly lower than those for the other two directions, with a difference of approximately 10 ksi (70 MPa) at longer lives. The same tendency is apparent for the notched specimens, but the difference is smaller.

5083-O Plate. Alloy 5083-O is used in thicknesses up to approximately 8 in. (20 cm) for cryogenic tankage, and fatigue

strength is an issue in this application. As illustrated in Fig. 5083.AS01, there is little evidence of a thickness effect over the range from 1.8 through 7.7 in. (4.6 through 19.6 cm) plate in the L or LT directions. Data points for the 7.5 and 7.7 in. (19 and 19.6 cm) thick plate fall well in the group with those for thinner plate. However, as noted for other alloys, the ST specimens tend to exhibit lower fatigue strengths than for the other two directions, and the ST specimens for the 6.0 to 7.7 in. (15 to 19.6 cm) thick plate fall lowest in the observed ranges.

These same trends are observed in rotating-bending fatigue data for thick 5083-H113 plate, as indicated by the data in Fig. 5083.RB04. In the L and LT directions, the fatigue strengths of smooth specimens from such thick plate are comparable to those of thinner plate, for which data are shown in the previous plot, Fig. 5083.RB03. In the ST direction, fatigue strengths are significantly lower, the ST endurance limit being only approximately 11 ksi (76 MPa) compared with approximately 19.5 ksi (134.4 MPa) for the L and LT directions. This is really a directional effect, heightened by the greater thickness (Section 3.4 in Chapter 3).

6.1.11 Variation in Fatigue Properties in Large Cross-Sectional and Long-Length Extruded Products

Several illustrations follow that show the variations in fatigue properties of relatively large cross sections and long lengths of extruded shapes.

Long 2014-T6 Extruded Lengths. Figure 2014.AS05 illustrates the results of axial-stress fatigue tests of specimens from the front and rear of long 2014-T6 extruded rotor blade lengths. At times, there have been questions as to whether the quality and performance of such long shapes deteriorate toward the end of the length. There is a fair amount of scatter in the data but no consistent trends indicating any consistent difference between these two locations in the length.

Long 6062-T6 Extruded Lengths. Figure 6062.AS02 illustrates that no consistent difference was found between the axial-stress ($R = 0.0$) fatigue lives of specimens from the center and rear of long 6062-T6 extruded rotor blades.

Large 7075-T6 Extruded Shapes. Studies have been made of variations in rotating-bending fatigue strength of 7075-T6 extruded shapes both along the length and within the cross section, the results of which are shown in Fig. 7075.RB08 and RB09, respectively. For both smooth and sharply notched ($K_t > 12$) specimens taken from the front and rear of relatively long extruded spar chords, there were no consistent differences evident in fatigue strength (Fig. 7075.RB08). Likewise, there were no apparent differences in fatigue life for specimens taken from various locations within the cross section of the spar chord (Fig. 7075.RB09).

6.1.12 Effect of Pressure Welds in Hollow Extrusions

When hollow extruded shapes, such as tube or rectangles, are produced, the metal must flow through the extrusion die and over one or two supports holding the blank part of the die that produces the hollow. When the metal rejoins on the other side of the die supports, an extrusion pressure weld is formed; that is, hot metal is forced together by the exterior surface of the die and bonds metallurgically. There has been a question about the metallurgical

quality and performance of the region formed where the metal “welds” in the process.

Figure 6062.AS01 illustrates the effect of the presence of such a weld on the fatigue strengths of extruded hollow 6061-T6 rotor blade stock, with smooth specimens taken away from and directly across the pressure weld and tested at two stress ratios ($R = -0.1$ and 0.0). In both cases, despite considerable scatter in the data, there is a discernable difference; specimens away from the weld had 3 to 5 ksi (21 to 35 MPa) higher fatigue strength on average for $R = 0.0$ and 2 to 3 ksi (14 to 21 MPa) higher for $R = -1.0$.

Figure 7075.AS13 illustrates the results of tests from a 7075-T73 extruded shape containing a pressure weld, with results for tests of transverse specimens away from and across the weld. For fatigue lives from 10^4 through 2×10^6 cycles, there is no apparent difference. At longer lives, the specimens containing the welds indicate approximately a 2 ksi (14 MPa) (10%) lower fatigue strength. Regrettably, no tests were run at lives beyond 10^7 .

It would be concluded from these tests that there is some negative impact of the pressure weld in a hollow extruded shape on the fatigue strengths of specimens taken locally across the weld. Of course, in a structure, the complete extruded shape is acting as a unit, and such effects would be expected to be negligible.

6.2 Casting Alloy Process Practices

6.2.1 Comparison of Casting Processes

Aluminum alloy castings are produced by a number of different casting processes, the most widely used being sand, permanent mold, and die casting, with some variations usually termed premium-strength, premium-quality, or high-strength castings of alloys covered by AMS-A-21180 (Ref 2). Among the data available in this book, several observations about casting practices may be made, as in the following paragraphs.

6.2.2 Improvements with Time

An additional factor within the data presented herein is the fact that they were generated in a period of significant advance in casting technology, and there is evidence that the improvements in commercial casting practices resulted in improved fatigue performance.

As illustrated in Fig. 355.AS03, comparisons were made of data for 355.0-T6 sand-cast test bars produced before and after 1955. The data for the newer castings clearly suggest some improvement, which is reasonable and to be expected. However, the differences are small enough to be subject to the aforementioned concerns about residual-stress patterns in cast test bar production, so it is difficult to place much emphasis on this finding. However, it does support the expected finding (Ref 3, 4) that improved casting practices leading to reduced porosity at the micro or macro levels will improve fatigue performance.

6.2.3 Sand, Permanent Mold, and Die Casting Differences

From the data available herein, it is difficult to make the case that any one casting process in general provides any superiority

over the other. For all of the casting processes, the detailed process control seems likely to be the more important factor.

It is appropriate to note that data from other sources, such as those from Juvinall (Ref 5), reproduced in Fig. 5.11 in Chapter 5, provide indications that the fatigue properties of permanent-mold-cast aluminum alloys may be expected to be superior to those of sand castings, the lowest band in his work.

6.2.4 Effects of Porosity

More specific information addressing the casting-quality issue is shown in Fig. 355.AS04, from axial-stress ($R = 0.0$) loading of 355.0-T6 cast test bars for which lower fatigue strengths were associated with greater porosity content. For three lots variously described as having heavy porosity, 0.7% voids, or 2.4% voids, the fatigue lives were well below those in Fig. 355.AS03, with the endurance limits indicated at approximately 6 or 7 ksi (41 or 48 MPa) compared to 10 to 15 ksi (69 to 103 MPa) for higher-quality cast test bars.

Data reported by Promisel, reproduced in Fig. 6.1 (Ref 6), support 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.

6.2.5 Premium Casting Practices

As noted in Section 5.5 in Chapter 5 and Ref 3 and 4, premium-quality or high-strength castings include compositions designed to

provide a superior combination of strength and ductility or toughness when produced by carefully designed casting process technology intended to provide high internal soundness and microstructural refinement. While there are few data in this book to demonstrate the point, it is 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.

Alloys considered premium strength by definition are those covered by AMS-A-21180 (Ref 2), including A201.0, A206, 224.0, 249.0, 354.0, A through D356.0, 358.0, and 359.0. Others displaying premium-strength characteristics include 204.0, 206.0, C355.0, and 365.0. Data included in this compendium covering those alloys were summarized in Table 5.1 in Chapter 5 and, for discussion of notch sensitivity, in Table 10.4 in Chapter 10. For more detail on these alloys and their characteristics, readers are referred to Ref 3, 4, and 5.

6.2.6 Squeeze Casting

None of the castings for which data are presented herein were produced by squeeze casting technology, but it is appropriate to note the potential benefits of that process in improving the fatigue properties of aluminum castings.

An example of squeeze casting applied to a wrought composition is provided by the rotating-bending data for squeeze-cast 6061-T6 plates in Fig. 6061.RB10. The band for wrought product 6061-T6 data has been included for comparison.

Smooth-specimen data points for squeeze-cast 6061-T6 compare favorably with the band for 6061-T6 wrought products, indicating

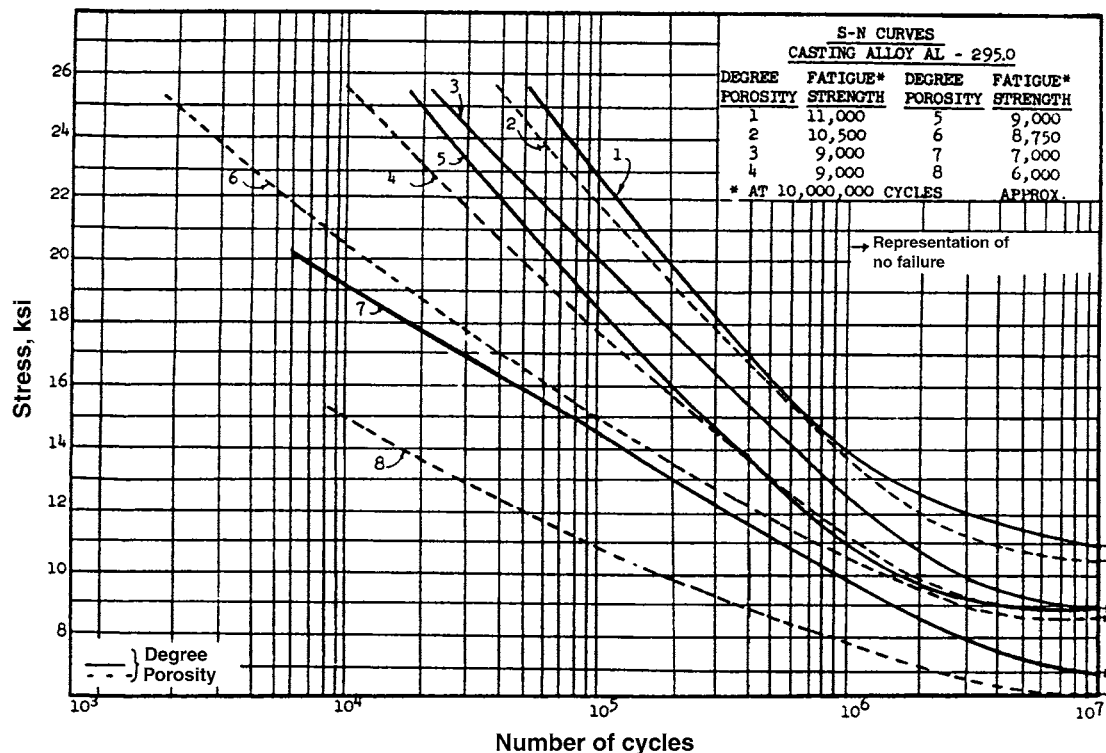


Fig. 6.1 Fatigue properties of 295.0 aluminum alloy castings with various degrees of porosity. Source: Ref 6

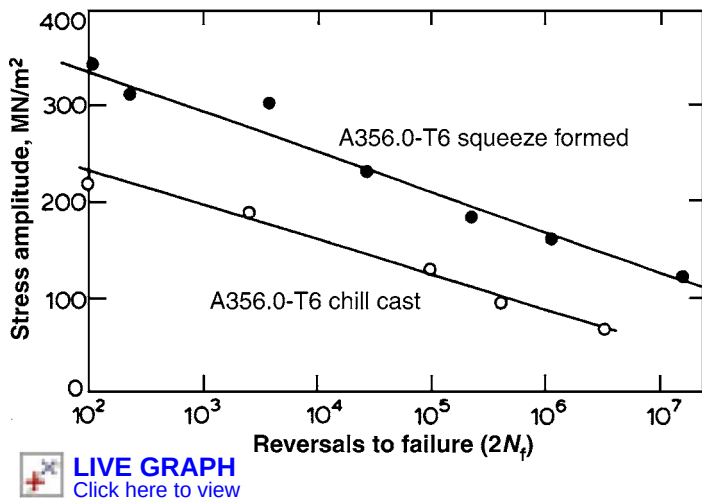


Fig. 6.2 Fatigue properties of conventionally cast and squeeze-cast aluminum alloy A356.0-T6. Source: Ref 7

reasonably good quality has been obtained. Data for sharply notched ($K_t > 12$) specimens also compared well with the band, except that as the endurance limit was approached, the data for squeeze-cast material fell along the lower limit of the band.

Another indication of the potential of squeeze casting is found in the work of Williams and Fisher (Ref 7), illustrated in Fig. 6.2, in which the axial-stress ($R = 0.0$) fatigue strengths of A356.0-T6 squeeze castings consistently performed better than conventionally cast A356.0-T6 castings.

Additional information on squeeze-cast aluminum alloys may be found in Ref 5.

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CHAPTER 7

Effects of Microstructure and Microporosity

BECAUSE NO MICROGRAPHS are available for the fatigue curve archives contained herein, it is beyond the scope of this book to deal in depth with the effects of microstructural features on fatigue performance. However, several characteristics of the metallurgical structure of aluminum alloy products that have been shown to have significant links to their behavior in fatigue are described below.

In the paragraphs that follow, the role of degree of recrystallization and grain size in addition to the level of discontinuities is discussed. While no micrographs are available to document the variations in microstructural features described, there is usually adequate descriptive information provided in the figure captions to illustrate the variations covered.

7.1 Effect of Degree of Recrystallization

Figure 2024.RB11 contains the results of tests of 2024-T4 extruded bar containing regions of both unrecrystallized and completely recrystallized material. The fatigue lives of specimens from unrecrystallized regions consistently had longer fatigue lives and higher endurance limits than those from recrystallized regions.

Data for 6061-T6 extruded shapes in Fig. 6061.RB05 and RB06 also illustrate that unrecrystallized structures can be expected to provide consistently higher fatigue strengths, not only for smooth specimens but also for those with either mild (Fig. 6061.RB05) or severe (Fig. 6061.RB06) stress concentrators. The fatigue strengths of unrecrystallized material are 2 to 5 ksi (14 to 35 MPa) higher than those of recrystallized material across the life range for all three types of specimen represented.

Figure 7050.FL01 contains the results of flexural fatigue ($R = -1.0$) tests of specimens representing various microstructures in a 7050-T74511 (previously known as T736511) extruded spar shape, including unrecrystallized, relatively fine-grained, and relatively coarse-grained regions. The unrecrystallized material exhibited fatigue strength approximately the same as that of the relatively fine-grained material and substantially (more than 10 ksi, or 70 MPa) above that of the coarse-grained material.

7.2 Grain Size

The data for 2017-T36 sheet in Fig. 2017.FL02 are among those illustrating that the fatigue strengths of fine-grained aluminum

products are generally significantly superior to those of comparable coarse-grained products; the difference in fatigue strength across the life range is indicated to be approximately 2 ksi (14 MPa), or approximately 10 to 15%.

In rotating-beam tests of 2011-T3 and T8, illustrated in Fig. 2011.RB02, grain counts of approximately 15,000 gr/mm³ resulted in higher endurance limits for both smooth and sharply notched ($K_t > 12$) specimens than grain counts of approximately 3000 to 7000 gr/mm³, although there was considerable scatter in the data. The results were consistent for the two tempers. Interestingly, the differences were less pronounced at shorter fatigue lives.

Rotating-beam tests of 2018-T61 (Fig. 2018.RB03 and RB04) also rather clearly showed the relative effects of grain size, with the coarse-grained specimens consistently falling on the lower edge or below the bands for both smooth and notched specimens, while specimens with the finer grain size usually had the longest lives at any given applied stress.

There are situations where significant differences in grain size are noted in specific products, such as the 2025-T6 forged propeller blades for which data are shown in Fig. 2025.RB06, where there appears to be very little, possibly no, significant effect of the observed grain-size difference on fatigue properties. Even in such cases, when the fatigue lives are analyzed stress by stress, there are often small differences favoring the fine-grained samples. Whether the magnitude of the effect is dependent on the quantitative difference in grain size or some other factor, such as actual degree of recrystallization, is impossible to tell from these data.

As noted in the previous section, large differences attributable to grain size are found for a 7050-T74511 extruded shape in Fig. 7050.FL01. Over the entire range of fatigue lives, the fatigue strengths of specimens representing relatively fine-grained microstructure are 10 to 15 ksi (70 to 103 MPa) higher than those for coarse-grained specimens and roughly comparable to the fatigue strengths of specimens from unrecrystallized regions of the extrusion.

It seems justified to conclude that, in general, the fatigue strengths of fine-grained aluminum alloy products are superior to those of relatively coarse-grained products of the same alloy and temper.

7.3 Ultrasonic Quality

Axial-stress fatigue tests were made of specimens from 2.5 in. (63 mm) thick 7075-T6 plate exhibiting several distinctly different

“hash” levels in ultrasonic quality inspections, *hash* being the term used to reflect the levels of ultrasonic response resulting from internal porosity or other discontinuities. Results are illustrated in Fig. 7075.AS11 from tests of both longitudinal (L) and short-transverse (ST) specimens taken from two regions, one with 1/8 in. (3.2 mm) hash level, the other with 3/8 in. (9.5 mm) hash, reflecting a higher level of internal discontinuities of some type.

For L specimens, there were no consistent or significant differences in fatigue lives of the specimens from the two regions in the plate. For the ST direction, however, the differences were quite dramatic, with the fatigue strengths of most specimens from the region with the higher hash level being on the order of 15 ksi (103 MPa) lower than those of the lower hash level. Interestingly, the ST fatigue strengths from the region with the lower hash level were little different from the L strengths, suggesting that 1/8 in. (3.2 mm) hash level is simply the baseline background noise. No micrographs are available to document the significance of these hash levels in terms of metallurgical quality.

7.4 Microporosity

Considerable effort is made in the production of aluminum alloy products, especially those going into applications where fatigue and fracture resistance are a critical performance requirement, to minimize internal microporosity (Ref 1). These include, among other things, controlling composition, improving ingot quality, and thermomechanical processing of ingot or billet before rolling, forging, or extruding to final product size. Nevertheless, some variations in microporosity are inevitable.

Detailed illustrations of variations in fatigue strength resulting from different levels of microporosity are not available from the data presented herein, and so, additional discussion of this subject

goes beyond the scope of this book. However, for specific information on the effects of microporosity on fatigue performance of aluminum alloys, readers are referred to the work of Bucci and others in Ref 2 to 8.

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CHAPTER 8

Influence of Fabrication Finishing Variables on Fatigue Properties

THE INFLUENCE OF A NUMBER of variables in the fabrication and finishing of aluminum components or structures is included in this chapter:

- Surface treatments and conditions
 - a. Anodizing and related oxide-based coatings
 - b. Automotive body sheet finishing
 - c. Porcelain enameling
 - d. Nitric acid and other etchants
 - e. Chemical milling
 - f. Extrusion die lines on the surface
 - g. Surface rolling and peening
 - h. Flash coating with copper
 - i. Ni-SiC electrochemical plating
- Joining techniques
 - a. Fusion welding
 - b. Flash welding
 - c. Brazing
 - d. Alforging
 - e. Riveting

8.1 Surface Treatments and Conditions

Especially for sheet products, the surface quality and finishing treatments have very definite effects on small-specimen fatigue strength. In discussing them, it is important to keep in perspective, however, that such differences may be relatively inconsequential, considering the impact of design-related stress concentrations and joints on structural performance.

8.1.1 Anodizing and Related Oxide-Based Coatings

Anodizing is a process of thickening the oxide coating on an aluminum alloy product, often sheet, to improve its corrosion resistance or alter its color and appearance. Experiments developed over the years have shown that the resulting thicker and relatively brittle protective oxide coating can lead to premature fatigue crack initiation compared to products with only the natural protective oxide coating found on most aluminum alloy products. Some examples are illustrated here.

Figure 2014.RB16 illustrates the impact of treating the surfaces of rotating-beam specimens machined from 2014-T6 extruded

shapes with alodine and anodizing treatments together with various sequences of precleaning and postsealing. The data fell into three distinct ranges, with the original untreated 2014-T6 extrusion having the highest fatigue strengths. Most samples with alodine and anodizing treatments and sealing had lower fatigue strength, the alkaline etch-anodize-water seal combination being most deleterious. Interestingly, when a nonetching alkaline porcelain and a special seal were applied, the results were comparable to those for the original material. Regrettably, the specific details of that precleaning and the special seal are not recorded.

For 2017-T4 in Fig. 2017.RB07, on the other hand, etching and alumilting had no consistent or significant effect on the fatigue strengths of smooth specimens but suggest some negative effects for notched specimens at very long fatigue lives. The latter effect is curious and suggests that the etching process may have deepened the notch beyond its original measurement, increasing its effective severity and/or the added oxide coating in the notch-hastened crack initiation.

Most other available results support the general trend in Fig. 2014.RB16 that thick oxide coating created by various anodizing-type processes tends to reduce fatigue strength.

Figure 2024.FL06 provides a comparison of flexural fatigue ($R = -1.0$) properties of Alclad 2024-T3 sheet prior to and following an Alumilite coating treatment, a type of anodizing. The fatigue strengths of the anodized sheet from 10^5 through 10^7 cycles of life are consistently lower by 2 to 5 ksi (14 to 35 MPa). However, as the endurance limit at 5×10^8 cycles is approached, the difference appears to become less significant.

Rotating-beam fatigue data for 2024-T4 extrusions in Fig. 2024.RB10 consistently indicate that Alodine and Iridite types of anodizing treatments had negative effects on fatigue strength, and, in this case, the effect is just as great at approximately the endurance limit as at shorter lives.

Figure 6061.FL05 provides a similar comparison for 6061-T6 sheet before and after anodizing and sealing, plus, in this case, some ultraviolet exposure to simulate service life. As in the case for 2024-T4, the fatigue strengths of the anodized product are lower than those of the original bare sheet over the shorter life range (i.e., 10^4 to 10^6 cycles). However, as cycles increase, the two curves come asymptotically together, and the endurance limits of bare and anodized 6061-T6 sheet are essentially equal. There is greater scatter but no discernable difference as a result

of the ultraviolet exposure; sheet given that treatment performed approximately as well as the original anodized sheet.

Figure 7075.FL08 illustrates data for Alclad 7075-T6 sheet given an Alumilite type of anodizing treatment and gold color. In this case, the fatigue strengths of the anodized specimens fell on the lower edge of or slightly below the band for as-fabricated Alclad 7075-T6 sheet.

Additional data for anodized 7075-T6 specimens are illustrated in Fig. 7075.RB11. These are interesting because the variables of coating thickness and type of acid used were included in the study. It appears that thin coatings, approximately 0.001 in. (0.025 mm) in thickness, of either type have no deleterious effect, but coatings 0.002 in. (0.051 mm) or more reduce fatigue strengths significantly. The negative effect seems significantly greater with sulfuric acid anodizing and with the thicker coatings. More detailed studies are shown in Fig. 7075.RB12 and RB13.

8.1.2 Automotive Body Sheet Finishing

Automotive outerbody sheet panels for doors, hoods, and trunk lids are typically formed into the required shape and subsequently painted, the latter usually requiring a high-temperature paint-bake cycle to cure the paint system. As part of the effort to evaluate several aluminum alloys for these applications, 2036-T4, 5182-O, 6009-T4, and 6010-T4 were put through a regimen where they were stretched 10% and then heated 8 h at 350 °F (175 °C) to simulate the autobody panel finishing process. The results are shown in Fig. 2036.FL01, 5182.FL01, 6009.FL01, and 6010.FL01 and summarized in Table 8.1.

The combination of stretching and aging had little overall effect—perhaps a small benefit—on the fatigue properties of 5182 and the 6xxx aluminum alloys, but the combination of 10% stretching plus 8 h at 350 °F (175 °C) seems to result in 2 to 3 ksi (14 to 21 MPa) reduction in the fatigue strength of 2036-T4. The latter finding is surprising, because the thermal treatment simulating the paint-bake cycle is similar to that used in aging 2xxx alloys from T4- to T6-type tempers, and so, this result may not be broadly representative.

Paint baking alone had a positive effect on the fatigue strength of 6151-T4 sheet at lower life cycles, as illustrated in Fig. 6151.FL01. At the endurance limit, however, the difference was small and likely insignificant.

8.1.3 Porcelain Enameling

Some aluminum alloys are given porcelain-enamel-coated surfaces for decorative purposes. The process involves curing at

very high temperatures for a short time (e.g., 10 min at 1000 °F, or 540 °C), which would be expected to result in some degradation in strength of strain-hardened or heat treated aluminum alloys.

Data for as-rolled and porcelain-enamelled 3003-H14 are presented in Fig. 3003.FL04. Data points for porcelain-enamelled specimens fall on the lower side of the range for 3003-H14, suggesting only a minor effect, even in sheet flexure where the effect may be expected to be greatest.

Data for 6061-T6 sheet in Fig. 6061.FL08 suggest a more detrimental effect, with most data for enamelled sheet given several different treatments falling below (sometimes far below) the band expected for 6061-T6 sheet and below the bulk of the points for the specific lot of 6061-T6 coated. The greater detrimental effect for 6061-T6 can be related to the firing of the enamelled sheet 10 min at 1000 °F (540 °C), which has a greater impact on the properties of a solution heat treated and aged alloy than on a relatively low-strength non-heat-treatable alloy such as 3003.

8.1.4 Nitric Acid and Other Etchants

Nitric acid may be encountered in some production operations or in service and will attack the surface of aluminum alloys. The detrimental effect of this surface attack on the fatigue properties of 6061-T6 sheet is illustrated in Fig. 6061.FL09. Fatigue strengths of sheet exposed to white fuming nitric acid at 180 °F (82 °C) for 90 days are consistently 4 to 8 ksi (28 to 55 MPa) lower than those of the original 6061-T6 sheet. At the endurance limit, the difference is approximately 4 ksi (28 MPa), or a reduction of 27%.

8.1.5 Chemical Milling

Figure 2024.FL09 illustrates the negative effect of chemical milling on the flexural fatigue ($R = -1.0$) strengths of 2024-T81 sheet. From 10^5 through 10^7 cycles, the chemical-milled sheet has 5 to 8 ksi (35 to 55 MPa) lower fatigue strengths than as-rolled 2024-T81 sheet. The difference becomes smaller approaching the fatigue limit (5×10^8 cycles) but still appears to be approximately 2 to 3 ksi (14 to 21 MPa).

This finding is supported by flexural ($R = -1.0$) data for 7075-T6 sheet in Fig. 7075.FL03, where the difference in fatigue strength throughout is approximately 7 to 8 ksi (48 to 55 MPa), or about 33%.

Interestingly, chemical milling has an even larger effect on axial-stress fatigue strengths. In order to judge the effect of chemical sizing on sheet as contrasted to machined surfaces, 1/16 in. (1.6 mm) thick sheet-type axial-stress specimens were prepared by taking 1/16 in. (1.6 mm) off of each side of 3/16 in. (4.8 mm) thick 2024-T81 sheet by the two methods. The chemical milling was done by two different companies. As the results in Fig. 2024.AS34 illustrate, chemical milling resulted in consistently lower fatigue strengths at a stress ratio of 0.0; the difference was largest at the endurance limit, where the chemical-milled specimens had 6 to 12 ksi (41 to 83 MPa) lower limits.

The same study was made for 7075-T6 sheet, the results of which are shown in Fig. 7075.AS08. While the differences were smaller, there is a clear and consistent reduction in fatigue strengths from chemical milling, in this case, by approximately 5 to 7 ksi (35 to 48 MPa).

Table 8.1 Effect of stretching and aging comparable to autobody sheet finishing on endurance limit (EL) at 5×10^8 cycles

Alloy and temper	Figure No.	Endurance limit					
		As fabricated		10% stretch		Stretch and age	
		ksi	MPa	ksi	MPa	ksi	MPa
2036-T4	2036.FL01	18.5	128	17.5	121	15.5	107
5182-O	5182.FL01	16.0	110	17.5	121	16.0	110
6009-T4	6009.FL01	16.5	114	18.0	124	17.0	117
6009-T6	6009.FL02	18.0	124	...	...	...	...
6010-T4	6010.FL01	18.0	124	18.0	124	18.5	128
6010-T6	6010.FL02	19.0	131	...	...	...	...

8.1.6 Extrusion Die Lines on the Surface

In flexural fatigue ($R = -1.0$) tests of a 2024-T4 extruded channel, data for which are shown in Fig. 2024.FL13, specimens taken from surfaces with relatively light and heavy die lines showed generally lower fatigue strengths than those of 2024-T3 or -T4 sheet and extrusions. With the light die lines, the differences were generally small, many of the specimens falling along the lower edge of the band of expected results. However, with severe die lines (regrettably not quantified), fatigue strengths were 5 to 8 ksi (35 to 55 MPa) lower than typically expected for the product.

8.1.7 Surface Rolling and Peening

Studies have been made over the years to determine the effectiveness of surface rolling or peening on the fatigue properties of aluminum alloys.

The results of one such study, shown in bar graphs in Fig. 2014.HT02 and HT03, involved controlled studies at two rotating-bending ($R = -1.0$) stresses of 40 and 50 ksi (275 and 345 MPa). Tests were made of specimens as-machined and after some were given one of two surface treatments designed to add compressive residual stresses near the surfaces at highest loading in bending tests: shot peening or cold rolling. Tests were made at room temperature as-treated and also after holding for 1000 h at 212 °F (100 °C) or for 1 h at 100, 200, or 300 °F (40, 95, or 150 °C); in addition, tests were made at those two temperatures, several after some stabilization.

Looking first at the results in tests at 40 ksi (275 MPa) (Fig. 2014.HT02) at room temperature, the positive effect of the cold rolling was quite dramatic; life was increased by approximately 2 orders of magnitude. There was a small, possibly insignificant, improvement from shot peening as well. The improvement resulting from cold rolling held up well at room temperature after 1 h exposures at 100 or 200 °F (40 or 95 °C) but was greatly diminished, as may be expected, by the long-time holding at 212 °F (100 °C) or a short time at 300 °F (150 °C).

A similar pattern was observed in the high-temperature tests at 40 ksi (275 MPa). The benefits of cold rolling the surface were still evident at 100 and 200 °F (40 and 95 °C), but after 1000 h at 212 or 300 °F (100 or 150 °C), the effect was largely erased. There was some suggestion that the shot peening may have been more effective in connection with high-temperature exposures, but the effect was small and may not prove statistically significant.

For the same series carried out at 50 ksi (345 MPa) maximum stress (Fig. 2014.HT03), the same trends were evident, but the magnitude of greatest improvement from cold rolling, in particular, was smaller, only 1 order of magnitude. As at 40 ksi (275 MPa), there is some evidence of benefit from shot peening, but it appears not statistically significant.

An interesting extension of that work was carried out later, and the results are contained in Fig. 2014.RB17. It too involved only a few specimens—some smooth, some sharply ($K_t > 12$) notched, all tested at room temperature at the same relatively high rotating-bending ($R = -1.0$) stress of 40 ksi (275 MPa). The results were curious in that, in this case, neither surface rolling nor shot peening resulted in any significant increase in life of smooth specimens beyond that of the original machined specimens from the

2014-T6 extrusion. However, for the sharply notched specimens, there was an order of magnitude increase in fatigue life as a result of shot peening, but it was relatively unaffected by surface rolling. It is unclear whether the effect of the shot peening on notched specimen life was to lessen the severity of the stress concentration or to improve the surrounding stress field by the imposition of compressive residual stresses, or perhaps both.

While these data demonstrate the potential impact of surface working to increase local beneficial residual stresses, the magnitude of the effect will unquestionably vary with the spatial and structural conditions surrounding any specific service application. Testing involving those conditions is recommended before conclusions are drawn.

Data are presented in Fig. 355.AS05 for 355.0-T6 cast test bars that had been sand, grit, or shot blasted prior to axial-stress ($R = 0.0$) testing. All three treatments resulted in improvements in endurance limit of 2 to 3 ksi (14 to 21 MPa), but there was little effect on fatigue strengths at 10^6 cycles or less. Whether this effect is from smoothing the surface or increasing the positive residual-stress patterns was not reported.

8.1.8 Flash Coating with Copper

From a very limited set of tests, illustrated in Fig. 2017.RB06, it appears that flash coating with copper provides some additional fatigue strength to 2017-T4. From the information now available, it is not clear if this was due to the additional thickness of copper not accounted for by the stress calculations, by some improvement in the surface characteristics, or by the superior fatigue strength of the copper that was used.

8.1.9 Ni-SiC Electrochemical Plating

Nickel containing silicon carbide particles was plated electrochemically on 5052-H38 specimens machined from 3/4 in. (19 mm) diameter rolled and drawn rod. Data from rotating-bending ($R = -1.0$) fatigue tests of the plated specimens are shown in Fig. 5052.RB10. As with the copper coating (Section 8.1.8), there was a fairly consistent increase in fatigue strength for the plated specimens, not consistently related to coating thickness. Once again, in retrospect, it is not clear if the differences are due to the added diameter of the specimen not included in the stress calculations or some more basic improvement as a result of the higher-strength coating. The difference seems to be larger than accounted for by a simple adjustment of the stress calculation for the added thickness.

8.2 Joining Techniques

8.2.1 Fusion Welding

The ultimate tensile and yield strengths of weldments in aluminum alloys are generally lower than those of strain-hardened or heat treated parent metal because the gas metal arc (GMAW) or gas tungsten arc welding processes result in a complete melting of the metal in the weld zone followed by resolidification, leading to a cast weld zone and a heat-affected zone on either side.

To explore the impact on fatigue strengths, axial-stress fatigue tests have been made of several aluminum alloys comparing the

Table 8.2 Effect of welding on fatigue strength

Alloy and temper	Filler alloy	Figure No.	Fatigue strength				
			Parent metal		Across weld		Difference(a), %
			ksi	MPa	ksi	MPa	
2219-T81	2319	2219.AS28	45.0	310	31.0	215	−32
5454-H32	5554	5454.AS03	40.0	275	29.0	200	−28
5456-H321	5556	5456.AS05	42.0	290	30.0	210	−25
5083-H113	5183	5083.AS06, AS07	39.0	270	29.0	200	−26
5086-H32	5356	5086.AS03	41.0	285	33.0	230	−20

Note: All tests at stress ratio $R = 0.0$. (a) Difference calculated using test (ksi) values.

Note: All tests at stress ratio $R = 0.0$. (a) Difference calculated using test (ksi) values.

performance of parent metal and GMAW joints using the recommended weld filler alloys. The results are summarized in Table 8.2 with the appropriate figure references.

Cross-weld fatigue strengths at 10^5 cycles are approximately 70 to 80% of those of the strain-hardened or heat treated parent metal. Comparisons with Fig. 5454.AS01 for 5454-O, Fig. 5456.AS01 for 5456-O, Fig. 5083.AS01 for 5083-O, and Fig. 5086.AS01 for 5086-O suggest that the fatigue strengths of welds are roughly comparable to those of the annealed parent metal.

Another perspective on the fatigue behavior of weldments is presented in Fig. 5456.AS06 and AS07, in which data for sheet-type specimens machined edgewise (AS06) and flatwise (AS07) from a 7/8 in. (22 mm) thick groove-welded (GMAW process; 5556 filler alloy) plate are shown. In each case, the weld bead was left in place on some specimens and machined off of others, and the differences in behavior were measured. For both specimen orientations, removing the weld bead resulted in approximately 10 to 12 ksi (70 to 83 MPa) higher fatigue strength across the life range. It is therefore always recommended that, if practical, the weld beads be dressed or completely removed if fatigue loading is a design issue.

For more information on the technology of joining aluminum alloys by welding and other techniques, readers are referred to Ref 1.

Repair of Castings by Fusion Welding. It is sometimes deemed necessary to repair defects in or damage to aluminum alloy castings by repair welding, generally by GMAW with a compatible high-silicon filler alloy such as 4043. Data for A357.0-T62 in Fig. A357.AS01 illustrate that specimens containing repair welds may perform essentially the same as those from the original casting. No detail is provided on the extent or location of the repair weld in the specimen.

8.2.2 Flash Welding

Rotating-bending ($R = -1.0$) fatigue tests were made of specimens across flash welds in 6061-T6 plate; the results are reported in Fig. 6061.RB09. At fatigue lives shorter than approximately 10^6 cycles, the fatigue strengths of the flash welds were lower than those of either 6061-T4 or -T6 (although not as low as those of 6061-O), but at longer lives and at the endurance limits, the flash welds performed as well as the parent metal.

8.2.3 Brazing

Figure 3003.FL05 shows the results of fatigue tests of 3003-H14 and No. 12 brazing sheet following their exposure to typical brazing cycles. No joints are involved in these tests, which were run solely to determine the extent of the thermal exposure on both the core and composite alloys. (No. 12 brazing sheet is 3003 with a 10% cladding of alloy 4343.)

The results showed no significant differences in the fatigue properties of the 3003 or brazing sheet following the exposure, but with an endurance limit of approximately 6.5 ksi (45 MPa), they are both substantially lower in fatigue strength than the original 3003-H14 sheet (Fig. 3003.FL04) and roughly comparable to 3003-O sheet (Fig. 3003.FL01).

8.2.4 Alforging

The Alforging process is a type of metallurgical pressure weld used to join extruded panels to provide longer continuous lengths for applications such as guard rails or railings. Flexural ($R = -1.0$) fatigue tests were made of transverse sheet-type specimens adjacent to and across such welds in 7005-T73 extruded panel, the results of which are shown in Fig. 7005.FL02.

For fatigue strengths in the 10^4 through 10^6 range, there are little if any significant differences between the parent extruded panel and the Alforged joint. However, for longer lives, beyond approximately 5×10^6 cycles, there is an indication that the fatigue strength in the weld region may be 4 ksi (28 MPa) or more lower than for the parent extrusion. Since no tests were run to lives exceeding 10^7 cycles, it is impossible to judge the magnitude of the effect, if any, at approximately the endurance limits.

8.2.5 Riveting

No data are presented herein for specimens containing rivets or rivet holes, although the data for stress-concentration factors of approximately 3 may be useful indicators of relative performance with rivet holes.

For specific attention to the subject of structural fatigue and design, readers are referred to the work of Sharp, Nordmark, and Menzemer (Ref 2), who address much of their guidance to the design of aluminum structures including structural joints for fatigue, and to *The Aluminum Design Manual* (Ref 3).

REFERENCES

1. *Welding Aluminum—Theory and Practice*, The Aluminum Association, Inc., Washington, D.C., 2001
2. M.L. Sharp, G.E. Nordmark, and C.C. Menzemer, *Fatigue Design of Aluminum Components and Structures*, John Wiley & Sons, New York, 1996
3. *The Aluminum Design Manual*, The Aluminum Association, Inc., Washington, D.C., 2005

CHAPTER 9

Effect of Temperature and Environment

THE EFFECTS OF FATIGUE TESTING at elevated temperatures and holding specimens at elevated temperature prior to testing at that temperature are examined below. The effects of subzero and cryogenic temperatures on the fatigue properties of aluminum alloys are also discussed. Finally, the effects of one of the most common environmental degradation factors, salt in the form of spray and saltwater immersion, are investigated.

9.1. High Temperatures

9.1.1 *Influence of High Temperature on Fatigue Strength of Wrought Alloys*

As with static strengths, fatigue strengths decrease with increase in temperature. Summary tables of rotating bending ($R = -1.0$) fatigue strengths as a function of temperature are shown in Tables A5.3 to A5.5 from Ref 1 and 2. Since these tables were generated from the entire archive from which $S-N$ curves were selected for inclusion in this publication, all of the values in Tables A5.3 to A5.5 may not be supported by graphical presentations herein.

Representative data for the alloys and tempers for which $S-N$ curves are shown herein have been extracted to show percentage decrease with temperature increase for representative alloys and tempers in Table 9.1.

As with static strength, the 2xxx alloys tend to retain their strengths more consistently than most other alloys when temperatures exceed 300 °F (150 °C), even after extended holding periods at temperature prior to testing. Up to and including 300 °F (150 °C), those alloys with the highest room-temperature strengths, like the 7xxx series, hold up well in comparison with the 2xxx series.

Among the non-heat-treatable alloys, the annealed tempers retain their strengths best at high temperatures, but the strengths themselves are still the lowest, since they have already been subjected to very high temperatures for recrystallization. As at room temperature, the Al-Mg-Mn alloys have the highest strengths at elevated temperatures.

Comparing the percentage losses in fatigue strength in Table 9.1 with those in tensile properties at comparable temperatures from Ref 1, the reductions in fatigue strength are generally smaller and show less effect of holding time at temperature prior to testing.

9.1.2 *Effect of Long Holding Times at Elevated Temperatures for Wrought Alloys*

In order to examine the effect of holding time at elevated temperatures on the fatigue strength at room temperature and at the holding temperature, axial-stress tests were made of several 2xxx alloys and tempers where specimens were held for 10,000, 30,000, or 50,000 h at 300 °F (150 °C) and then tests at room temperature or at 300 °F (150 °C). In the tests at room temperature, the specimens were allowed to cool to room temperature before testing, and in the tests at 300 °F (150 °C), as usual, the specimens were simply stabilized for 1/2 h at temperature before testing. For the long holding periods, the specimens were held in holding furnaces and were not under stress.

2219-T851 Plate. In Figures 2219.AS13 to AS15, both at room temperature and at 300 °F (150 °C), the fatigue lives of both smooth and notched ($K_t = 3$) specimens at shorter cycle lives ($\leq 10^6$) were significantly lower than without the prior holding period at 300 °F (150 °C). However, for smooth specimens at longer lives, the difference diminished, and beyond 10^7 cycles, there was no evident difference related to the prior exposure. For notched specimens, the reduced strength resulting from the high-temperature exposure persisted, and at room temperature, the endurance limit for preheated specimens was approximately 4 ksi (28 MPa) lower than for the non-preheated specimens. The results were essentially the same regardless of the length of time of exposure.

2219-T87 Plate. Most trends observed for 2219-T851 plate also followed through for 2219-T87 plate (Fig. 2219.AS24 to AS26). Long prior exposure at 300 °F (150 °C) had little effect on long-life smooth-specimen fatigue strengths, despite some reductions at shorter lives. For notched specimens at room temperature, there was some consistent 4 to 8 ksi (28 to 55 MPa) reduction at all lives.

2020-T651 Plate. Alloy 2020-T651 (Fig. 2020.AS01 to AS11) exhibited among the largest reductions from long-time preheating at 300 °F (150 °C) observed for any alloys, especially for smooth specimens where the losses were approximately 4 to 8 ksi (28 to 55 MPa) over the whole life range. For notched specimens, the losses were similar to those for other alloys and tempers. As with other alloys, the time at temperature beyond 10,000 h had little additional effect.

Table 9.1 Endurance limits (EL) at 5×10^8 cycles of some aluminum alloys at high temperatures

Alloy and temper(a)	Product(b)	Type of specimen(c)	Figure No.	Endurance limit, ksi							Room-temperature (RT) value, %						
				Temperature, °F							Temperature, °F						
				RT	212	300	400	500	600	700	RT	212	300	400	500	600	700
1100-O	R&D rod	Sm	1100.HT01	5.0	...	4.0	3.5	2.5	...	...	100	...	80	70	50	...	...
1100-H16	R&D rod	Sm	1100.HT02	8.0	...	4.0	2.5	2.0	...	...	100	...	50	31	25	...	...
1100-H18	R&D rod	Sm	1100.HT03	9.0	...	3.5	3.0	2.5	...	...	100	...	39	33	28	...	...
1100-H26	R&D rod	Sm	1100.HT04	8.0	...	3.0	2.5	2.0	...	...	100	...	38	31	25	...	...
1350-H19	R&D rod	Sm	1350.HT01	7.0	5.0	...	...	...	...	...	100	71	...	...	...	...	...
2011-T3S	R&D rod	Sm	2011.HT01	18.5	...	7.5	5.0	3.0	...	...	100	...	41	27	16	...	...
2014-T6	R&D rod	Sm	2014.HT01	18.0	...	...	8.5	5.5	5.0	...	100	...	...	47	31	28	...
2017-T4S	R&D rod	Sm	2017.HT01	15.0	...	13.0	8.5	6.0	...	...	100	...	87	57	40	...	...
2017-T4	Extr.	Sm	2017.HT02	18.0	...	16.5	10.0	6.5	6.0	...	100	...	92	56	36	33	...
2018-T6S	R&D rod	Sm	2018.HT01	16.5	...	12.0	7.0	5.5	...	...	100	...	73	42	33	...	...
2018-T61S	Forging	Sm	2018.HT02	17.0	...	10.0	8.0	7.0	...	...	100	...	59	47	41	...	...
2218-T6	Forging	Sm	2218.HT01	16.5	...	12.0	8.5	6.0	...	...	100	...	73	52	36	...	...
2618-T6	Forging	Sm	2618.HT01	19.0	...	...	12.0	7.5	5.0	...	100	...	...	63	39	26	...
2618-T6	Forging	Sm	2618.HT02	17.0	...	13.5	10.5	8.0	6.5	...	100	...	79	62	47	38	...
2020-T651	R&D rod	Sm	2020.HT01	19.0	...	19.5	14.5	9.0	5.5	...	100	...	103	76	47	29	...
2020-T651	R&D rod	N	2020.HT02	5.5	...	5.5	5.0	4.5	3.5	...	100	...	100	91	82	64	...
2020-T6	Extr.	Sm	2020.HT03	21.0	...	15.5	12.5	...	...	...	100	...	74	60	...	...	...
2024-T4S	R&D rod	Sm	2024.HT01	20.0	...	14.0	9.0	6.0	...	...	100	...	70	45	30	...	...
2025-T6S	R&D rod	Sm	2025.HT01	17.5	...	9.5	7.0	4.0	...	...	100	...	54	40	23	...	...
2027-T6S	R&D rod	Sm	2027.HT01	13.0	...	11.5	8.0	4.0	...	...	100	...	88	62	31	...	...
3003-O	R&D rod	Sm	3003.HT01	7.0	...	6.0	3.5	2.0	...	...	100	...	86	50	29	...	...
3003-H14	R&D rod	Sm	3003.HT02	9.0	...	6.0	3.0	2.0	...	...	100	...	67	33	22	...	...
3003-H18	R&D rod	Sm	3003.HT03	10.0	...	6.5	5.0	3.5	...	...	100	...	65	50	35	...	...
3003-H24	R&D rod	Sm	3003.HT04	9.0	...	6.0	5.0	...	...	...	100	...	67	56	...	...	...
3004-O	R&D rod	Sm	3004.HT01	14.0	...	9.0	8.0	7.0	...	...	100	...	64	57	50	...	...
3004-H14	R&D rod	Sm	3004.HT02	16.0	...	13.0	10.0	8.5	...	...	100	...	81	63	53	...	...
3004-H18	R&D rod	Sm	3004.HT03	18.0	...	11.0	8.0	5.0	...	...	100	...	61	44	28	...	...
3004-H19	R&D rod	Sm	3004.HT04	18.0	...	11.0	7.5	6.0	...	...	100	...	61	42	33	...	...
3004-H34	R&D rod	Sm	3004.HT05	16.0	...	13.0	10.0	8.0	...	...	100	...	81	63	50	...	...
3004-H38	R&D rod	Sm	3004.HT06	18.0	...	12.0	9.5	6.0	...	...	100	...	67	53	33	...	...
3004-H39	R&D rod	Sm	3004.HT07	18.0	...	12.5	8.5	6.5	...	...	100	...	69	47	36	...	...
4032-T6	R&D rod	Sm	4032.HT01	17.0	...	12.0	7.0	5.0	...	...	100	...	71	41	29	...	...
4032-T6S	R&D rod	Sm	4032.HT02	10.0	...	9.0	6.5	3.5	...	...	100	...	90	65	35	...	...
5005-H19	R&D rod	Sm	5005.HT01	16.0	15.0	10.5	...	...	...	...	100	94	66	...	...	...	...
5050-O	R&D rod	Sm	5050.HT01	12.5	...	8.0	5.0	4.0	...	...	100	...	64	40	32	...	...
5050-H34	R&D rod	Sm	5050.HT02	16.0	...	8.0	5.0	3.5	...	...	100	...	50	31	22	...	...
5050-H38	R&D rod	Sm	5050.HT03	18.0	...	9.0	5.0	4.0	...	...	100	...	50	28	22	...	...
5052-O	R&D rod	Sm	5052.HT01	16.0	...	10.0	8.0	7.0	...	...	100	...	63	50	44	...	...
5052-H14	R&D rod	Sm	5052.HT02	18.0	...	13.5	10.5	6.0	...	...	100	...	75	58	33	...	...
5052-H18	R&D rod	Sm	5052.HT03	20.0	...	14.0	11.0	6.0	...	...	100	...	70	55	30	...	...
5052-H34	R&D rod	Sm	5052.HT04	18.0	...	13.0	10.5	...	...	...	100	...	72	58	...	...	...
5052-H36	R&D rod	Sm	5052.HT05	19.0	...	12.5	9.5	...	...	...	100	...	66	50	...	...	...
5052-H38	R&D rod	Sm	5052.HT06	20.0	...	13.0	9.5	6.5	...	...	100	...	65	48	33	...	...
5154-O	R&D rod	Sm	5154.HT01	18.5	...	16.0	11.5	6.5	...	...	100	...	86	62	35	...	...
5154-H32, H34	R&D rod	Sm	5154.HT02	20.5	...	14.5	9.5	6.0	...	...	100	...	71	46	29	...	...
5154-H34	R&D rod	Sm	5154.HT03	21.5	...	18.0	...	...	...	...	100	...	84	...	...	...	...
5454-O	Plate	Sm	5454.HT01	20.0	...	11.5	11.0	8.5	4.5	...	100	...	58	55	43	23	...
5454-H32	Plate	Sm	5454.HT02	20.0	...	12.5	12.0	8.5	5.0	...	100	...	63	60	43	25	...

(continued)

(a) "S" added to temper designation; these lots were stabilized for extended periods at test temperature prior to testing at the same temperature. (b) R&D, rolled and drawn; Extr., extruded shape; PMTB, permanent mold test bar; SCTB, sand cast test bar; DCTB, die cast test bar. (c) Sm, smooth (unnotched); N, sharply notched ($K_t > 12$); CN, cast notched ($K_t \sim 10$). (d) Obsolete alloy. (e) Direct comparison of lots not available. Room-temperature (RT) endurance limit estimated from data for other applicable lots

Table 9.1 (continued)

Alloy and temper(a)	Product(b)	Type of specimen(c)	Figure No.	Endurance limit, ksi							Room-temperature (RT) value, %						
				Temperature, °F							Temperature, °F						
				RT	212	300	400	500	600	700	RT	212	300	400	500	600	700
5454-H34	R&D rod	Sm	5454.HT03	21.0	...	12.5	9.5	...	...	...	100	...	60	45	...	...	...
5056-O	R&D rod	Sm	5056.HT01	20.5	...	15.0	...	7.0	...	...	100	...	73	...	34	...	...
5056-H32	R&D rod	Sm	5056.HT02	22.0	...	16.0	...	6.0	...	...	100	...	73	...	27	...	...
5056-H34	R&D rod	Sm	5056.HT03	23.5	...	15.0	...	6.0	...	...	100	...	64	...	26	...	...
5356-O	R&D rod	Sm	5356.HT01	18.0	...	15.5	...	7.0	...	...	100	...	86	...	39	...	...
5356-H32	R&D rod	Sm	5356.HT02	20.0	...	15.5	...	6.0	...	...	100	...	78	...	30	...	...
5356-H34	R&D rod	Sm	5356.HT03	20.0	...	14.5	...	7.5	...	...	100	...	73	...	38	...	...
5456-O	Plate	Sm	5456.HT01	22.5	...	15.5	10.0	9.0	5.5	...	100	...	69	44	40	24	...
5456-H321	Plate	Sm	5456.HT02	23.0	...	14.0	10.5	6.5	5.5	...	100	...	61	46	28	24	...
5083-O	Plate	Sm	5083.HT01	20.0	...	15.0	10.5	7.0	5.5	...	100	...	75	53	35	28	...
5083-H113	Plate	Sm	5083.HT02	21.0	...	13.5	10.5	7.0	4.0	...	100	...	64	50	33	19	...
5086-O	Plate	Sm	5086.HT01	20.0	...	12.0	9.0	6.0	3.5	...	100	...	60	45	30	18	...
5086-H32	Plate	Sm	5086.HT02	21.0	...	15.0	11.5	8.0	3.5	...	100	...	71	55	38	17	...
6201-T6	R&D rod	Sm	6201.HT01	15.0	8.5	5.0	...	...	...	...	100	...	33	...	...	...	...
6051-T6S	R&D rod	Sm	6051.HT01	11.0	...	7.0	4.0	2.0	...	...	100	...	64	36	18	...	...
6151-T6	Forging	Sm	6151.HT01	12.0	...	9.0	7.0	2.5	...	...	100	...	75	58	21	...	...
6151-T6S	Forging	Sm	6151.HT02	12.0	...	9.0	5.5	2.5	...	...	100	...	75	46	21	...	...
6053-T6S	R&D rod	Sm	6053.HT01	12.0	...	9.0	6.0	4.0	...	...	100	...	75	50	33	...	...
6063-O	Extr.	Sm	6063.HT01, HT02, HT03	7.5	...	4.5	3.5	...	...	...	100	...	60	47	...	...	...
6063-T42	Extr.	Sm	6063.HT01, HT02, HT03	10.0	...	6.5	4.5	2.5	...	...	100	...	65	45	25	...	...
6063-T5	Extr.	Sm	6063.HT01, HT02	10.0	...	6.5	4.5	...	...	...	100	...	65	45	...	...	...
6063-T6	Extr.	Sm	6063.HT01, HT02, HT03	10.0	...	6.5	4.5	2.5	...	...	100	...	65	45	25	...	...
7070-T6S(d)	R&D rod	Sm	7070.HT01	15.0(e)	...	9.5	6.0	4.0	...	...	100	...	63	40	27	...	...
7073-T6(d)	Forging	Sm	7073.HT01	15.0	...	7.5	5.5	4.0	...	...	100	...	50	37	27	...	...
7074-T6(d)	Extr.	Sm	7074.HT01	21.0	...	17.0	9.0	6.5	...	...	100	...	81	43	31	...	...
7075-T6, T651	R&D rod	Sm	7075.HT01	22.0	...	20.0	13.0	7.5	6.5	...	100	...	91	59	34	30	...
7075-T6, T651	R&D rod	N	7075.HT02	8.0	...	5.0	3.5	2.5	2.0	...	100	...	63	44	31	25	...
7075-T6	R&D rod	Sm	7075.HT03	22.0	...	14.5	9.0	7.5	...	...	100	...	66	41	34	...	...
7075-T6S	R&D rod	Sm	7075.HT04	22.0	...	12.0	8.0	7.0	...	...	100	...	55	36	32	...	...
7076-T6	Forging	Sm	7076.HT01	19.0	...	16.0	7.5	6.0	...	...	100	...	84	39	32	...	...
7178-T6	R&D rod	Sm	7178.HT01	24.0	...	20.0	...	10.5	...	4.5	100	...	83	...	44	...	19
7178-T6	R&D rod	N	7178.HT02	7.0(e)	...	6.5	...	3.0	...	...	100	...	93	...	43	...	...
7178-T6	R&D rod	Sm	7178.HT03	22.0	...	20.0	13.0	...	...	...	100	...	91	59	...	...	...
7178-T651	R&D rod	Sm	7178.HT03	22.0	...	16.0	10.0	...	...	...	100	...	73	45	...	...	...
7079-T6(d)	R&D rod	Sm	7079.HT01	20.0(e)	...	18.0	10.5	10.0	7.5	5.5	100	...	90	53	50	38	28
7079-T6(d)	R&D rod	N	7079.HT02	6.5	...	6.5	4.5	3.0	2.0	1.5	100	...	100	69	46	31	23
7079-T6(d)	Forging	Sm	7079.HT03	22.0	...	17.0	9.5	...	...	...	100	...	77	43	...	...	...
222.0-T2	SCTB	Sm	222.HT01	9.5	...	8.0	5.0	4.0	...	...	100	...	84	53	42	...	...
224.0-T62	SCTB	Sm	224.HT01	12.0	...	...	7.0	6.0	...	...	100	...	...	58	50	...	...
A232.0-T551	PMTB	Sm	A232.HT01	13.0(e)	...	10.5	8.0	7.0	...	...	100	...	81	62	54	...	...
A232.0-T551S	PMTB	Sm	A232.HT02	13.0(e)	...	10.0	7.0	5.0	...	...	100	...	77	54	38	...	...
D232.0-T5	PMTB	Sm	D232.HT01	13.0(e)	...	10.0	8.0	6.0	...	...	100	...	77	62	46	...	...
D232.0-T5S	PMTB	Sm	D232.HT02	13.0(e)	...	8.0	7.5	5.5	...	...	100	...	62	58	42	...	...

(continued)

(a) "S" added to temper designation; these lots were stabilized for extended periods at test temperature prior to testing at the same temperature. (b) R&D, rolled and drawn; Extr., extruded shape; PMTB, permanent mold test bar; SCTB, sand cast test bar; DCTB, die cast test bar. (c) Sm, smooth (unnotched); N, sharply notched ($K_t > 12$); CN, cast notched ($K_t \sim 10$). (d) Obsolete alloy. (e) Direct comparison of lots not available. Room-temperature (RT) endurance limit estimated from data for other applicable lots

Table 9.1 (continued)

Alloy and temper(a)	Product(b)	Type of specimen(c)	Figure No.	Endurance limit, ksi							Room-temperature (RT) value, %						
				Temperature, °F							Temperature, °F						
				RT	212	300	400	500	600	700	RT	212	300	400	500	600	700
A240.0-F	SCTB	Sm	A240.HT01	17.5	...	12.5	10.5	8.5	5.5	...	100	...	71	60	49	31	...
242.0-T2	SCTB	Sm	242.HT01	8.0	...	7.5	6.5	5.0	3.0	...	100	...	94	81	63	38	...
242.0-T2S	SCTB	Sm	242.HT02	8.0	...	7.0	5.5	4.5	...	...	100	...	88	69	56	...	...
242.0-T571	SCTB	Sm	242.HT03	15.0	...	13.5	8.0	6.0	4.0	...	100	...	90	53	40	27	...
242.0-T571S	SCTB	Sm	242.HT04	11.0	...	9.0	6.5	5.0	4.0	...	100	...	82	59	45	36	...
242.0-T6	SCTB	Sm	242.HT05	12.0(e)	...	8.5	...	...	...	...	...	...	71	0	0	...	...
242.0-T6S	SCTB	Sm	242.HT05	12.0(e)	...	7.0	6.5	3.0	...	...	...	...	58	54	25	...	...
242.0-T75	SCTB	Sm	242.HT06	11.0(e)	...	9.0	7.0	5.5	3.0	...	100	...	82	64	50	27	...
242.0-T77S	SCTB	Sm	242.HT07	10.5	...	6.5	5.5	5.0	3.0	...	100	...	62	52	48	29	...
249.0-T63	SCTB	Sm	249.HT01	11.0	...	9.0	...	...	...	...	100	...	82	...	...	...	...
295.0-T95	SCTB	Sm	295.HT01	8.0(e)	...	6.5	5.0	3.5	...	...	100	...	81	63	44	...	...
295.0-T95S	SCTB	Sm	295.HT02	8.0(e)	...	5.5	4.0	3.0	...	...	100	...	69	50	38	...	...
319.0-T5	SCTB	Sm	319.HT01	11.0	...	8.0	7.0	5.0	3.5	...	100	...	73	64	45	32	...
333.0-T5	PMTB	Sm	333.HT01	13.5	...	9.5	7.5	6.0	4.5	...	100	...	70	56	44	33	...
333.0-T7	PMTB	Sm	333.HT02	12.5	...	9.5	6.5	5.5	3.5	...	100	...	76	52	44	28	...
354.0-T61	PMTB	Sm	354.HT01	19.5	...	15.0	8.5	5.5	4.0	...	100	...	77	44	28	21	...
355.0-T51	PMTB	Sm	355.HT01	15.0(e)	...	9.0	7.0	5.0	3.5	...	100	...	60	47	33	23	...
355.0-T51S	SCTB	Sm	355.HT02	14.0	...	7.5	5.0	3.5	2.5	...	100	...	54	36	25	18	...
355.0-T62	PMTB	Sm	355.HT03	15.5	...	12.0	8.0	4.0	3.5	...	100	...	77	52	26	23	...
355.0-T7S	SCTB	Sm	355.HT04	10.5	...	8.5	5.0	3.5	2.5	...	100	...	81	48	33	24	...
355.0-T71	PMTB	Sm	355.HT05	13.0	...	10.5	8.0	5.0	2.5	...	100	...	81	62	38	19	...
A355.0-T51	SCTB	Sm	A355.HT01	8.0	...	7.0	6.0	4.5	...	...	100	...	88	75	56	...	...
A355.0-T51S	SCTB	Sm	A355.HT02	8.0	...	6.5	5.5	4.0	...	...	100	...	81	69	50	...	...
A355.0-T71	SCTB	Sm	A355.HT03	10.0(e)	...	7.5	6.0	4.0	...	...	100	...	75	60	40	...	...
C355.0-T51	PMTB	Sm	C355.HT01	14.0	...	12.0	9.0	5.0	3.5	...	100	...	86	64	36	25	...
356.0-T51S	SCTB	Sm	356.HT01	8.0	...	6.5	4.0	3.0	...	...	100	...	81	50	38	...	...
356.0-T7S	SCTB	Sm	356.HT02	9.5	...	7.5	4.0	3.0	...	...	100	...	79	42	32	...	...
A357.0-T61	PMTB	Sm	A357.HT01	15.0	...	7.5	6.5	5.5	...	...	100	...	50	43	37	...	...
359.0-T61	PMTB	Sm	359.HT01	16.5	...	12.0	4.0	...	...	...	100	...	73	24	...	...	...
380.0-F	DCTB	Sm	380.HT01	20.0	...	10.0	7.0	3.5	...	...	100	...	50	35	18	...	...
380.0-F	DCTB	N	380.HT02	7.5	...	4.5	4.5	4.0	...	...	100	...	60	60	53	...	...
380.0-F	DCTB	CN	380.HT03	7.5	...	4.0	4.0	3.5	...	...	100	...	53	53	47	...	...
413.0-FS	DCTB	Sm	413.HT01	19.0	...	11.0	6.5	5.5	3.0	...	100	...	58	34	29	16	...
514.0-F	SCTB	Sm	514.HT01	8.0	...	7.0	6.0	...	...	...	100	...	88	75	...	...	...
514.0-FS	SCTB	Sm	514.HT02	8.0	...	7.5	5.0	4.0	...	...	100	...	94	63	50	...	...
518.0-F	DCTB	Sm	518.HT01	20.0	...	7.5	6.0	3.0	...	...	100	...	38	30	15	...	...
518.0-F	DCTB	N	518.HT02	5.5	...	4.5	3.5	2.5	...	...	100	...	82	64	45	...	...
518.0-F	DCTB	CN	518.HT03	8.0	...	3.5	3.0	2.5	...	...	100	...	44	38	31	...	...

(a) "S" added to temper designation; these lots were stabilized for extended periods at test temperature prior to testing at the same temperature. (b) R&D, rolled and drawn; Extr., extruded shape; PMTB, permanent mold test bar; SCTB, sand cast test bar; DCTB, die cast test bar. (c) Sm, smooth (unnotched); N, sharply notched ($K_t > 12$); CN, cast notched ($K_t \sim 10$). (d) Obsolete alloy. (e) Direct comparison of lots not available. Room-temperature (RT) endurance limit estimated from data for other applicable lots

Table 9.2 Average smooth-specimen endurance limits (EL) at 5×10^8 cycles of some cast aluminum alloys at high temperatures by alloy and by casting process(c)

		Endurance limit, ksi					Room-temperature (RT) value, %				
		Temperature, °F					Temperature, °F				
Class	Stabilize(a)	RT	300	400	500	600	RT	300	400	500	600
By alloy series											
2xx.0	No	11.8	9.5	6.5	5.7	3.9	100	81	55	44	31
2xx.0	Yes	10.8	7.6	6.1	4.4	3.5	100	71	57	42	32
3xx.0	No	14.1	10.0	7.0	4.9	3.6	100	72	52	37	25
3xx.0	Yes	10.0	7.3	4.7	3.4	2.5	100	75	49	35	21
4xx.0	Yes	19.0	11.0	6.5	5.5	3.0	100	58	34	29	16
5xx.0	No	14.0	7.2	6.0	3.0	...	100	63	52	15	...
5xx.0	Yes	8.0	7.5	5.0	4.0	...	100	94	63	50	...
By casting process											
Sand cast	No	10.5	8.2	6.6	5.1	3.8	100	81	65	49	32
Sand cast	Yes	9.8	7.2	5.1	3.8	3.0	100	75	54	40	27
PM cast(b)	No	14.6	10.0	7.4	5.5	3.6	100	75	52	39	25
PM cast(b)	Yes	13.0	9.0	7.3	5.3	...	100	69	56	40	...
Die cast	No	19.8	9.8	6.8	3.8	3.0	100	49	34	19	16
Die cast	Yes	20.0	7.5	6.0	3.0	...	100	58	34	29	16
All castings											
All	No	13.1	9.6	7.0	5.1	4.0	100	75	56	41	30
All	Yes	10.9	7.7	5.5	4.1	3.0	100	73	53	39	24

(a) These lots were stabilized for extended periods at test temperature prior to testing at same temperature. (b) PM, permanent mold. (c) Taken from Table 9.1

2024-T851 and -T86 Plate. The patterns for losses from prolonged exposure at 300 °F (150 °C) for 2024-T851 and -T86 (Fig. 2024.AS18 to AS21 and AS30 to AS33) were generally similar to those of the other alloys, with the larger losses resulting from the first 10,000 h of exposure.

9.1.3 Influence of High Temperature on Fatigue Strength of Cast Alloys

It is useful in the case of the casting alloys to look closer at the high-temperature fatigue strengths by alloy group, casting process, and degree of stabilization. The data for castings in Table 9.1 have been analyzed in that manner, and average values of fatigue strength ($R = -1.0$) are illustrated in Table 9.2.

The average values in Table 9.2 illustrate that:

- Stabilization had a significant and consistent effect on the room-temperature and high-temperature fatigue strength of the casting alloy, regardless of alloy type or casting process.
- The 2xx.0 alloys did not have the highest strengths at room temperature but, on average, retained their strengths better at the higher temperatures (at or above 400 °F, or 200 °C).
- No trends were evident by casting type at high temperatures; the sand castings seemed to retain their strengths best at high temperatures, but their comparison points at room temperature were the lowest. At high temperature, die-cast alloys looked poorly in percentage terms but, in this case, because they have unusually (and possibly not typically) high strengths at room temperature.

9.2 Subzero Temperatures

Aluminum alloys are widely used for subzero-temperature applications, including cryogenic tankage for liquefied natural gas (−260 °F, or −160 °C), liquid nitrogen (−320 °F, or −195 °C), liq-

Table 9.3 Effect of subzero temperatures on fatigue strength at 10^5 cycles of some aluminum alloys, $R = 0.0$

Alloy and temper	Figure No.	Fatigue strength (10^5 cycles), ksi		Difference from room temperature, %
		−320 °F	Room temperature	
5454-H32	5454.AS03	45.0	39.0	+15
5454-H32(a)	5454.AS03	36.0	29.0	+24
5454-H32(b)	5454.AS03	18.0	10.0	+80
5456-H321	5456.AS05	47.0	42.0	+12
5456-H321(a)	5456.AS05	35.0	30.0	+17
5456-H321(b)	5456.AS05	17.0	10.0	+70
5083-H113	5083.AS07	44.0	40.0	+10
5083-H113(a)	5083.AS07	34.0	29.0	+17
5086-H32	5086.AS03	47.0	41.0	+15
5086-H32(a)	5086.AS03	36.0	28.0	+28

(a) Specimen taken across the weld zone. (b) Notched specimen taken from across the weld, with notch in weld zone

uid hydrogen (−423 °F, or −253 °C), and liquid helium (−452 °F, or −269 °C). In order to study fatigue properties at cryogenic temperatures, axial-stress fatigue tests were made of several alloys commonly used for such applications at room temperature and −320 °F (−195 °C), both with and without welds. Both smooth and notched ($K_t = 3$) specimens were tested for most alloys.

In the tests at −320 °F (−195 °C), the specimens were held in a cryostat filled with liquefied nitrogen. The test durations varied but were carried out to a maximum of only 10^6 cycles, so, in the summary (Table 9.3) with the figure references, fatigue strengths at 10^5 cycles are used for the comparisons.

As presented in Table 9.3, the fatigue strengths of these alloys, both smooth and notched, welded and parent metal, are higher at −320 °F (−195 °C) than at room temperature. For the parent alloys, the increase for smooth specimens was 10 to 15%; for the welds, 17 to 28%; and for the two cases where notched specimens across the welds were tested, the difference was 70 to 80%.

Table 9.4 Effect of 3.5% NaCl spray on fatigue strength of some aluminum alloys

Alloy and temper	Figure No.	Stress ratio, R	Fatigue strength (10^6 cycles), ksi		Difference from ambient, %
			Ambient air	3.5 % NaCl	
Smooth specimens					
2014-T6	2014.AS09	0.0	22.0	11.0	−50
2024-T351	2024.AS36	+0.1	30.0(a)	16.0	−47
2036-T4	2036.AS01	0.0	30.0	15.0	−50
5182-O	5182.AS01	0.0	21.0	17.0	−20
6009-T4	6009.AS01	0.0	22.0	16.0	−27
6009-T6	6009.AS02	0.0	27.0	10.0	−63
6009-T62	6009.AS03	+0.1	26.0	12.0	−54
6010-T4	6010.AS01	0.0	24.0	11.0	−54
6061-T6	6061.AS04	0.0	27.0	13.0	−52
7046-T63	7046.AS01	0.0	33.0	24.0	−33
Notched ($K_t = 3$) specimens					
2014-T6	2014.AS10	0.0	13.0	6.5	−50
6061-T6	6061.AS04	+0.1	16.0	10.0	−38
Notched ($K_t = 12$) specimen					
2014-T6	2014.AS11	0.0	11.0	7.5	−32

(a) Estimated from Goodman diagram

(a) Estimated from Goodman diagram

Cryogenic temperatures are clearly not a problem for 5xxx aluminum alloys.

A few short life tests at -320°F (-195°C) were also carried out for 2219-T87, the results of which are presented in Fig. 2219.AS28 and AS29. In this case, the results at the low temperature for both smooth and notched specimens were approximately the same as or slightly lower than at room temperature, although the ranges of cycles do not overlap well for comparison.

9.3 Effect of Environment

Aluminum alloys are quite resistant to many environmental conditions, including many chemicals, and so are often used to contain and transport such materials (Ref 3). However, the fatigue performance of some alloys, especially the 2xxx and 7xxx alloys, is negatively affected by chloride environments, and so, a series of tests have been conducted over the years to determine the extent of this effect on fatigue properties.

In the environmental tests summarized in Table 9.4, exposures were made with specimens either immersed in a 3.5% sodium chloride (3.5% NaCl) solution throughout the test or intermittently sprayed with the 3.5% NaCl solution. This is similar to the salinity of open ocean seawater. Since the tests were typically run out only to 10^6 to 10^7 cycles, the basis of comparison is the fatigue strength at 10^6 cycles.

All of the tested alloys and tempers exhibited some significant reduction in fatigue strength as a result of the intermittent 3.5% salt spray. Of the alloys and tempers for which comparisons may be made, 5182-O, 6009-T4, and 7046-T6 experienced the least reduction in smooth-specimen fatigue strength, approximately 25%, while most of the others exhibited approximately 50% reduction.

The smaller effect for 7046-T6 does not appear to hold up at lives longer than 10^6 , because fatigue strength of that alloy continues to decrease sharply with increase in life in the salt spray, while most other alloys and tempers have plateaued by 5×10^6 cycles.

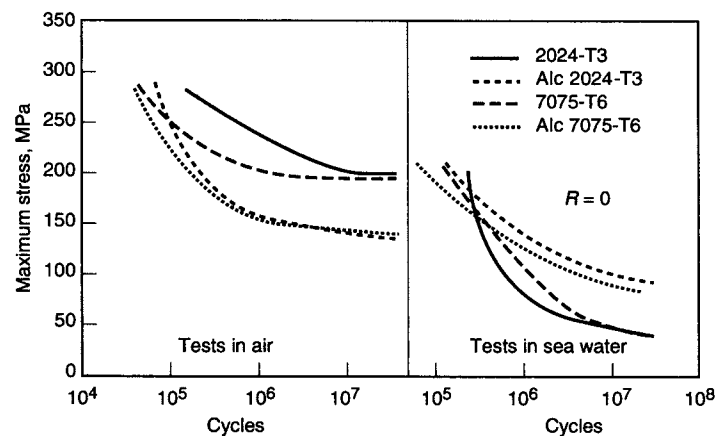


Fig. 9.1 Axial-stress fatigue strengths of 0.03 in. (0.8 mm) thick bare and Alclad (Alc) 2024-T3 and 7075-T6 sheet in air and seawater, $R = 0.0$. Source: Ref 4

 **LIVE GRAPH**
Click here to view

The relatively good performance of the 5182-O and 6009-T4 may be the best indicators of alloy choices for severe environments; both of these alloys and tempers appear to have fatigue strengths at 10^7 cycles at or above 10 ksi (70 MPa).

Only 2014-T6 and 6061-T6 were tested in 3.5% intermittent salt spray with notched specimens; these two experienced significant reduction in fatigue life, only mildly less than for smooth specimens. Apparently, even the severe notch ($K_t = 12$) did not override the salt-spray effect.

Other published work supports the negative effects of environments like seawater on the fatigue performance of aluminum alloys, especially those of the high-strength 2xxx and 7xxx series, as illustrated in Fig. 9.1 (Ref 4). Unlike the case with sustained-load stress-corrosion cracking, which is usually limited to the short-transverse direction, fatigue degradation by environment occurs even in the longitudinal and long-transverse directions.

The corrosion fatigue performance of high-strength 7xxx alloys may, in general, be upgraded by overaging to more corrosion-

resistant T7 tempers (Ref 4–10). With 2xxx alloys, more corrosion-resistant, precipitation-hardened T8-type tempers provide a better combination of strength and fatigue resistance at high endurance times than naturally aged T3 and T4 tempers. However, artificial aging of 2xxx alloys is accompanied by loss in toughness with resultant decrease in fatigue crack growth resistance at intermediate and high stress intensities (Ref 2, 4).

Less degradation from environmental factors is expected in the 1xxx, 3xxx, 5xxx, and 6xxx series. Another illustration is provided in Fig. 9.2 (Ref 4).

Fatigue response to environmental factors varies with environment and with alloy and temper. Therefore, final alloy selection for any specific design should be based on data obtained with all of the anticipated factors present. Because environmental interaction with fatigue is a rate-controlled process, interaction of time-dependent fatigue parameters, such as frequency, waveform, and load history, should be factored into the fatigue analysis (Ref 5, 11, 12).

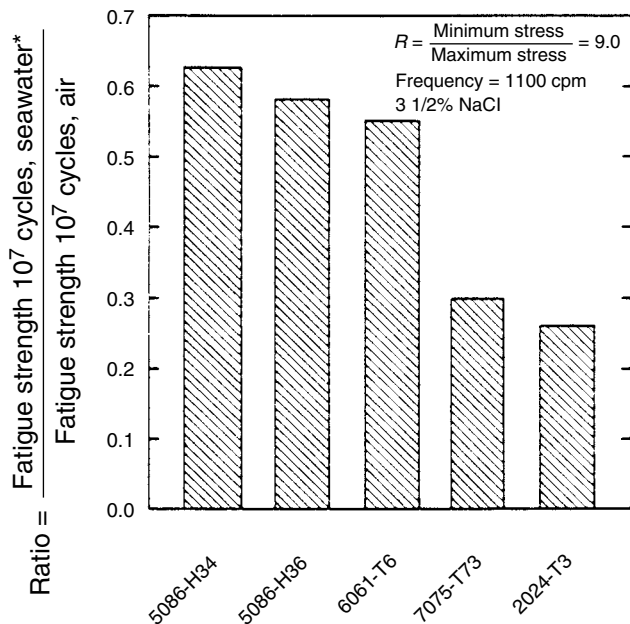


Fig. 9.2 Comparison of axial-stress fatigue strengths of 0.032 in. (0.813 mm) aluminum alloy sheet in air and seawater, $R = 0.0$. Source: Ref 4

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CHAPTER 10

Effect of Stress Concentrations,
Primarily Sharp Notches

THE EFFECT OF ABRUPT CHANGES in the surface geometry of an aluminum component, simulated by notched specimens, is analyzed in this chapter. Fatigue failures almost always are initiated at such geometric discontinuities, thus making the latter a subject of great interest.

10.1 Notch Severity

As one would expect, an increase in notch severity as defined by notch root radius or by theoretical stress-concentration factor, K_t , reduces fatigue strengths throughout the life range; fatigue strengths or endurance limits decrease with increase in notch severity.

This is illustrated by representative sets of data for several aluminum alloys in Table 10.1; in each of these cases, fatigue strengths were determined with two or three different notch severities. Fatigue strength reduction factors were calculated and included in Table 10.1 as the percent reduction in fatigue strength for each design of notch from the smooth-specimen fatigue strength. For this purpose, either the endurance limit (EL) at

5×10^8 cycles was used or, if that value was not sufficiently well defined, the fatigue strength (FS) at 10^7 cycles was used as the basis of the comparisons. The results are also plotted in Fig. 10.1 as EL or FS as a function of the theoretical stress-concentration factor, K_t (Ref 1).

It is clear from a plot of these data that as stress-concentration severity begins to increase, say from $K_t = 1$ to 3, the amount of reduction in fatigue strength, however defined, is steep. On a Cartesian plot such as Fig. 10.1, fatigue strength then levels off to nearly asymptotically approach some lower level with further increase in K_t . On a logarithmic plot, as in Fig. 10.2, fatigue strengths appear to continue to drop, but beyond K_t of 12 to 20, the precision and sensitivity (ergo, usefulness) of this number diminishes.

Data for 7046-T63 plate in Fig. 7046.RB01 illustrate that for some alloys, perhaps particularly high-strength alloys, notch severities of $K_t = 3$ are enough to reduce fatigue strengths as much as do more severe notches, $K_t = > 12$. The notch endurance limit at $K_t = 3$ was approximately 11 to 12 ksi (76 to 83 MPa), about 50% of that for smooth specimens, and there was little, if any, further degradation in going to $K_t = > 12$.

Table 10.1 Fatigue strength reduction factor (FSRF) as a function of notch severity (K_t)

		Fatigue strength (FS) or endurance limit (EL) with FSRF at indicated theoretical notch severity, K_t (b)										
		$K_t = 1$		$K_t = 3$			$K_t = 4.4$			$K_t > 12$		
Alloy and temper	Figure No.(a)	ksi	MPa	ksi	MPa	FSRF(c), %	ksi	MPa	FSRF(c), %	ksi	MPa	FSRF(c), %
Room temperature												
2014-T6	2014.AS09–AS11	17 (EL)	117 (EL)	12.5 (EL)	86.2 (EL)	–26	...	...	...	5 (EL)	34.5 (EL)	–71
2219-T87	2219.AS18–AS20	24 (EL)	165 (EL)	...	...	...	9.5 (EL)	65.5 (EL)	–60	7.5 (EL)	51.7 (EL)	–69
2020-T651	2020.AS02–AS04	31 (EL)	214 (EL)	...	...	...	10.5 (EL)	72.4 (EL)	–66	9 (EL)	62.1 (EL)	–71
2024-T851	2024.AS12–AS14	26 (FS)	179 (FS)	...	...	...	9.5 (FS)	65.5 (FS)	–63	6.5 (FS)	44.8 (FS)	–75
2025-T6	2025.RB07	16 (EL)	110 (EL)	9.5 (EL)	65.5 (EL)	–41	...	...	...	7.5 (EL)	51.7 (EL)	–53
7075-T651	7075.AS14–AS16	36 (FS)	248 (FS)	14 (FS)	96.5 (FS)	–61	...	...	...	11 (FS)	75.8 (FS)	–69
7075-T7351	7075.AS25–AS27	37 (FS)	255 (FS)	12.5 (FS)	86.2 (FS)	–66	...	...	...	8.5 (FS)	58.6 (FS)	–77
7175-T66	7175.AS01–AS03	39 (FS)	269 (FS)	11.5 (FS)	79.3 (FS)	–71	...	...	...	12 (FS)	82.7 (FS)	–69
7178-T76510	7178.AS20–AS25	34 (FS)	234 (FS)	12 (FS)	82.7 (FS)	–65	...	...	...	9 (FS)	62.1 (FS)	–74
7178-T76510(d)	7178.AS20–AS25	21 (FS)	145 (FS)	6.5 (FS)	44.8 (FS)	–69	...	...	...	6 (FS)	41.4 (FS)	–71
300 °F (150 °C)												
2219-T87	2219.AS21-AS23	18 (EL)	124 (EL)	...	...	...	7 (EL)	48 (EL)	–61	6.5 (EL)	48.8(EL)	–64
2024-T851	2024.AS15-AS17	20 (EL)	138 (EL)	...	...	...	8 (EL)	55 (EL)	–60	5 (EL)	34.5 (EL)	–75

Note: K_t is theoretical stress-concentration factor at root of notch, in accordance with Neuber. Source: Ref 1. (a) Fatigue loading indicated by figure code. AS, axial; RB, rotating beam. For this set of data, $R = -1.0$ for RB, and $R = 0.0$ for all these AS values. (b) EL at 5×10^8 cycles, FS at 10^7 cycles. (c) FSRF, percent reduction at specific K_t from value at $K_t = 1$ (smooth specimen). (d) Specimens direction is short transverse; all others are longitudinal.

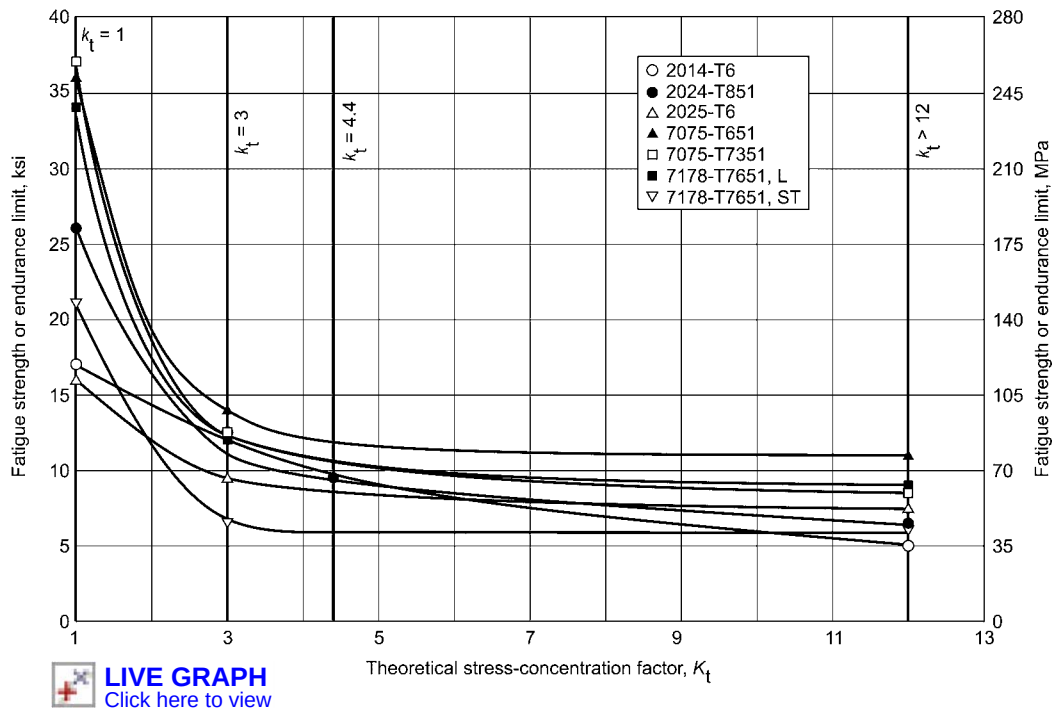


Fig. 10.1 Cartesian plot of notch fatigue strength as a function of theoretical stress-concentration factor for selected 2xxx- and 7xxx-series aluminum wrought alloys. L, long; ST, short transverse

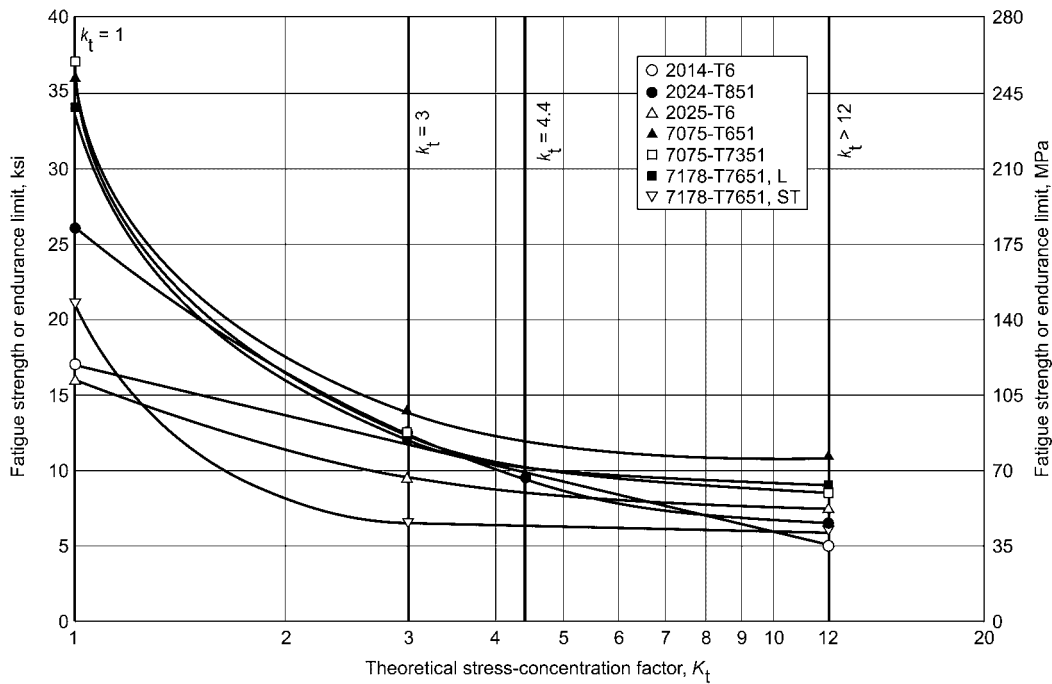


Fig. 10.2 Semi-log plot of notch fatigue strength as a function of theoretical stress-concentration factor. L, long; ST, short transverse

10.2 Notches and Strain-Hardening Wrought Alloys

Differences in the effect of strain hardening on fatigue notch sensitivity are illustrated by reviewing rotating-bending ($R = -1.0$) data for a variety of alloys in Table 10.2.

From these data, and given the precision of defining endurance limits (± 1 ksi, or 7 MPa), it appears that the impact of stress concentrators on endurance limit remains approximately the same regardless of the amount of strain hardening given non-heat-treatable alloys 3003 and 3004. The possible exception is for extremely highly strain-hardened material (H19, H39), for which the detrimental effect may be larger.

Table 10.2 Sharp-notch endurance limit (EL) at 5×10^8 cycles for wrought strain-hardenable aluminum alloys ($R = -1.0$)

Alloy and temper	Figure No.	EL, smooth $K_t = 1$		EL, notched $K_t \geq 12$		Fatigue strength reduction factor(a), %
		ksi	MPa	ksi	MPa	
3003-O	3003.RB01	6.0	41.4	3.0	20.7	-50
3003-H14	3003.RB02	8.0	55.2	5.0	34.5	-38
3003-H18	3003.RB04	8.0	55.2	4.0	27.6	-50
3004-O	3004.RB01	14.5	100	6.5	44.8	-54
3004-H14	3004.RB02	16.5	114	8.5	58.6	-48
3004-H18	3004.RB03	19.5	134	11.0	75.8	-44
3004-H19	3004.RB04	18.5	128	6.5	44.8	-65
3004-H34	3004.RB05	17.5	121	9.0	62.1	-49
3004-H38	3004.RB06	18.5	128	8.0	55.2	-57
3004-H39	3004.RB07	18.5	128	7.5	51.7	-60
5005-H14	5005.RB01	12.0	82.7	3.5	24.1	-71
5005-H18	5005.RB01	14.0	96.5	2.0	13.8	-86
5005-H19	5005.RB02	14.0	96.5	3.0	20.7	-79
5050-O	5050.RB01	12.5	86.2	5.0	34.5	-52
5050-H34	5050.RB02	16.0	110	7.0	48.3	-56
5050-H38	5050.RB03	18.0	124	7.0	48.3	-61
5052-O	5052.RB01	15.5	107	6.5	44.8	-61
5052-H14	5052.RB02	18.5	127	10.0	68.9	-46
5052-H16	5052.RB03	18.0	124	6.0	41.4	-67
5052-H18	5052.RB04	20.5	141	8.0	55.2	-61
5052-H34	5052.RB06	18.0	124	9.0	62.1	-50
5052-H36	5052.RB07	20.0	138	3.5	24.1	-82
5052-H38	5052.RB08	21.0	145	7.5	51.7	-64

(a) Percent reduction at specific K_t from value at $K_t = 1.0$ (smooth specimen)

For the higher-strength 5xxx alloys, such as 5005, 5050, and 5052, the decreases associated with severe notches are greater, as may be expected, and they show stronger evidence of more severe reductions in fatigue strength as the amount of strain hardening increases. There are noticeable deviations from this pattern, however, with the notch fatigue strengths of 5052-H14 being the largest apparent outliers.

10.3 Notches and Solution Heat Treating and Precipitation Aging Wrought Alloys

Data contained in Table 10.3 and Fig. 10.1 permit some judgments about the effects of heat treatment and precipitation aging on the notch fatigue performance of aluminum alloys.

First, by comparison of the fatigue strength reduction factors for heat treated aluminum alloys in Table 10.3 with those for strain-hardened alloys in Table 10.2, it seems that the reductions with the very sharp notches for the heat treated alloys are as large as or larger than most of those for strain-hardened alloys, except for those with the greatest amounts of cold work. As would be expected, high-strength heat treated alloys are more susceptible to notch fatigue strength reduction than are annealed or lightly strain-hardened alloys.

The second observation possible from Table 10.3 and Fig. 10.1 addresses the effect of natural aging (T3, T4) and precipitation aging past the peak strength, as in a comparison of the notch effects for 7075 in the T651 (peak strength aged) and T7351 (aged past peak, i.e., overaged for improved stress-corrosion resistance)

temper. The general trends are quite similar for almost all of the heat treated tempers, and based on these limited data and the precision of the EL values, it is difficult to assign any significance to the small differences observed.

10.4 Notches in the Surface of Clad Sheet

To study the effect of notches in the surface of Alclad 7075-T6 sheet, tests were made of standard sheet and sheet with sharp (0.0002 in., or 0.005 mm, V-shaped, $K_t = 19$) notches into approximately the full depth of the cladding. As illustrated in Fig. 7075.FL09, there was a negative effect of such notches, with fatigue lives approximately one-half those of unnotched specimens, but the difference in endurance limits appears to be only 1 to 2 ksi (7 to 14 MPa).

10.5 Notches in Casting Alloys

In order to assist in assessing the relative notch sensitivities of the casting alloys in fatigue, the fatigue strength reduction factors (FSRF, the percentage reduction in fatigue strength) for all casting alloys for which both smooth and sharply notched ($K_t > 12$) data are available, are summarized by casting process in Table 10.4.

Although the analysis is not very systematic, because of the variable number of alloys of different composition and process types tested, some interesting trends appear when the broad averages in Table 10.4 are reviewed. Looking at the results by process,

Table 10.3 Sharp-notch endurance limit (EL) at 5×10^8 cycles for heat treated aluminum alloys ($R = -1.0$)

Alloy and temper	Figure No.	EL, smooth $K_t = 1$		EL, notched $K_t \geq 12$		Fatigue strength reduction factor(a), %
		ksi	MPa	ksi	MPa	
2014-O	2014.RB01	10.5	72.4	6.0	41.4	-43
2014-T4	2014.RB02	15.0	103	8.5	58.6	-43
2014-T6	2014.RB07	18.0	124	7.5	51.7	-58
2219-T31	2219.RB05	14.0	96.5	5.0	34.5	-64
2219-T62	2219.RB11	15.5	107	5.0	34.5	-68
2219-T851	2219.RB17	15.0	103	5.5	37.9	-63
2024-O	2024.RB01	12.0	82.7	4.0	27.6	-67
2024-T3	2024.RB02, RB03	17.0	117	6.0	41.4	-65
2024-T4	2024.RB06	20.0	138	7.5	51.7	-63
2024-T6	2024.RB12	23.5	162	10.0	68.9	-57
2024-T81	2024.RB16	17.5	121	6.0	41.4	-66
2024-T84	2024.RB21	18.0	124	7.0	48.3	-61
2024-T86	2024.RB23	18.5	128	6.0	41.4	-68
7075-T6	7075.RB01	22.5	155	9.0	62.1	-60
7075-T73	7075.RB16	19.0	131	6.5	44.8	-66
7075-T76	7075.RB17	20.5	141	6.5	44.8	-68

(a) Percent reduction at specific K_t from value at $K_t = 1.0$ (smooth specimen)**Table 10.4 Sharp-notch endurance limits (EL) at 5×10^8 cycles for some aluminum casting alloys ($R = -1.0$)**

Alloy and temper	Figure No.	EL at 5×10^8 cycles		Fatigue strength reduction factor(a), %
		Smooth, $K_t = 1$	Notched, $K_t > 12$	
Sand casting (SC)				
213.0-F	213.RB02	10.0	7.5	−25
224.0-T62	224.RB01	12.5	7.5	−40
240.0-F	240.RB01, RB02	18.0	10.0	−44
242.0-O	242.RB01	13.5	10.0	−26
242.0-T571	242.RB04	12.0	9.0	−25
242.0-T75	242.RB08	9.5	5.5	−42
242.0-T77	242.RB09, RB11	11.0	7.5	−32
249.0-T63	249.RB01	10.0	6.0	−40
308.0-F	308.RB02	12.0	7.0	−42
319.0-F	319.RB01	12.0	9.0	−25
319.0-T5	319.RB02	11.5	8.0	−30
319.0-T6	319.RB03	13.0	10.5	−19
319.0-T71	319.RB04	10.5	8.5	−19
355.0-T51	355.RB02	10.0	6.0	−40
355.0-T61	355.RB07	9.5	7.5	−21
355.0-T7	355.RB12	10.5	7.0	−33
355.0-T71	355.RB13, RB14	10.5	7.0	−33
356.0-T51	356.RB01, RB03	10.0	7.0	−30
356.0-T6	356.RB07–RB09	10.5	7.5	−29
356.0-T71	356.RB12, RB13	8.0	7.0	−13
B443.0-F	B443.RB02	8.5	5.5	−35
712.0-F	712.RB01	10.0	7.0	−30
A712.0-F	A712.RB02	9.5	6.5	−32
852.0-T5	852.RB02	10.0	6.0	−40
SC average		10.9	7.5	−31
Permanent mold casting (PM)				
213.0-F	213.RB01	21.0	10.0	−52
242.0-T571	242.RB02, RB03	15.5	8.0	−48
242.0-T61	242.RB07	14.0	6.5	−54
296.0-T6	296.RB01	12.5	9.0	−28
296.0-T7	296.RB02	9.5	6.5	−32
308.0-F	308.RB01	13.5	8.0	−41
332.0-T5	332.RB01	14.0	8.0	−43
333.0-O	333.RB01, RB02	13.0	7.5	−42
333.0-T6	333.RB01, RB02	15.0	10.0	−33
333.0-T7	333.RB05	13.0	8.0	−38
336.0-T551	336.RB01	14.0	8.0	−43
A344.0-T4	A344.RB01	9.0	4.0	−56
354.0-T61	354.RB01, RB02	17.0	11.0	−35
355.0-T51	355.RB01	13.0	7.5	−42

(continued)

(a) Percent reduction at specific K_t from value at $K_t = 1.0$ (smooth specimen)

Table 10.4 (continued)

Alloy and temper	Figure No.	EL at 5×10^8 cycles		Fatigue strength reduction factor(a), %
		Smooth, $K_t = 1$	Notched, $K_t > 12$	
355.0-T6	355.RB03–RB06	10.0	8.0	–20
355.0-T62	355.RB08–RB10	13.0	6.5	–50
355.0-T7	355.RB11	13.0	8.5	–35
355.0-T71	355.RB15, RB16	11.5	7.5	–35
C355.0-T61	C355.RB02	12.5	10.0	–20
356.0-T6	356.RB05	12.5	8.0	–36
356.0-T7	356.RB11	11.0	5.0	–55
A356.0-T6	A356.RB01	13.5	7.5	–44
A357.0-T61	A357.RB01	13.0	7.0	–46
A357.0-T62	A357.RB02	12.0	6.0	–50
359.0-T61	359.RB01	15.5	11.0	–29
359.0-T62	359.RB02	15.0	9.0	–40
B443.0-F	B443.RB01	7.5	4.0	–47
C712.0-F	C712.RB01	11.0	7.0	–36
852.0-T5	852.RB01	11.0	5.0	–55
PM average		13.0	7.7	–41
Plaster casting (PC)				
355.0-T62	355.RB10	15.0	8.0	–47
356.0-T6	356.RB04	12.5	8.5	–32
356.0-T61	356.RB10	13.0	7.5	–42
A356.0-T61	A356.RB03, RB04	12.0	8.0	–33
PC Average		13.1	8.0	–39
Premium-quality permanent mold				
A356.0-T6	A356.RB02	10.0	8.0	–20
Die casting (DC)				
380.0-F	380.RB01	21.5	7.5	–65
390.0-F	390.RB01	19.0	10.0	–47
413.0-F	413.RB02	13.5	6.0	–56
518.0-F	518.RB01, RB02	17.0	6.0	–65
DC average		17.8	7.4	–58
Axial stress, $R = 0.0$				
355.0-T6 (SC)	355.AS02, AS07	10.0	8.0	–20
380.0-F (DC)	380.AS01, AS02	19.0	5.0	–74
518.0-F (DC)	518.AS01, AS02	22.0	7.0	–68

(a) Percent reduction at specific K_t from value at $K_t = 1.0$ (smooth specimen)

independent of the individual alloys, the following is found, especially among the rotating-bending data:

- The smooth-specimen fatigue strengths of the permanent mold (PM) and plaster cast (PC) castings average approximately 2 ksi (14 MPa) higher than those of sand castings (SC). Die castings (DC) have the highest fatigue strengths, averaging approximately 4 ksi (28 MPa) higher than the PM or PC castings. As noted earlier, this may be related to higher residual compressive stresses on the surface of die castings resulting from the cast-to-size technology, but that is speculation; there are no data to confirm that.
- Notch fatigue strengths from the sharply notched ($K_t > 12$) specimens are approximately the same for all types of castings.
- The result of the previous two observations is that the DC appear most notch-sensitive, with a fatigue strength reduction factor (FSRF) of near 60%, while the SC appear least sensitive, with an FSRF of approximately 30%. It is important to note, however, that this difference relates more to the variation in smooth-specimen strength than to the notched-specimen strength.
- Among the individual alloys, 240.0-F, 242.0-O, and 319.0-T6 stand out for sand castings; 213.0-F, 333.0-T6, 354.0-T61, and C355.0-T61 stand out for the permanent mold castings;

and 390.0-F stands out for the die castings, all having sharp-notch fatigue strengths of 10 ksi (70 MPa) or more.

The very sharp ($K_t > 12$) notch levels of almost all of the casting alloys, together with the trends noted with notch severity in Table 10.1, suggest to the author that this very severe stress concentrator ($K_t > 12$) may not be the best choice for screening alloys for sensitivity to stress raisers in fatigue. This is not an easy judgment, because this sharp notch is extremely useful in static toughness testing, and the ratio of notch tensile strength to tensile yield strength is directly correlated with fracture toughness (Ref 2). Unfortunately, there are no fatigue data available for castings based on any other less severe stress raiser.

REFERENCES

1. H. Neuber, *Theory of Notch Stresses; Principles for Exact Stress Calculation*, Springer Press, Berlin, 1945, English translation by F.A. Raven, David Taylor Model Basin, published by J.D. Edwards, Ann Arbor, MI, 1946
2. J.T. Staley, W.G. Truckner, R.J. Bucci, and A.B. Thakker, Improving Fatigue Resistance of Aluminum Aircraft Alloys, *Aluminum*, Vol 53, 1977, p 667–669

APPENDIX 1

The Aluminum Association Alloy and Temper Designation Systems

THE ALUMINUM ASSOCIATION Alloy and Temper Designation System is recognized by the American National Standards Institute (ANSI) as the U.S. national standard and is incorporated into ANSI standards H35.1 and H35.2. The maintenance of the system is managed by the Aluminum Association, Inc., under the ANSI charter. In addition, there is an international accord recognizing the Aluminum Association wrought alloy designation system as the de facto international standard; this accord has been ratified by almost all aluminum-producing countries.

The alloy designation system is briefly described as follows, first for wrought alloys and then for cast alloys, and these explanations are followed by a brief description of the temper designation system. More detailed information on The Aluminum Association Alloy and Temper Designation System may be gained from study of Section 1.0 of the Aluminum Association publication, *Aluminum Standards and Data*.

The alloy designation system for wrought alloys includes the following conventions and designations:

First digit	Principal alloying constituent(s)
Second digit	Variations of initial alloy
Third and fourth digits	Individual alloy variations (number has no significance but is unique)
1xxx	Pure Al (99.00% or greater)
2xxx	Al-Cu Alloys
3xxx	Al-Mn Alloys
4xxx	Al-Si Alloys
5xxx	Al-Mg Alloys
6xxx	Al-Mg-Si Alloys
7xxx	Al-Zn Alloys
8xxx	Al + other elements
9xxx	Unused series

The alloy designation system for cast alloys includes the following conventions and designations:

First digit	Principal alloying constituent(s)
Second and third digit	Specific alloy designation (number has no significance but is unique)
Fourth digit	Casting (0) or ingot (1, 2) designation
Variations	Indicated by preceding letter (A, B, C)
1xxx	Pure Al (99.00% or greater)
2xxx	Al-Cu Alloys
3xxx	Al-Si + Cu and/or Mg
4xxx	Al-Si Alloys
5xxx	Al-Mg Alloys
7xxx	Al-Zn Alloys
8xxx	Al-Sn Alloys
9xxx	Al + other elements
6xxx	Unused series

The temper designation system includes the following definitions and conventions:

F	As-fabricated
O	Annealed
H	Strain hardened (wrought products only)
W	Solution heat treated
T	Thermally treated to produce tempers other than F, O, H (usually solution heat treated, quenched, and precipitation hardened)
Numeric additions	Indicate specific variations (e.g., T6 = solution heat treated and precipitation hardened)

APPENDIX 2

Metrication of Aluminum Properties

THE DATA PRESENTED in this book were generated using the engineering/English system of measurement and units.

To present the information in the most useful manner, the conventional engineering/English units are generally cited first, followed by metric conversions in the style of the International System of Units (SI).

The procedures used to produce the metricated values require description for several reasons. In general, the procedures parallel the aluminum industry standard of using rounded values where appropriate. These rounded figures reflect those that may be used in a metric environment. The aluminum industry standard procedure is documented in Appendix A of Ref 1, and the differences are also reflected in Ref 2 and 3. Some exceptions to the standard procedures were used in this publication when the type of data being presented did not reflect the pattern assumed when the procedure was established.

General Procedures

Product Dimensions. Where aluminum alloy product thickness ranges are cited, the conversions represent the standard metric size ranges in Ref 3, which were determined originally with the procedures described in Ref 1. Thus, the metric thickness ranges are not odd numbers but rounded sizes likely to be used in a metric environment. They also reflect the sizes used by the aluminum industry to fill metric orders.

Specimen Dimensions. Because the intent while describing test procedures is to be precise, specimen dimensions are generally exact metric conversions. Gage lengths are reported as the metric standard.

Stresses/Strengths. Values of stress and strength have been converted to metric units with regular conversion factors (1 MPa = 6.897 ksi) then rounded in accordance with the following patterns:

- For all stresses above 10 ksi, metric stress/strength values have been rounded to the nearest 5 MPa, which is the standard aluminum industry practice (Ref 1).
- For stress/strength below 10 ksi, the metric values have been rounded to the nearest whole MPa. This practice best represents the trend in properties with respect to time and temperature at the very high temperatures for which such low stress values are generally observed.

Elongation Values. Only the values determined in accordance with U.S. test standards are included. For round specimens, gage length is four times the diameter (4D); for sheet-type specimens, gage length is 2 in. (50 mm); for wire, gage length is 10 in. (25 cm). Metric (SI) standards call for 5D gage lengths; however, because standard conversions do not exist, they are not provided. Estimates of 5D gage length elongation can be made using the Aluminum Association (Ref 2) guidelines as follows:

If elongation in 4D is:	For 5D, reduce value by the following:
≥24%	3
12–23%	2
5–11%	1
> 1 ≤ 4%	0.5–1
≤1%	0

Temperature. Values of test/exposure temperature in degrees Fahrenheit (°F) when converted to degrees Celsius (°C) have generally been rounded to the nearest 5 °C in accordance with the standard aluminum industry practice. However, the following exceptions were made. Since for subzero temperatures, the original tests were made using specific engineering fluids (generally liquefied gases) at well-defined temperatures; the scientifically determined temperatures for those fluids are used, such as the following:

- Liquid helium: –452 °F or –269 °C
- Liquid hydrogen: –423 °F or –253 °C
- Liquid nitrogen: –320 °F or –196 °C
- Liquid petroleum gas: –112 °F or –80 °C
- Liquid ethyl and dry ice: –18 °F or –28 °C

For elevated temperatures used to describe fabricating practices where rounded values may distort the actual test results, the near exact conversions have been used:

- 350 °F has been converted to 177 °C
- 420 °F has been converted to 215 °C

REFERENCES

1. *Tan Sheets—Tempers for Aluminum and Aluminum Alloy Products—Metric*, The Aluminum Association, Nov 2005

2. *Aluminum Standards and Data*, The Aluminum Association, 2006

3. *Aluminum Standards and Data—Metric SI*, The Aluminum Association, 2006

APPENDIX 3

Glossary

cast aluminum alloys. Alloys used primarily for casting directly to finished or near-finished shape without mechanical working.

casting processes. There are many variations of each of the following processes, but these are the categories used in presenting the aluminum alloy data:

- Sand cast (SC)—cast by gravity flow in nonpermanent sand molds
- Permanent mold cast (PM)—cast by gravity flow in hard alloy reusable molds
- Die cast (DC)—cast by pressure injection into hard alloy reusable molds
- Plaster cast (PC)—cast by gravity or pressure into high-quality smooth plaster dies
- Premium quality (PCP)—cast by any of the aforementioned processes but usually in permanent molds with high-strength alloys in accordance with AMS-A-21180 plus special quality-control practices to ensure good internal soundness

endurance limit (EL). The fatigue stress that may be applied an unlimited number of repetitions without causing failure; defined in the aluminum industry as the fatigue strength at 500,000,000 (5×10^8) cycles.

fatigue strength (FS). The maximum stress associated with a specific number of repetitions of applied stress, for example, fatigue strength at 10^5 cycles.

fatigue strength reduction factor (FSRF). The percent reduction in fatigue strength at a specific number of cycles or in endurance limit caused by tests of specimens containing stress-concentrating notches.

hash level, ultrasonic. Ultrasonic hash level is a reference to the vibration-like ultrasonic scan seen on the detector screen when various levels of microstructural soundness are being reflected from the alloy being analyzed. High hash levels are associated with greater porosity and/or microstructural discontinuities.

modified Goodman diagram (GD). A Cartesian scale plot, generally with maximum stress in a cycle on the ordinate and the minimum stress on the abscissa. Lines of common life are then drawn, enabling life estimates at all stress ratios.

S-N curve. A plot of stress (S) versus the number of cycles to failure (N). Generally, S is plotted on a linear scale, while N is plotted on a logarithmic scale. The stress can be the maximum stress, with the stress ratio, R , given (as in this book); however, the mean stress may be plotted as well.

specimen directions. The direction that a test specimen is oriented relative to the processing direction.

- Longitudinal (L)—parallel to the principal grain flow of the material
- Long transverse (LT)—normal to but in the principal plane of the grain flow
- Short transverse (ST)—through the thickness or normal to the principal plane of the grain flow

stress ratio (R). The ratio of the minimum stress in a cycle of fatigue loading to the maximum stress in that cycle. A stress ratio of -1.0 means that in each cycle, the stress goes from some value in compression to the same value in tension. A stress ratio of $-\infty$ means the loading goes from some value in compression to zero. A stress ratio of 0 (zero) means the loading goes from zero to some value in tension.

theoretical stress-concentration factor (K_t). An estimate, according to Neuber (Ref 1), of the magnitude of concentration at the root of a notch; that is, a K_t of 3 means the theoretical increase in stress at the tip of the notch is three times that in an unnotched or smooth specimen.

wrought aluminum alloys. Alloys used for producing mill products such as sheet, plate, forgings, and rolled or extruded shapes; alloys wrought by working ingot or billet.

REFERENCE

1. H. Neuber, *Theory of Notch Stresses; Principles for Exact Stress Calculation*, Springer Press, Berlin, 1945; English translation by F.A. Raven, David Taylor Model Basin, published by J.D. Edwards, Ann Arbor, MI, 1946

APPENDIX 4

Abbreviations and Symbols

A	area	GT	index for modified Goodman diagrams at elevated temperature
AA	Aluminum Association		
AFS	American Foundry Society		
AMS	Aerospace Material Specification		
ANSI	American National Standards Institute	H	strain-hardened temper designation; numbers after letter “H” represent the nominal (not actual) amount of cold work and whether or not the material has been stabilized or partially annealed after cold working
AS	index for axial-stress fatigue curves at room, subzero, and elevated temperatures	HB	Brinell hardness number
ASM	short version of ASM International (formerly the American Society for Metals)	HIP	hot isostatic pressing
ASME	American Society of Mechanical Engineers	HT	index for rotating-beam bending fatigue data at elevated temperature
ASTM	short version of ASTM International (formerly American Society for Testing and Materials)		
AWS	American Welding Society		
CHT	continuous heat treatment process	I	moment of inertia
cpm	cycles per minute		
CTE	coefficient of thermal expansion	K_c	plane-stress fracture toughness; critical value of plane-stress-intensity factor
da/dt	crack growth rate (time derivative of crack length)	K_I	(applied) plane-strain stress-intensity factor
DC	die casting	K_{Ic}	plane-strain fracture toughness; critical value of plane-strain-intensity factor
E	modulus of elasticity	K_t	theoretical stress-intensity factor
EL	endurance limit	ksi	units of stress in kilopounds per square inch; 1000 psi
F	temper of wrought or cast aluminum designating the as-fabricated condition	L	longitudinal test specimen; major axis of specimen is parallel to the principal grain flow of the material
FCGR	fatigue crack growth rate	LT	long-transverse test specimen; major axis of specimen is normal to but in plane of the principal grain flow of the material
FL	index for flexural fatigue data at room temperature		
FS	fatigue strength		
FSRF	fatigue strength reduction factor = notch fatigue strength divided by smooth-specimen fatigue strength; generally calculated at the endurance limit	M	moment
		MPa	units of stress in megapascals; 1 MPa = 6.897 × ksi
GD	index for modified Goodman diagrams at room temperature	NADCA	North American Die Casting Association
GMAW	gas metal arc welding	NTS	notch tensile strength
gr/mm³	grains per cubic millimeter; a measure of grain count, thus grain size	NYR	notch-yield ratio = notch tensile strength (NTS) divided by tensile yield strength (TYS)

O	annealed temper designation	SS ST	(supersaturated) solid solution short-transverse test specimen; major axis of specimen is normal to the plane of the principal grain flow of the material; for sheet material, it is the direction of the thickness
PC PCP	plaster cast premium-quality casting; usually cast in permanent molds		
PM	permanent mold	T4, T4x, T4xx	temper designations for solution heat treat and quench
R	cyclic stress ratio of minimum to maximum stress	T5, T5x, T5xx	temper designations for artificial aging from as-extruded condition
RB RT	index for reverse-bending rotating-beam data room temperature	T6, T6x, T6xx T7, T7x, T7xx	temper designations for solution heat treat, quench, and artificial aging temper designations for solution heat treat, quench, and overage
SC SCC	sand casting stress-corrosion cracking	TMS TYS	The Minerals, Metals and Materials Society tensile yield strength

APPENDIX 5

Tabular Summaries of Fatigue Strengths

ROTATING-BEAM FATIGUE data tests were made of R.R. Moore specimens (Fig. A5.1) in R.R. Moore rotating-beam fatigue machines in accordance with ASTM test methods in existence at the time. Stresses were completely reversed in bending (stress ratio, R , was -1.0). The tests were made over the period from about 1950 through about 1985. Test speeds ranged from about 3500 to 10,000 rpm (no speed of testing effect was ever noted over this range).

In general, each fatigue curve was generated from tests of 10 to 15 specimens, and bands for specific alloys, temper, and products were developed with specimens representing several different material samples (i.e., different production lots and composition). A number of these specimens were used to identify the highest stress that would not cause failure in 500 million cycles which

was identified as the endurance limit. An average fatigue curve was drawn through the completed data set, and the table entries are the intersections of the average line with the respective cyclic lives. There was no atmospheric control in the testing laboratories.

Rotating-beam fatigue strengths are shown in Table A5.1 for wrought aluminum alloys and Table A5.2 for cast aluminum alloys. The metric/SI units shown in the tables were calculated by multiplying the fatigue strength values measured in engineering units by the conversion factor of $1 \text{ MPa} = 6.897 \text{ ksi}$, and then rounded by the aluminum industry standard to the nearest 5 MPa, except in the case of values less than 10 ksi, for which the converted value was not rounded.

The alloys are presented in Table A5.1 in numeric order.

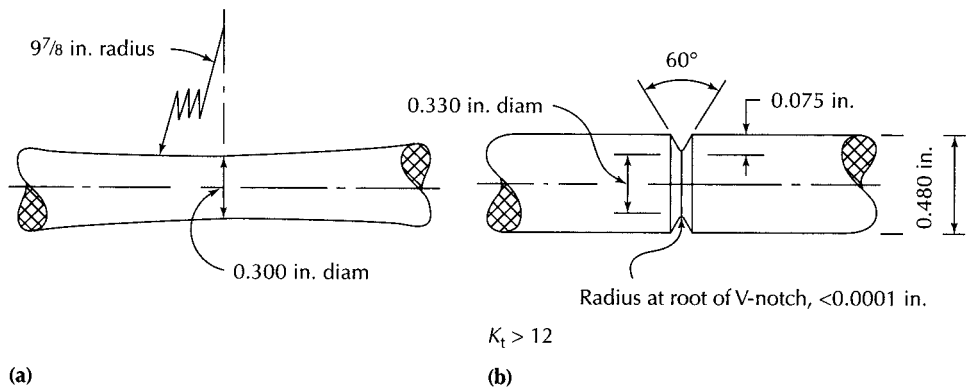


Fig. A5.1 (a) Smooth and (b) notched R.R. Moore rotating-beam specimens

Table A5.1 Rotating-beam reversed-bending fatigue strengths of wrought alloys at room temperature

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Wrought alloys																
1100 smooth specimens																
O	Rolled rod and shapes	4	...	...	...	...	8	55	6.5	45	5.5	38	5	34	5	34
H14	Rolled rod and shapes	1	...	...	...	...	13	90	10	70	9	62	8	55	7	48
H16	Rolled rod and shapes	2	...	...	19	130	14	95	11.5	80	10	70	9	62	8	55
H18	Rolled rod and shapes	2	...	...	22	150	16.5	115	13.5	95	11	75	10	70	9	62
H26	Rolled rod and shapes	1	...	...	19	130	14	95	11.5	80	10	70	9	62	8	55
1100 notched specimens(a)																
H16	Rolled rod and shapes	1	...	...	18	125	13	90	8	55	5.5	38	4	28	4	28
H18	Rolled rod and shapes	2	...	...	18	125	13	90	8	55	5.5	38	4	28	4	28
H26	Rolled rod and shapes	1	...	...	18	125	13	90	8	55	5.5	38	4	28	4	28
1160 smooth specimens																
H12	Rolled rod and shapes	1	...	...	11	75	8	55	6.5	45	5.5	38	4.5	31	4	28
H18	Rolled rod and shapes	1	...	...	19	130	13	90	10	70	8.5	59	7	48	6.5	45
1160 notched specimens(a)																
H12	Rolled rod and shapes	1	...	...	11	75	7.5	52	5.5	38	4.5	31	3.5	24	3	21
H18	Rolled rod and shapes	1	...	...	18	125	11	75	7	48	5	34	4	28	3	21
1350 smooth specimens																
H12	Rolled rod and shapes, wire	3	...	...	16	110	12.5	85	10	70	8	55	6.5	45	6	41
H19	Rolled rod and shapes	1	...	...	22.5	155	16	110	12.5	85	10	70	8	55	7	48
1350 notched specimens(a)																
H12	Rolled rod and shapes	1	...	...	10	70	7	48	4	28	3	21	2.5	17	2	14
H19	Rolled rod and shapes	1	...	...	...	...	14	95	7.5	52	4	28	3	21	3	21
2011 smooth specimens																
T3	Rolled rod and shapes	2	...	...	46	315	35	240	26.5	185	22.5	155	19.5	135	18	125
T6	Rolled rod and shapes	2	...	...	50	345	39	270	30	205	23.5	160	20	140	18	125
T8	Rolled rod and shapes	2	...	...	46	315	37	255	27.5	190	22	150	19	130	18	125
2011 notched specimens(a)																
T3	Rolled rod and shapes	1	...	...	28	195	23	160	16	110	12	85	10.5	70	10	70
T8	Rolled rod and shapes	1	...	...	24	165	17	115	11.5	80	9.5	66	8.5	59	8.5	59
2014 smooth specimens																
O	Rolled rod and shapes	2	...	...	...	...	18.5	130	15	105	13.5	95	12.5	85	12	85
T4	Rolled rod and shapes, plate, forgings, extrusions	15	...	...	58	400	42	290	34	235	27	185	22	150	20	140
T6	Rolled rod and shapes, plate, forgings, extrusions	54	...	...	52	360	39	270	30	205	24	165	19	130	18	125
T61	Forgings	2	...	...	52	360	39	270	30	205	24	165	19	130	18	125
T64	Extrusions	3	...	...	52	360	39	270	30	205	24	165	19	130	18	125
T651	Plate; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...			36	250	28	195	22	150	18	125	18	125
T652	Forgings; stress-relieved material, thickness > 3.5 in. (90 mm)	1	...	...	50	345	36	250	29	200	23	160	19	130	18	125

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
2014 notched specimens(a)																
O	Rolled rod and shapes	2	...	...	13	90	9	62	8	55	7	48	6	41	6	41
T4	Rolled rod and shapes, plate, forgings, extrusions	10	...	...	31	215	21	145	14	95	10	70	9	62	9	62
T6	Rolled rod and shapes, plate, forgings, extrusions	35	...	...	31	215	21	145	14	95	10	70	9	62	9	62
T61	Forgings	1	...	...	31	215	21	145	14	95	10	70	9	62	9	62
T64	Forgings	3	...	...	31	215	21	145	14	95	10	70	9	62	9	62
T651	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	...	...	20	140	13	90	9	62	7	48	6	41
T652	Forgings; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	30	205	16.5	115	10	70	5.5	38	...	...	...	...
2017 smooth specimens																
O	Rolled rod and shapes	2	...	...	...	...	21	145	19	130	17	115	14.5	100	13	90
T4	Rolled rod and shapes, plate, extrusions	6	...	...	...	...	40	275	32	220	24	165	19	130	18	125
2017 notched specimens(a)																
O	Rolled rod and shapes	2	...	...	15	105	10.5	70	8	55	7	48	6.5	45	6.5	45
T4	Rolled rod and shapes, plate, extrusions	5	...	...	29	200	20	140	16	110	10	70	9	62	8	55
2018 smooth specimens																
O	Rolled rod and shapes	1	...	...	...	...	...	...	16	110	13	90	10	70	9	62
T61	Rolled rod and shapes, forgings	7	...	...	53	365	42	290	29	200	23	160	19.5	135	17	115
2018 notched specimens(a)																
O	Rolled rod and shapes	1	...	...	...	...	11	75	9	62	8	55	7	48	7	48
T61	Rolled rod and shapes, forgings	7	...	...	27	185	20	140	14	95	11	75	9	62	8.5	59
2020 smooth specimens																
O	Plate	1	...	...	21	145	18	125	16	110	15	105	14.5	100	14	95
T6	Rolled rod and shapes, plates, forgings, extrusions	9	...	...	53	365	40	275	30	205	24	165	21.5	150	21	145
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	9	...	...	53	365	40	275	30	205	24	165	20.5	141	19	130
	Rolled rod and shapes; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	53	365	40	275	30	205	24	165	20.5	141	19	130
2020 notched specimens(a)																
O	Rolled rod and shapes	1	...	...	16	110	8	55	7	48	6.5	45	6.5	45	...	...
T6	Rolled rod and shapes, plates, forgings, extrusions	8	...	...	32	220	23	160	14	95	9	62	6.5	45	5.5	38

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
Temper	Product form	No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	9	...	...	33	230	22	150	12.5	85	8	55	6	41	5.5	38
	Rolled rod and shapes; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	33	230	22	150	12.5	85	8	55	6	41	5.5	38
2024 smooth specimens																
O	Rolled rod and shapes	1	...	...	...	...	22	150	20	140	17	115	15	105	13	90
T34	Rolled rod and shapes	1	...	...	56	385	43	295	31	215	24	165	21	145	20	140
T351	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	2	...	...	...	...	42	290	30	205	22	150	16.5	115	15.5	105
T36	Rolled rod and shapes, plate	2			55	380	40	275	32	220	24	165	20	140	18	125
T4	Rolled rod and shapes, plate, extrusions	20	...	...	56	385	43	295	31	215	24	165	21	145	20	140
T6	Rolled rod and shapes, plate, forgings, extrusions	8	...	...	54	370	43	295	31	215	24	165	20	140	18	125
T81	Plate	1	...	...	54	370	43	295	31	215	23	160	19	130	17	115
T84	Rolled rod and shapes	1	...	...	...	...	43	295	31	215	24	165	20	140	18	125
T851	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	8	...	...	49	340	36	250	28	195	23	160	16	110	15	105
	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	6	...	...	...	...	35	240	25	170	19	130	15	105	14	95
T8511	Extrusions; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	56	385	43	295	31	215	24	165	21	145	20	140
T852	Forgings; stress-relieved material, thickness >3.5 in. (90 mm)	2	...	...	...	...	39	270	28	195	21	145	16	110	15.5	105
T86	Rolled rod and shapes, plate	3	...	...	57	395	43	295	31	215	24	165	20	140	18	125
2024 notched specimens(a)																
O	Rolled rod and shapes	1	...	...	15	105	12.5	85	10	70	8	55	7	48	6	41
T34	Rolled rod and shapes	1	...	...	...	...	18	125	15	105	12	85	9	62	8	55
T351	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	2	...	...	30	205	21	145	13	90	9	62	8	55	7	48
T36	Rolled rod and shapes, plate	2	...	...	...	...	21	145	13	90	10	70	9	62	8.5	59

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
		No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
Temper	Product form			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
T4	Rolled rod and shapes, plate, extrusions	14	...	...	32	220	24	165	17	115	13	90	11	75	11	75
T6	Rolled rod and shapes, plate, forgings, extrusions	8	...	...	29	200	18	125	13	90	10	70	9	62	8	55
T81	Forgings	1	...	...	31	215	17	115	11	75	10	70	9	62	8.5	59
T84	Rolled rod and shapes	1	...	...	29	200	16	110	10	70	9	62	8	55	7.5	52
T851	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	8	...	...	29	200	17	115	11	75	8	55	7	48	6	41
	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	6	...	...	25	170	15	105	9	62	7	48	6	41	5	34
T8511	Extrusions; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	29	200	17	115	11	75	8	55	7	48	6	41
T852	Forgings; stress-relieved material, thickness >3.5 in. (90 mm)	2	...	...	25	170	15	105	9	62	6	41	5.5	38	5	34
T86	Rolled rod and shapes, plate	3	...	...	29	200	18	125	13	90	9	62	8	55	7	48
2025 smooth specimens																
O	Extrusions	1	...	...	...	...	...	...	...	...	...	...	...	...	9	62
T4	Rolled rod and shapes, extrusions	3	...	...	...	...	35	240	26	180	21	145	17	115	15	105
T6	Rolled rod and shapes, forgings, extrusions	27	...	...	...	...	35	240	26	180	21	145	17	115	15	105
2025 notched specimens(a)																
T6	Rolled rod and shapes, forgings	4	...	...	...	...	18	125	13	90	11	75	10	70	9	62
2027 smooth specimens																
T6	Rolled rod and shapes	1	...	...	...	...	...	...	27	185	20	140	15	105	13	90
2027 notched specimens(a)																
T6	Rolled rod and shapes	1	...	...	...	...	20	140	12	85	10	70	9	62	8	55
2117 smooth specimens																
T4	Extrusions	1	...	...	...	...	...	...	...	...	21	145	16	110	14	95
2118 smooth specimens																
T61	Rolled rod and shapes	1	...	...	...	...	38	260	27	185	23	160	21	145	20	140
2125 smooth specimens																
T6	Rolled rod and shapes	1	...	...	...	...	...	...	...	...	20	140	15	105	13	90
2125 notched specimens(a)																
T6	Rolled rod and shapes	1	...	...	...	...	...	...	9	62	8	55	7.5	52	7	48
2127 smooth specimens																
T6	Rolled rod and shapes	1	...	...	...	...	...	...	28	195	20	140	13	90	12	85
2217 smooth specimens																
T4	Rolled rod and shapes	1	...	...	...	...	...	...	...	...	23	160	18	125	16	110

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
2218 smooth specimens																
T61	Rolled rod and shapes, forgings	4	...	...	50	345	40	275	32	220	26	180	21	145	19	130
2218 notched specimens(a)																
T61	Rolled rod and shapes, forgings	4	...	...	...	...	18	125	15	105	13	90	12	85	11	75
2219 smooth specimens																
T31	Plate	1	...	...	...	...	36	250	25	170	19	130	16	110	14	95
T37	Plate	1	...	...	...	...	36	250	25	170	19	130	16	110	14	95
T6	Forgings, extrusions	5	...	...	42	290	32	220	25	170	20	140	17	115	16	110
T62	Plate, extrusions	7	...	...	46	315	35	240	26	180	21	145	18	125	16	110
T81	Extrusions	4	...	...	46	315	35	240	26	180	21	145	18	125	16	110
T851	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	6	...	...	46	315	35	240	26	180	21	145	16.5	115	15	105
	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	46	315	35	240	26	180	21	145	16.5	115	15	105
T8511	Extrusions; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	46	315	35	240	26	180	21	145	16.5	115	16	110
	Extrusions; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	...	...	35	240	26	180	21	145	16.5	115	16	110
T852	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	...	...	35	240	26	180	21	145	18	125	16	110
	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	2	...	...	40	275	32	220	25	170	19	130	16	110	15	105
T87	Plate, forgings	6	...	...	46	315	35	240	26	180	19	130	16	110	14	95
2219 notched specimens(a)																
T31	Plate	1	...	...	28	195	18	125	11	75	8	55	7	48	6	41
T37	Plate	1	...	...	28	195	18	125	11	75	8	55	7	48	6	41
T6	Forgings, extrusions	3	...	...	28	195	15	105	10	70	9	62	8	55	7	48
T62	Plate, extrusions	4	...	...	27	185	15	105	9	62	7	48	6	41	5.5	38
T81	Extrusions	4	...	...	27	185	15	105	9	62	7	48	6	41	5.5	38
T851	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	6	...	...	28	195	15	105	9	62	7	48	6	41	5.5	38
T8511	Extrusions; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	28	195	15	105	9	62	7	48	6	41	5.5	38
	Extrusions; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	28	195	15	105	9	62	7	48	6	41	5.5	38
T852	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	2	...	...	...	...	15	105	10	70	8	55	7	48	6.5	45
T87	Plate, forgings	5	...	...	27	185	15	105	9	62	7	48	6	41	5	34

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch <0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
2225 smooth specimens																
T6	Ingot	1	...	...	41	285	28	195	18	125	13	90	11	75	10	70
2225 notched specimens(a)																
T6	Ingot	1	...	...	...	...	17	115	12	85	10	70	9	62	...	...
2227 smooth specimens																
T6	Rolled rod and shapes	1	...	...	...	...	...	...	26	180	21	145	17	115	15	105
2317 smooth specimens																
T4	Forgings	1	...	...	...	...	...	...	24	165	19	130	15	105	13.5	93
2518 smooth specimens																
T6	Rolled rod and shapes	1	...	...	...	...	42	290	31	215	24	165	19	130	17	115
2618 smooth specimens																
T6	Forgings, extrusions	2	...	...	50.5	350	39	270	30	205	24	165	20	140	19	130
T61	Forgings	2	...	...	50.5	350	39	270	30	205	24	165	20	140	19	130
T651	Plate; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	...	...	36	250	27	185	21	145	18	125	17	115
T6511	Extrusions; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	...	...	39	270	30	205	22	150	16.5	115	15	105
2618 notched specimens(a)																
T6	Forgings, extrusions	2	...	...	25	170	20	140	13.5	95	10	70	9	62	8.5	59
T61	Forgings	2	...	...	25	170	20	140	13.5	95	10	70	9	62	8.5	59
T651	Plate; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	...	...	16	110	10.5	70	8.5	59	7.5	52	7	48
T6511	Extrusions; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	27	185	13	90	9.5	66	8	55	7	48	6	41
3003 smooth specimens																
O	Rolled rod and shapes	3	14.5	100	12	85	10.5	70	9	62	8	55	7.5	52	7	48
H14	Rolled rod and shapes	1	27	185	21	145	17	115	12	85	10	70	9	62	9	62
H16	Rolled rod and shapes	1	...	...	24	165	18	125	12.5	85	10.5	70	9.5	66	9.5	66
H18	Rolled rod and shapes	3	...	...	28	195	19	130	14	95	11.5	80	10.5	70	10	70
H24	Rolled rod and shapes	1	...	...	21	145	17	115	12	85	10	70	9	62	9	62
3003 notched specimens(a)																
O	Rolled rod and shapes	1	...	...	10	70	6	41	4.5	31	4	28	3.5	24	3.5	24
H14	Rolled rod and shapes	1	...	...	17	115	11	75	6.5	45	5	34	4.5	31	4	28
H16	Rolled rod and shapes	1	...	...	18	125	11.5	80	7.5	52	6	41	5.5	38	5	34
H18	Rolled rod and shapes	1	...	...	19	130	11.5	80	8.5	59	7	48	6	41	5.5	38
H24	Rolled rod and shapes	1	...	...	17	115	11	75	6.5	45	5	34	4.5	31	4	28
3004 smooth specimens																
O	Extrusions	3	...	...	24	165	19.5	135	16.5	115	15.5	105	14.5	100	14	95
H14	Rolled rod and shapes, plate	2	38	260	31	215	25	170	20	140	17.5	120	16.5	115	16	110
HI8	Rolled rod and shapes	3	42	290	34	235	28.5	195	23	160	20.5	140	19	130	18	125

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
Temper	Product form	No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
H19	Rolled rod and shapes	1			37	255	29.5	205	23	160	20.5	140	19	130	18	125
H34	Rolled rod and shapes	1	38	260	31	215	25	170	20	140	17.5	120	16.5	115	16	110
H38	Rolled rod and shapes	2	42	290	34	235	28.5	195	23	160	20.5	140	19	130	18	125
H39	Rolled rod and shapes	1	...	...	37	255	29.5	205	23	160	20.5	140	19	130	18	125
3004 notched specimens(a)																
O	Extrusions	1	20	140	16	110	12	85	7	48	6	41	5.5	38	5	34
H14	Rolled rod and shapes, plate	1	35	240	25	170	16	110	11	76	10	69	9	62	9	62
H18	Rolled rod and shapes	1	40	275	28	195	19	130	16	110	11	75	10	70	9	62
H19	Rolled rod and shapes	1	...	...	28	195	19	130	16	110	11	75	10	70	9	62
H34	Rolled rod and shapes	1	35	240	25	170	16	110	11	75	10	70	9	62	9	62
H38	Rolled rod and shapes	1	40	275	28	195	19	130	16	110	11	75	10	70	9	62
H39	Rolled rod and shapes	1	41	285	28	195	19	130	16	110	11	75	10	70	9	62
4032 smooth specimens																
T6	Rolled rod and shapes	2	...	...	45	310	38	260	30	205	24	165	18	125	16.5	115
4032 notched specimens(a)																
T6	Rolled rod and shapes	2	...	...	27	185	20	140	16	110	13	90	11	76	10	70
4043 smooth specimens																
O	Rolled rod and shapes	1	...	...	...	...	...	...	7.5	52	6.5	45	6	41	6	41
H18	Rolled rod and shapes	1	...	...	...	...	...	...	13.5	95	11	75	9	62	8	55
5005 smooth specimens																
H14	Rolled rod and shapes	1	...	...	25	170	19	130	14.5	100	12.5	85	12	85	12	85
H18	Rolled rod and shapes	1	...	...	28	195	22	150	17	115	14.5	100	14	95	14	95
H19	Rolled rod and shapes	1	...	...	30	205	22.5	155	18	125	16	110	16	110	16	110
5005 notched specimens(a)																
H14	Rolled rod and shapes	1	...	...	17	115	13	90	6	41	4	28	3	21	3	21
H18	Rolled rod and shapes	1	...	...	21	145	14	95	7	48	4	28	3	21	3	21
H19	Rolled rod and shapes	1	...	...	22	150	14	95	7	48	4	28	3	21	3	21
5050 smooth specimens																
O	Rolled rod and shapes	1	30	205	23	160	17.5	120	14.5	100	13.5	95	13	90	12.5	85
H34	Rolled rod and shapes	1	40	275	30.5	210	22.5	155	19	130	17.5	120	16.5	115	16	110
H38	Rolled rod and shapes	1	43	295	33	230	25	170	20.5	140	19	130	18.5	130	18	125
5050 notched specimens(a)																
O	Rolled rod and shapes	1	22	150	15	105	9.5	66	6.5	45	5.5	38	5	34	5	34
H34	Rolled rod and shapes	1	35	240	25	170	16	110	10	70	8.5	59	7.5	52	7	48
H38	Rolled rod and shapes	1	39	270	26	180	16	110	10	70	8.5	59	7.5	52	7	48
5052 smooth specimens																
O	Rolled rod and shapes	1	41	285	31	215	23.5	160	19.5	135	17.5	120	16.5	115	16	110
H14	Rolled rod and shapes	1	...	...	38	260	26	180	20.5	140	19	130	18	125	18	125
H16	Rolled rod and shapes	2	...	...	39	270	28	195	22	150	20	140	19	130	19	130
H18	Rolled rod and shapes	1	52	360	41	285	29.5	205	24	165	22.5	155	21	145	20	140
H34	Rolled rod and shapes	1	...	...	38	260	26	180	20.5	140	19	130	18	125	18	125
H36	Rolled rod and shapes	1	...	...	39	270	28	195	22	150	20	140	19	130	19	130
H38	Rolled rod and shapes	1	52	360	41	285	29.5	205	24	165	22.5	155	21	145	20	140
5052 notched specimens(a)																
O	Rolled rod and shapes	1	29	200	18	125	10.5	70	8	55	7.5	52	7	48	6.5	45
H14	Rolled rod and shapes	1	41	285	27	185	18	125	12	85	10	70	8.5	59	8	55

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch <0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
		No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
Temper	Product form			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
H18	Rolled rod and shapes	1	43	295	30	205	18.5	130	12	85	10	70	8.5	59	8	55
H34	Rolled rod and shapes	1	41	285	27	185	18	125	12	85	10	70	8.5	59	8	55
H38	Rolled rod and shapes	1	43	295	30	205	18.5	130	12	85	10	70	8.5	59	8	55
5056 smooth specimens																
O	Rolled rod and shapes	6	53	365	41	285	30	205	23	160	21	145	20	140	20	140
H16	Extrusions	1	...	...	...	...	30	205	23	160	21	145	20	140	20	140
H32	Rolled rod and shapes	1	...	...	43.5	300	32	220	25	170	25	170	22	150	22	150
H34	Rolled rod and shapes	1	...	...	46.5	320	35	240	27.5	190	24.5	170	23.5	160	23.5	160
H36	Rolled rod and shapes	1	...	...	...	...	36	250	29	200	25	170	24	165	24	165
H38	Rolled rod and shapes	1	...	...	49.5	340	38	260	29	200	25.5	175	25	170	25	170
5056 notched specimens(a)																
O	Rolled rod and shapes	2	33	230	21	145	14	95	10	70	9	62	8.5	59	8.5	59
H32	Rolled rod and shapes	1	...	...	27	185	17	115	11.5	80	10	70	9.5	66	9	62
H34	Rolled rod and shapes	1	...	...	27	185	17	115	11.5	80	10	70	9.5	66	9	62
H38	Rolled rod and shapes	1	...	...	27	185	17	115	11	75	10	70	9	62	9	62
5083 smooth specimens																
O	Plate	1	...	...	40	275	31	215	24	165	22.5	155	22	150	22	150
H112	Rolled rod and shapes, extrusions	2	...	...	42	290	31	215	25	170	23.5	160	23	160	23	160
H113	Plate	3	...	...	42	290	31	215	25	170	23.5	160	23	160	23	160
H311	Rolled rod and shapes	1	...	...	42	290	31	215	25	170	24.5	170	24	165	24	165
H321	Plate	1	...	...	42	290	31	215	25	170	23.5	160	23	160	23	160
5083 notched specimens(a)																
O	Plate	4	...	...	24	165	16	110	11	75	9	62	8	55	8	55
H112	Extrusions	1	...	...	25	170	17	115	12	85	10	70	9	62	9	62
H113	Plate	3	...	...	27	185	17	115	10	70	8.5	59	8	55	7.5	52
5086 smooth specimens																
O	Rolled rod and shapes, plate	3	48	330	40	275	28.5	195	24	165	22.5	155	22	150	21.5	150
H112	Rolled rod and shapes, extrusions	3	...	...	40	275	28.5	195	24	165	22.5	155	22	150	21	145
H113	Plate	1	...	...	42	290	30	205	25	170	24	165	23	160	23	160
H311	Rolled rod and shapes	1	...	...	...	...	...	...	24	165	22.5	155	22	150	21.5	150
H32	Plate	1	...	...	40	275	28.5	195	24	165	22.5	155	22	150	21.5	150
H34	Plate	1	...	...	42	290	30	205	25	170	24	165	23	160	23	160
5086 notched specimens(a)																
O	Plate	2	30	205	21	145	14	95	10	70	8.5	59	8	55	7	48
H112	Extrusions	1	...	...	24	165	16	110	11	75	8.5	59	8	55	7	48
H113	Plate	1	...	...	26	180	16	110	11	75	8.5	59	8	55	7	48
H32	Plate	1	...	...	24	165	16	110	11	75	8.5	59	8	55	7	48
H34	Plate	1	...	...	24	165	15	105	11	75	8.5	59	7	48	6	41
5152 smooth specimens																
O	Rolled rod and shapes	1	...	...	...	...	...	...	...	...	17.5	120	16.5	115	16	110
H16	Rolled rod and shapes	1	...	...	...	...	...	...	...	...	20	140	19	130	19	130
H36	Rolled rod and shapes	1	...	...	...	...	...	...	22	150	20	140	19	130	19	130
5154 smooth specimens																
O	Rolled rod and shapes, plate	4	54	370	39	270	27	185	20.5	140	18	125	17.5	120	17	115

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch <0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
H34	Rolled rod and shapes, plate	4	...	...	39	270	29	200	23	160	21	145	20	140	20	140
H38	Rolled rod and shapes	2	62	425	44	305	32	220	26	180	24	165	23	160	22	150
5154 notched specimens(a)																
O	Rolled rod and shapes, plate	4	31	215	21	145	13.5	95	9.5	66	8	55	8	55	8	55
H34	Rolled rod and shapes, plate	4	...	...	24	165	13.5	95	9.5	66	8	55	8	55	8	55
H38	Rolled rod and shapes	2	...	...	24	165	13.5	95	9.5	66	8	55	8	55	8	55
5356 smooth specimens																
O	Rolled rod and shapes, plate	2	...	...	41	285	30	205	22	150	19	130	18	125	18	125
H32	Rolled rod and shapes	1	...	...	44	305	32	220	24	165	21	145	20	140	20	140
H321	Plate	3	...	...	44	305	32	220	24	165	21	145	20	140	20	140
H34	Rolled rod and shapes	1	...	...	44	305	32	220	24	165	21	145	20	140	20	140
5356 notched specimens(a)																
O	Rolled rod and shapes, plate	2	...	...	22	150	15	105	9	62	8	55	7	48	7	48
H32	Rolled rod and shapes	1	...	...	22	150	11	75	9	62	8	55	7	48	7	48
H321	Plate	3	37	255	21	145	14	95	10	70	9	62	8	55	8	55
H34	Rolled rod and shapes	1	...	...	21	145	11	75	9	62	8	55	8	55	8	55
5454 smooth specimens																
O	Rolled rod and shapes, plate	5	...	...	33	230	26	180	22	150	21	145	20	140	20	140
H112	Rolled rod and shapes	1	...	...	36	250	28	195	23	160	22	150	21	145	21	145
H311	Rolled rod and shapes, extrusions	2	...	...	36	250	28	195	22	150	21	145	20	140	20	140
H32	Plate	1	53	365	36	250	28	195	22	150	21	145	20	140	20	140
H34	Rolled rod and shapes, plate	3	...	...	36	250	28	195	23	160	22	150	21	145	21	145
5454 notched specimens(a)																
O	Rolled rod and shapes, plate	4	30	205	21	145	14	95	10	70	8	55	7.5	52	7	48
H311	Extrusions	1	...	...	25	170	16	110	12	85	10	70	9	62	8	55
H32	Plate	1	...	...	25	170	16	110	12	85	9	62	7.5	52	7	48
H34	Rolled rod and shapes, plate	3	...	...	25	170	16	110	10	70	8	55	7.5	52	7	48
5456 smooth specimens																
O	Rolled rod and shapes, plate	5	...	...	42	290	32	220	25	170	23	160	22.5	155	22.5	155
H311	Rolled rod and shapes, extrusions	4	...	...	44	305	34	235	26	180	24	165	23.5	160	23	160
H321	Plate	6	...	...	44	305	34	235	26	180	24	165	23.5	160	23	160
H343	Forgings	2	...	...	44	305	34	235	26	180	24	165	23.5	160	23	160
5456 notched specimens(a)																
O	Plate	4	32	220	25	170	16	110	10	70	8	55	7.5	52	7	48
H311	Extrusions	3	...	...	25	170	15	105	10	70	8	55	7.5	52	7	48
H321	Plate	5	...	...	25	170	16	110	10	70	8	55	6.5	45	6.5	45
H343	Forgings	2	...	...	25	170	16	110	10	70	8	55	7.5	52	7	48

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch <0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
6011 notched specimens(a)																
T6	Plate	1	...	...	30	205	16	110	9	62	7	48	6	41	...	...
6051 smooth specimens																
T4	Rolled rod and shapes	1	...	...	...	...	...	...	21	145	15	105	12	85	11	75
T6	Rolled rod and shapes	2	...	...	...	...	...	...	21	145	15	105	12	85	11	75
6053 smooth specimens																
O	Rolled rod and shapes	2	...	...	...	...	12.5	85	11	75	9.5	66	8.5	59	8	55
H16	Rolled rod and shapes	1	...	...	23.5	160	19	130	15	105	13.5	95	12	85	11	75
T4	Rolled rod and shapes	1	...	...	36.5	250	29	200	22	150	17.5	120	14.5	100	13	90
T6	Rolled rod and shapes, extrusions	3	47	325	36.5	250	29	200	22	150	17.5	120	14.5	100	13	90
6053 notched specimens(a)																
O	Rolled rod and shapes	2	...	...	10.5	70	8	55	6.5	45	6	41	5.5	38	5.5	38
H16	Rolled rod and shapes	1	...	...	16	110	10	70	6	41	5	34	4	28	4	28
T4	Rolled rod and shapes	1	...	...	23	160	16.5	115	11.5	80	8	55	7.5	52	7	48
T6	Rolled rod and shapes, extrusions	3	41	285	23	160	16.5	115	11.5	80	8	55	7.5	52	7	48
6061 smooth specimens																
O	Rolled rod and shapes	2	...	...	22	150	16	110	13.5	95	11	75	9.5	66	9	62
T4	Rolled rod and shapes, extrusions	4	...	...	36	250	29	200	23	160	17	115	14	95	13	90
T6	Rolled rod and shapes, plate, forgings, extrusions	18	60	415	44	305	31	215	23	160	17	115	15	105	13.5	95
T651	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	44	305	31	215	23	160	17	115	15	105	13.5	95
T652	Forgings; stress-relieved material, thicness >3.5 in. (90 mm)	1	...	...	42	290	30	205	23	160	17	115	15	105	13.5	95
T8	Rolled rod and shapes, plate	2	...	...	...	...	...	...	23	160	17	115	14	95	13	90
6061 notched specimens(a)																
O	Rolled rod and shapes	1	...	...	12	85	10	70	8	55	7	48	6.5	45	6.5	45
T4	Rolled rod and shapes, extrusions	3	...	...	25	170	18	125	12	85	9	62	8.5	59	8	55
T6	Rolled rod and shapes, plate, forgings, extrusions	14	43	295	29	200	17	115	12	85	8	55	7	48	7	48
T651	Plate stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	29	200	17	115	12	85	8	55	7	48	7	48
T652	Forgings; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	26	180	16	110	11	75	8	55	6	41	6	41
T8	Rolled rod and shapes	1	...	...	...	...	13.5	95	10	70	8	55	7	48	7	48
6062 smooth specimens(b)																
O	Rolled rod and shapes, extrusions	2	...	...	13	90	11	75	10	70	9	62	8	55	8	55
T4	Extrusions	1	...	...	31	215	25	170	21	145	17	115	14	95	12	85
T6	Extrusions	2	...	...	40	275	29	200	21	145	17	115	14	95	12	85

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
Temper	Product form	No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
6062 notched specimens(a)(b)																
O	Extrusions	1	...	...	10	70	7	48	6	41	5	34	4.5	31	4	28
T4	Extrusions	1	...	...	22	150	15	105	10	70	8	55	7.5	52	7	48
T6	Extrusions	2	44	305	26	180	15	105	10	70	8	55	6.5	45	6	41
6063 smooth specimens																
O	Extrusions	1	...	...	11.5	80	10	70	9	62	8	55	7.5	52	7.5	52
T42	Extrusions	1	...	...	26.5	185	19.5	135	16	110	13.5	95	11	75	10	70
T5	Extrusions	1	...	...	28	195	20.5	140	15.5	105	12	85	10.5	70	10	70
T6	Extrusions	1	...	...	34	235	23.5	160	16.5	115	13.5	95	11	75	10	70
T832	Extrusions	1	...	...	...	...	26	180	19.5	135	16	110	12.5	85	12	85
6063 notched specimens(a)																
O	Extrusions	1	...	...	9	62	7	48	5	34	4	28	3.5	24	3	21
T42	Extrusions	1	...	...	28	195	18	125	11.5	80	10	70	9.5	66	9	62
T5	Extrusions	1	...	...	21	145	13	90	8	55	6.5	45	6	41	6	41
T6	Extrusions	1	...	...	28	195	18	125	11.5	80	9	62	7.5	52	7	48
T832	Extrusions	1	...	...	17	115	8	55	6	41	5	34	4.5	31	...	...
6064 smooth specimens(b)																
T3	Rolled rod and shapes	1	...	...	45	310	33	230	26	180	21	145	18	125	17	115
T6	Rolled rod and shapes	1	...	...	41	285	31	215	23	160	17	115	14.5	100	13.5	95
T81	Rolled rod and shapes	1	...	...	50	345	37	255	26	180	21	145	18	125	17	115
6064 notched specimens(a)(b)																
T3	Rolled rod and shapes	1	...	...	40	275	27	185	18	125	14.5	100	12.5	85	12	85
T6	Rolled rod and shapes	1	...	...	27	185	17.5	120	12	85	9.5	66	8.5	59	8	55
T81	Rolled rod and shapes	1	...	...	36.5	250	25	170	16	110	11	75	10	70	10	70
6070 smooth specimens																
T6	Extrusions	5	...	...	48	330	35	240	25	170	18	125	15.5	105	14	95
6070 notched specimens(a)																
T6	Extrusions	5	...	...	28	195	18	125	11	75	7	48	6	41	5	34
6071 smooth specimens(b)																
T451	Plate	1	...	...	...	...	32	220	23	160	18	125	14	95	13	90
T6	Extrusions	1	...	...	50	345	38	260	28.5	195	22	150	17.5	120	16.5	115
T651	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	...	...	32	220	23	160	18	125	14	95	13	90
6071 notched specimens(a)(b)																
T451	Plate	1	...	...	27	185	17	115	11	75	7	48	6.5	45	6	41
T6	Extrusions	1	...	...	29	200	18	125	11	75	7	48	6.5	45	6	41
T651	Plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	1	...	...	31	215	19	130	11	75	7	48	6.5	45	6	41
6101 smooth specimens																
T6	Rolled rod and shapes	1	...	...	30	205	22	150	17	115	13	90	10	70	9	62
T61	Extrusions	1	...	...	27	185	21	145	15.5	105	12	85	10	70	9	62
T62	Extrusions	1	...	...	30	205	23	160	16.5	115	12.5	85	10	70	9	62
T64	Extrusions	1	...	...	16	110	12	85	10	70	8.5	59	7.5	52	7	48
T8	Extrusions	1	...	...	32	220	24	165	18	125	15	105	12	85	10.5	70
6101 notched specimens(a)																
T6	Rolled rod and shapes	1	...	...	22	150	14	95	9	62	7	48	6.5	45	6	41

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
		No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
Temper	Product form			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
T61	Extrusions	1	...	...	22	150	14	95	9	62	7	48	6.5	45	6	41
T62	Extrusions	1	...	...	22	150	14	95	9	62	7	48	6.5	45	6	41
T64	Extrusions	1	...	...	13	90	9	62	7	48	6	41	4.5	31	4	28
T8	Extrusions	1	...	...	22	150	14	95	10	70	9	62	7.5	52	7	48
6151 smooth specimens																
T6	Rolled rod and shapes, forgings	5	58	400	43	295	30	205	22	150	17	115	13	90	12	85
6151 notched specimens(a)																
T6	Rolled rod and shapes, forgings	3	46	315	28	195	16	110	10	70	7	48	6	41	6	41
6153 smooth specimens																
T4	Extrusions	1	...	...	...	...	...	...	...	...	19	130	14.5	100	13	90
T6	Extrusions	1	...	...	...	...	...	...	...	...	19	130	14.5	100	13	90
6201 smooth specimens																
T81	Rolled rod and shapes	1	...	...	...	...	29	200	22	150	18	125	16	110	15	105
6201 notched specimens(a)																
T81	Rolled rod and shapes	1	...	...	23	160	14	95	7.5	52	4.5	31	3	21	3	21
6262 smooth specimens																
T9	Rolled rod and shapes	13	...	...	43	295	32	220	22	150	16	110	13.5	95	13	90
6262 notched specimens(a)																
T9	Rolled rod and shapes	9	...	...	29	200	16	110	9	62	6	41	5	34	5	34
6351 smooth specimens																
T6	Extrusions	1	...	...	46	315	36	250	26	180	20	140	16.5	115	15.5	105
6351 notched specimens(a)																
T6	Extrusions	1	...	...	32	220	19	130	10	70	7.5	52	6.5	45	6	41
7001 smooth specimens(b)																
T6	Plate	1	...	...	...	...	40	275	32	220	26	180	24	165	23	160
T7	Plate	1	...	...	...	...	37	255	30	205	25	170	22	150	21.5	150
W51	Plate	1	...	...	...	...	37	255	30	205	25	170	22	150	21.5	150
7001 notched specimens(a)(b)																
T6	Plate	1	...	...	25	170	17	115	11	75	8	55	7	48	7	48
T7	Plate	1	...	...	...	...	17	115	10	70	8	55	7.5	52	7	48
W51	Plate	1	...	...	...	...	16	110	9.5	66	6.5	45	6	41	5.5	38
7002 smooth specimens(b)																
T6	Plate	1	...	...	...	...	40	275	30	205	26	180	25	170	24	165
7002 notched specimens(a)(b)																
T6	Plate	1	...	...	...	...	20	140	13	90	9	62	8	55	7.5	52
7005 smooth specimens																
T53	Extrusions	1	...	...	...	...	36	250	29	200	24	165	19.5	135	18	125
T6	Extrusions	1	...	...	...	...	36	250	29	200	24	165	21	145	20	140
T63	Extrusions	1	...	...	...	...	36	250	29	200	24	165	21	145	20	140
7005 notched specimens(a)																
T53	Extrusions	1	...	...	25	170	17	115	11	75	8	55	6	41	5.5	38
T6	Extrusions	1	...	...	25	170	17	115	11	75	7	48	5	34	4.5	31
T63	Extrusions	1	...	...	25	170	17	115	11	75	6	41	4	28	3.5	24

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch <0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
7006 smooth specimens(b)																
T53	Extrusions	1	...	...	...	...	...	...	...	...	24	165	23	160	22	150
T6	Rolled rod and shapes, plate, extrusions	4	...	...	...	...	36	250	29	200	25	170	22	150	21.5	150
T63	Plate	1	...	...	...	...	38	260	31	215	26	180	24	165	23	160
7006 notched specimens(a)(b)																
T53	Extrusions	1	...	...	...	...	...	...	11	75	8	55	6	41	5	34
T6	Rolled rod and shapes, plate, extrusions	3	...	...	26	180	19	130	13	90	9	62	8	55	7.5	52
T63	Plate	1	...	...	26	180	19	130	13	90	9	62	8	55	7.5	52
7038 smooth specimens(b)																
T6	Plate	1	...	...	...	...	40	275	32	220	26	180	24	165	...	...
7038 notched specimens(a)(b)																
T6	Plate	1	...	...	30	205	22	150	15	105	10	70	9	62	8	55
7039 smooth specimens																
T53	Extrusions Plate,	1	...	...	...	...	...	...	28	195	25	170	23	160	22	150
T6	extrusions	4	...	...	52	360	39	270	31	215	25	170	23	160	22	150
7039 notched specimens(a)																
T6	Plate, extrusions	3	...	...	26	180	18	125	11	75	8	55	6.5	45	6	41
7070 smooth specimens(b)																
O	Rolled rod and shapes	1	...	...	...	...	...	...	23	160	21	145	20	140	19	130
T6	Rolled rod and shapes, forgings	2	...	...	...	...	...	...	26	180	24	165	22	150	21	145
7070 notched specimens(a)(b)																
O	Rolled rod and shapes	1	...	...	27	185	18	125	11	75	8.5	59	7.5	52	7	48
T6	Rolled rod and shapes	1	...	...	...	...	18	125	11	75	8.5	59	7.5	52	7	48
7073 smooth specimens																
T6	Plate, forgings	2	...	...	...	...	...	...	26	180	20	140	16	110	15	105
7074 smooth specimens																
T6	Rolled rod and shapes, forgings, extrusions	4	...	...	...	...	40	275	30	205	26	180	22	150	21	145
7074 notched specimens(a)																
T6	Rolled rod and shapes, extrusions	3	...	...	...	...	23	160	18	125	14	95	11.5	80	10.5	70
7075 smooth specimens																
O	Rolled rod and shapes	1	33	230	27	185	22	150	19	130	18	125	17.5	120	17	115
T6	Rolled rod and shapes, plate, forgings, extrusions	59	...	...	55	380	40	275	29	200	24	165	22	150	22	150
T651	Rolled rod and shapes, plate; stress-relieved thickness material, ≤ 3.5 in. (90 mm)	8	...	...	55	380	40	275	29	200	24	165	22	150	22	150
	Plate; stress-relieved material, thickness > 3.5 in. (90 mm)	7	...	...	53	365	34	235	24	165	19	130	16.5	115	16	110

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
T6510	Extrusions; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	...	...	40	275	29	200	24	165	22	150	22	150
	Extrusions; stress-relieved material, thickness > 3.5 in. (90 mm)	1	...	...	...	...	40	275	29	200	24	165	22	150	22	150
T652	Forgings; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	...	...	37	255	29	200	24	165	21	145	20	140
T73	Rolled rod and shapes, plate, forgings	13	...	...	53	365	37	255	29	200	24	165	22	150	22	150
T7351	Plate	7	...	...	53	365	37	255	29	200	24	165	21	145	20	140
T7352	Forgings	1	...	...	...	...	34	235	25	170	23	160	...	...	...	...
W	Rolled rod and shapes, extrusions	4	...	...	60	415	44	305	32	220	28	195	26	180	25	170
7075 notched specimens(a)																
O	Rolled rod and shapes	2	28	195	18	125	12	85	10	70	9	62	8	55	7.5	52
T6	Rolled rod and shapes, plate, forgings, extrusions	52	54	370	31	215	21	145	14	95	11	75	10	70	9	62
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	7	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
	Plate; stress-relieved material, thickness > 3.5 in. (90 mm)	7	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
T6510	Extrusions; stress-relieved material; thickness ≤ 3.5 in. (90 mm)	1	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
	Extrusions; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	1	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
T652	Forgings	1	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
T73	Rolled rod and shapes, plate, forgings	12	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
T7351	Plate	7	...	...	29	200	18	125	11.5	80	8	55	7	48	6.5	45
T7352	Forgings	1	...	...	24	165	15	105	10	70	7.5	52	6	41	...	...
W	Rolled rod and shapes, extrusions	4	...	...	32	220	20	140	13	90	10	70	8	55	7.5	52
7076 smooth specimens																
T6	Rolled rod and shapes, forgings	28	...	...	...	...	38	260	29	200	24	165	22	150	21	145
T61	Forgings	4	...	...	51.5	355	38.5	265	30.5	210	26.5	185	24	165	22	150
7076 notched specimens(a)																
T6	Rolled rod and shapes, forgings	28	...	...	32	220	22	150	14	95	10	70	9	62	8.5	59
T61	Forgings	4	48	330	31	215	21.5	150	14	95	9	62	6.5	45	6	41

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
Temper	Product form	No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
7079 smooth specimens(b)																
T6	Rolled rod and shapes, plate, forgings, extrusions	26	...	...	54	370	40	275	29	200	24	165	22	150	22	150
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	8	...	...	54	370	40	275	29	200	24	165	22	150	22	150
	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	7	...	...	52	360	34	235	23.5	160	18.5	130	16.5	115	16	110
T652	Forgings; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	54	370	40	275	29	200	24	165	22	150	22	150
7079 notched specimens(a)(b)																
T6	Rolled rod and shapes, plate, forgings, extrusions	21	...	...	29	200	16	110	11.5	80	9	62	8	55	7.5	52
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤3.5 in. (90 mm)	7	...	...	29	200	16	110	11.5	80	9	62	8	55	7.5	52
	Plate; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	29	200	16	110	10	70	8.5	59	7	48	6.5	45
T652	Forgings; stress-relieved material, thickness >3.5 in. (90 mm)	1	...	...	29	200	18	125	11.5	80	8	55	6.5	45	...	...
7080 smooth specimens(b)																
T7	Forgings	1	...	...	...	...	37	255	29	200	25	170	23	160	22	150
7080 notched specimens(a)(b)																
T7	Forgings	1	...	...	...	...	18	125	11	75	8.5	59	...	...	...	...
7106 smooth specimens(b)																
T53	Extrusions	1	...	...	48	330	36	250	28	195	23.5	160	21.5	150	21	145
T6	Plate, extrusions	3	...	...	48	330	36	250	28	195	23.5	160	21.5	150	21	145
T6351	Plate	4	...	...	48	330	36	250	28	195	23.5	160	21.5	150	21	145
7106 notched specimens(a)(b)																
T53	Extrusions	1	...	...	...	...	17.5	120	10	70	7.5	52	6	41	5.5	38
T6	Plate, extrusions	3	...	...	...	...	17.5	120	10	70	7.5	52	6	41	5.5	38
T6351	Plate	4	...	...	...	...	17.5	120	10	70	7.5	52	6	41	5.5	38
7139 smooth specimens(b)																
T53	Extrusions	1	...	...	...	...	...	...	28	195	25	170	24	165	23	160
T6	Plate, extrusions	3	...	...	54	370	38	260	30	205	26	180	24	165	23	160
T6351	Plate	2	...	...	54	370	38	260	30	205	26	180	24	165	23	160
7139 notched specimens(a)(b)																
T53	Extrusions	1	...	...	...	...	...	...	...	...	...	...	6	41	5.5	38
T6	Plate, extrusions	2	...	...	27	185	16	110	9.5	66	7	48	6	41	5.5	38
T6351	Plate	2	...	...	27	185	16	110	9.5	66	7	48	6	41	5.5	38

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
7175 smooth specimens																
T6	Rolled rod and shapes, extrusions	3	...	...	...	...	40	275	29	200	24	165	22	150	21	145
T7352	Forgings	1	...	...	48	330	34	235	25	170	23	160	21	145	20	140
7175 notched specimens(a)																
T6	Rolled rod and shapes, extrusions	2	...	...	...	...	23	160	18	125	14	95	13	90	12	85
T7352	Forgings	1	...	...	25	170	15	105	10	70	7	48	6.5	45	6	41
7177 smooth specimens																
T6	Rolled rod and shapes	1	...	...	...	...	42	290	31	215	27	185	24	165	23	160
7178 smooth specimens																
T6	Rolled rod and shapes, plate, forgings, extrusions	9	...	...	59	405	47	325	36	250	29	200	25.5	175	24.5	170
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	4	...	...	...	...	47	325	36	250	29	200	25	170	23	160
T6510	Extrusions; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	2	...	...	...	...	42	290	33	230	29	200	25.5	175	24.5	170
7178 notched specimens(a)																
T6	Rolled rod and shapes, plate, forgings, extrusions	8	...	...	28	195	19	130	13	90	10	70	9	62	8	55
T651	Rolled rod and shapes, plate; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	4	...	...	28	195	19	130	13	90	9	62	6	41	5.5	38
T6510	Extrusions; stress-relieved material, thickness ≤ 3.5 in. (90 mm)	2	...	...	28	195	17	115	11	75	7.5	52	6.5	45	6	41
7179 smooth specimens(b)																
T652	Forgings; stress-relieved material, thickness > 3.5 in. (90 mm)	1	...	...	...	...	36	250	26	180	23	160	23	160	22	150
7179 notched specimens(a)(b)																
T652	Forgings; stress-relieved material, thickness > 3.5 in. (90 mm)	1	...	...	...	...	17	115	11	75	8.5	59	7	48	6.5	45
7270 smooth specimens																
T6	Forgings	1	...	...	...	...	...	...	21	145	21	145	19	130	18.5	130
7277 smooth specimens																
T6	Rolled rod and shapes, forgings, extrusions	2	...	...	...	...	42	290	31	215	25.5	175	22	150	20	140

(continued)

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch < 0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.1 (continued)

Temper	Product form	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
7277 notched specimens(a)																
T6	Rolled rod and shapes, forgings, extrusions	3	...	...	30	205	20	140	14.5	100	11	75	10	70	9.5	66
7370 smooth specimens																
T6	Rolled rod and shapes, forgings	2	...	...	...	...	33	230	26	180	22.5	155	21	145	20	140
7370 notched specimens(a)																
T6	Rolled rod and shapes, forgings	3	...	...	...	...	20.5	140	12.5	85	9.5	66	8.5	59	8	55
8280 smooth specimens																
H12	Plate	1	...	...	...	...	14.5	100	12	85	10.5	70	10	70	9.5	66
8280 notched specimens(a)																
H12	Plate	1	...	...	...	...	...	...	...	...	3.5	24	3	21	3	21

Approximate average values as determined by test in R.R. Moore rotating-beam fatigue machines. Approximate completely reversed flexural stresses. (a) Values determined using specimens containing a single 60° sharp V-notch, 0.075 in. (1.91 mm) deep with root diameter of 0.330 in. (8.38 mm) and a root radius at base of notch <0.0005 in. (0.0125 mm) ($K_t > 12$). (b) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.2 Rotating-beam reversed-bending fatigue strengths of cast alloys at room temperature

		Fatigue strengths at indicated cycles										Endurance limit at 5 × 10 ⁸ cycles	
Alloy	Temper	10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles		ksi	MPa
		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
Cast alloys													
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.O	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

(continued)

Metric values of strength determined by multiplying strengths originally determined in English units by conversion factor of 6.897.

English units measured by nearest 0.5 ksi; metric units rounded to nearest MPa. Source: Aluminum Association and Alcoa publications

Table A5.2 (continued)

		Fatigue strengths at indicated cycles										Endurance limit at 5 × 10 ⁸ cycles	
		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
Alloy	Temper	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
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
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.O	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 factor of 6.897.

English units measured by nearest 0.5 ksi; metric units rounded to nearest MPa. Source: Aluminum Association and Alcoa publications

Elevated temperature cantilever-beam data tests were made of specimens (Fig. A5.2) in elevated-temperature cantilever-beam fatigue machines in accordance with ASTM test methods in existence at the time. Test temperatures ranging from 75 to 600 °F (25 to 315 °C) were used. The tests were started after a holding time of 1/2 h, allowing the specimens to reach the test temperature, but the specimens had previously been soaked for the indicated time at the test temperature to represent service exposure. The bending stress in such specimens was completely reversed ($R = -1.0$). Test speeds were about 3450 rpm. The tests were made over a period from about 1950 through about 1980. There was no atmospheric control in the testing laboratories.

In general, each fatigue curve was generated from tests of 10 to 15 specimens, and bands for specific alloys, tempers, and products usually representing several samples (lots). A number of the specimens were used to identify the highest stress that would not cause failure in 10 million cycles. An average fatigue curve was drawn through the completed data set, usually with appropriate extrapolation to 500 million cycles, which was identified as the endurance limit. The table entries are the intersections of the average line with the respective cyclic lives.

Elevated temperature cantilever-beam fatigue data are presented in Table A5.3.

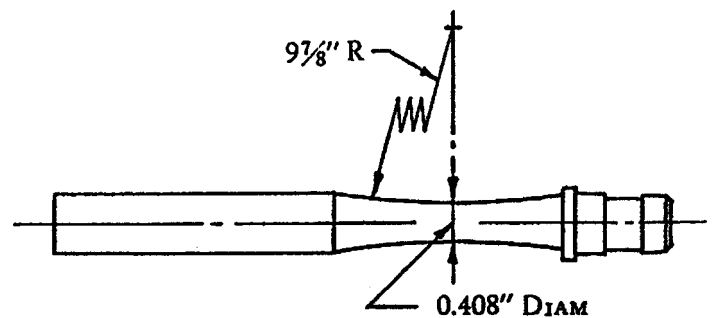


Fig. A5.2 Elevated-temperature rotating-bending smooth specimen. Dimensions in inches

The metric/SI units shown in the table were calculated by multiplying the fatigue strength values measured in engineering units by the conversion factor of 1 MPa = 6.897 ksi, and then rounded by the aluminum industry standard to the nearest 5 MPa, except in the case of values less than 10 ksi, for which the converted value was not rounded.

The alloys are presented in Table A5.3 in numeric order.

Table A5.3 Cantilever-beam bending fatigue strengths of wrought aluminum alloys at elevated temperatures

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles		
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles						
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa			
1100	O	Rolled rod and shapes	75	25	4	...	...	8	55	6.5	45	5.5	38	5	34	5	34			
			300	150	1	...	...	6.5	45	5.5	38	5	34	4.5	31	4	28			
			400	205	1	...	...	5.5	38	5	34	4.5	31	4	28	3.5	24			
			500	260	1	...	...	5	34	4.5	31	4	28	3.5	24	3	21			
	H16	Rolled rod and shapes	75	25	2	19	130	14	95	11.5	80	10	70	9	62	8	55			
			300	150	1	15	105	11	75	8	55	6	41	5	34	4	28			
			400	205	1	13.5	95	10	70	7	48	4.5	31	3.5	24	2.5	17			
			500	260	1	11	75	8	55	5	34	3.5	24	2.5	17	2	14			
	H18	Rolled rod and shapes	75	25	2	22	150	16.5	115	13.5	95	11	75	10	70	9	62			
			300	150	1	17	115	12	85	8.5	59	6	41	4.5	31	4	28			
			400	205	1	15	105	10	70	7	48	4.5	31	3	21	2.5	17			
			500	260	1	9	62	7	48	5	34	3.5	24	2.5	17	2	14			
	H26	Rolled rod and shapes	75	25	1	19	130	14	95	11.5	80	10	70	9	62	8	55			
			300	150	1	15	105	11	75	8	55	6	41	5	34	4	28			
			400	205	1	13.5	95	10	70	7	48	4.5	31	3.5	24	2.5	17			
			500	260	1	...	...	5	34	4	28	3.5	24	2.5	17	2	14			
1350	H19	Rolled rod and shapes	75	25	1	22.5	155	16	110	12.5	85	10	70	8	55	7	48			
			212	100	1	21	145	15	105	11	75	8	55	6	41	6	41			
			2014	T4	Rolled rod and shapes, plate, forgings, extrusions	75	25	15	58	400	42	290	34	235	27	185	22	150	20	140
						300	150	2	...	...	...	...	24	165	19	130	15	105	13	90
T6	Rolled rod and shapes, plate, forgings, extrusions	75		25	54	52	360	39	270	30	205	24	165	19	130	18	125			
		300		150	3	...	...	33	230	25	170	19	130	14.5	100	13.5	95			
		400	205	3	...	...	28	195	21	145	15	105	10	70	9	62				
		500	260	3	...	...	20	140	14.5	100	9.5	66	6	41	5.5	38				
		600	315	1	15	105	12	85	9.5	66	7	48	5.5	38	5	34				
2018	T61	Rolled rod and shapes, forgings	75	25	7	53	365	42	290	29	200	23	160	19	130	17	115			
			300	150	3	...	...	28.5	195	23	160	17	115	13	90	11	75			
			400	205	3	...	...	26.5	185	21	145	14	95	9.5	66	8.5	59			
			500	260	3	...	...	21	145	14.5	100	9	62	6	41	5	34			
2020	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	9	53	365	40	275	30	205	24	165	21.5	150	21	145			
			300	150	2	...	...	30	205	24	165	19.5	135	16.5	115	15.5	105			
			400	205	1	...	...	29	200	23	160	17.5	120	13.5	95	12	85			
			500	260	1	...	...	27	185	20.5	140	16.5	115	14.5	100	14.5	100			
	T651	Rolled rod and shapes, plate	75	25	9	53	365	40	275	30	205	24	165	20.5	140	19	130			
			300	150	1	...	...	40	275	30	205	24	165	20.5	140	19	130			
			400	205	1	...	...	37	255	27	185	20.5	140	16.5	115	14.5	100			
			500	260	1	34	235	26	180	19	130	14	95	11	75	9.5	66			
			600	315	1	21.5	150	15.5	105	12	85	9	62	6.5	45	5.5	38			

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.3 (continued)

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa				
2024	T4	Rolled rod and shapes, plate, extrusions	75	25	20	56	385	43	295	31	215	24	165	21	145	20	140		
2118	T6	Extrusions	300	150	1	...	...	37	255	26	180	20	140	17.5	120	17	115		
			400	205	1	...	...	29	200	21.5	150	16	110	13	90	12.5	85		
			500	260	1	...	...	23	160	16.5	115	11	75	9	62	8.5	59		
			600	315	1	19	130	15	105	12	85	9.5	66	8	55	7.5	52		
		Rolled rod and shapes, plate	300	150	1	...	...	...	...	23.5	160	18.5	130	17	115	16.5	115		
			400	205	1	...	...	...	...	21.5	150	16	110	12	85	10	70		
			500	260	1	...	...	21	145	15	105	11	75	6.5	45	6	41		
2119	T6	Forgings	600	315	1	14	95	11	75	8.5	59	5.5	38	4.5	31	4	28		
			400	205	1	...	...	26	180	19	130	13	90	9.5	66	...	...		
			600	315	1	21	145	15.5	105	11	75	7.5	52	5	34	...	...		
2218	T61	Rolled rod and shapes, forgings	75	25	4	50	345	40	275	32	220	26	180	21	145	19	130		
				300	150	2	...	...	...	...	25	170	20	140	16	110	15	105	
				400	205	2	...	...	...	...	20	140	15	105	12	85	11	75	
				500	260	2	27	185	21.5	150	15	105	11	75	8	55	7	48	
			Rolled rod and shapes	600	315	1	...	...	13	90	10	70	7	48	5	34	4	28	
2219	T6	Forgings, extrusions	75	25	5	42	290	32	220	25	170	20	140	17	115	16	110		
		Forgings	300	150	3	...	...	27	185	22	150	17	115	14.5	100	13.5	95		
			400	205	1	...	...	25	170	19	130	15	105	12	85	10.5	70		
			500	260	3	27.5	190	22	150	16	110	12	85	9	62	8	55		
			600	315	2	22.5	155	17.5	120	12.5	85	8.5	59	6.5	45	6	41		
2618	T6	Forgings, extrusions	75	25	2	50.5	350	39	270	30	205	24	165	20	140	19	130		
		Forgings	400	205	2	...	...	28	195	22	150	17	115	13.5	95	13	90		
			500	260	2	...	...	23	160	17	115	12.5	85	9	62	8.5	59		
			600	315	2	25	170	19	130	14	95	9.5	66	6	41	5.5	38		
3003	O	Rolled rod and shapes	75	25	3	12	85	10.5	70	9	62	8	55	7.5	52	7	48		
				300	150	1	9	62	8	55	7	48	6.5	45	6	41	6	41	
				400	205	1	6.5	45	5.5	38	4.5	31	4	28	3.5	24	3.5	24	
				500	260	1	4.5	31	3.5	24	3	21	2.5	17	2	14	2	14	
	H14	Rolled rod and shapes	75	25	1	21	145	17	115	12	85	10	70	9	62	9	62		
				300	150	1	17	115	13	90	10	70	7.5	52	6	41	5.5	38	
				400	205	1	15	105	11	75	8	55	5.5	38	4.5	31	4	28	
				500	260	1	12	85	8	55	5	34	3.5	24	3	21	2.5	17	
	H18	Rolled rod and shapes	75	25	3	28	195	19	130	14	95	11.5	80	10.5	70	10	70		
				300	150	1	22	150	16	110	12	85	9	62	6.5	45	5.5	38	
				400	205	1	18.5	130	13	90	8.5	59	6	41	5.5	38	5	34	
				500	260	1	8	55	6	41	5	34	4.5	31	4	28	4	28	
	H24	Rolled rod and shapes	75	25	1	21	145	17	115	12	85	10	70	9	62	9	62		
				300	150	1	18	125	13.5	95	10	70	7.5	52	6	41	5.5	38	
				400	205	1	16.5	115	12	85	8.5	59	6	41	4.5	31	4	28	
				75	25	3	24	165	19.5	134	16.5	114	15.5	107	14.5	100	14	97	

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.3 (continued)

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
3004	O	Rolled rod and shapes	300	150	2	18	125	14	95	11.5	80	10	70	9.5	66	9	62		
			400	205	2	16.5	115	13	90	10.5	70	9	62	8.5	59	8	55		
			500	260	2	15	105	11	75	9.5	66	7.5	52	7	48	6.5	45		
	H14	Rolled rod and shapes, plate	75	25	2	31	215	25	170	20	140	17.5	120	16.5	115	16	110		
			Rolled rod and shapes	300	150	1	26	180	21	145	17	115	15	105	13.5	95	13	90	
				400	205	1	24	165	18	125	14.5	100	12	85	10.5	70	10	70	
	H18	Rolled rod and shapes		500	260	1	21.5	150	15.5	105	11.5	80	9.5	66	8.5	59	8	55	
			75	25	3	34	235	28.5	195	23	160	20.5	140	19	130	18	125		
			300	150	1	27.5	190	22.5	155	18.5	130	14.5	100	12	85	11	75		
	H19	Rolled rod and shapes	400	205	1	25	170	19	130	15	105	11	75	9	62	8	55		
			500	260	1	21	145	14.5	100	10.5	70	7	48	5.5	38	5	34		
			75	25	1	37	255	29.5	205	23	160	20.5	140	19	130	18	125		
	H38	Rolled rod and shapes	300	150	1	...	...	25	170	19	130	15	105	12	85	11	75		
			400	205	1	...	...	21.5	150	14.5	100	10	70	8.5	59	8	55		
			500	260	1	20	140	12	85	8.5	59	7	48	6	41	6	41		
			75	25	2	34	235	28.5	195	23	160	20.5	140	19	130	18	125		
			300	150	1	27.5	190	21.5	150	18	125	15.5	105	14	95	13	90		
			400	205	1	24.5	170	18	125	14.5	100	12	85	10.5	70	10	70		
	H39	Rolled rod and shapes	500	260	1	21	145	15	105	11	75	9	62	8	55	7.5	52		
			75	25	1	37	255	29.5	205	23	160	20.5	140	19	130	18	125		
			300	150	1	...	...	25	170	19	130	16.5	115	13.5	95	12.5	85		
	4032	T6	Rolled rod and shapes	400	205	1	27	185	21	145	15	105	10.5	70	9	62	8.5	59	
				500	260	1	20	140	13.5	95	10	70	7	48	6.5	45	6	41	
				75	25	2	52	360	38	260	30	205	24	165	18	125	16.5	115	
300				150	1	...	...	30	205	24	165	18	125	13	90	11.5	80		
5005	H19	Rolled rod and shapes	400	205	1	...	...	27	185	20	140	13	90	8	55	7	48		
			500	260	1	...	...	19	130	12	85	8	55	5.5	38	5	34		
			75	25	1	30	205	22.5	155	18	125	16	110	16	110	16	110		
5050	O	Rolled rod and shapes	212	100	1	27	185	22	150	18	125	16	110	15	105	15	105		
			300	150	1	25	170	20.5	140	17.5	120	15	105	12	85	10.5	70		
			75	25	1	23	160	17.5	120	14.5	100	13.5	95	13	90	12.5	85		
	H34	Rolled rod and shapes	300	150	1	16.5	115	12.5	85	9.5	66	8.5	59	8	55	8	55		
			400	205	1	15	105	10.5	70	8	55	6.5	45	6	41	6	41		
			500	260	1	13	90	9.5	66	6.5	45	4.5	31	4	28	4	28		
			75	25	1	30.5	210	22.5	155	19	130	17.5	120	16.5	115	16	110		
			300	150	1	26	180	21	145	16	110	12	85	9	62	8	55		
			400	205	1	21	145	15.5	105	11.5	80	8	55	6	41	6	41		
	H38	Rolled rod	500	260	1	16	110	11.5	80	7	48	5	34	4	28	4	28		
			75	25	1	33	230	25	170	20.5	140	19	130	18.5	130	18	125		
			300	150	1	...	...	22	150	17.5	120	13.5	95	10.5	70	9.5	66		
5052	O	Rolled rod and shapes	400	205	1	21	145	15.5	105	11.5	80	8	55	6	41	6	41		
			500	260	1	16	110	11.5	80	7	48	5	34	4	28	4	28		
			75	25	1	31	215	23.5	160	19.5	135	17.5	120	16.5	115	16	110		
			300	150	2	21	145	17	115	14	95	11.5	80	10	70	10	70		
			400	205	2	19.5	135	14.5	100	11	75	9.5	66	8.5	59	8	55		
			500	260	2	17	115	12	85	9	62	7.5	52	7	48				

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.3 (continued)

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
5052	H14	Rolled rod and shapes	75	25	1	38	260	26	180	20.5	140	19	130	18	125	18	125		
			300	150	1	...	...	24	165	19	130	16	110	14.5	100	14	95		
			400	205	1	26	180	20	140	15	105	13	90	10.5	70	10	70		
			500	260	1	23	160	15	105	10	70	7	48	6.5	45	6	41		
	H18	Rolled rod and shapes	75	25	1	41	285	29.5	205	24	165	22.5	155	21	145	20	140		
			300	150	1	...	...	24	165	19	130	16	110	14.5	100	14	95		
			400	205	1	...	...	20	140	15	105	13	90	10.5	70	10	70		
			500	260	1	22	150	15	105	10	70	7	48	6.5	45	6	41		
	H34	Rolled rod and shapes	75	25	1	38	260	26	180	20.5	140	19	130	18	125	18	125		
			300	150	1	...	...	24	165	19	130	16	110	14.5	100	14	95		
			400	205	1	25.5	175	20	140	15	105	13	90	10.5	70	10	70		
			500	260	1	...	...	15	105	10	70	7	48	6.5	45	6	41		
	H38	Rolled rod and shapes	75	25	1	41	285	29.5	205	24	165	22.5	155	21	145	20	140		
			300	150	1	...	...	24	165	19	130	16	110	14.5	100	14	95		
			400	205	1	26	180	20	140	15	105	13	90	10.5	70	10	70		
			500	260	1	22	150	15	105	10	70	7	48	6.5	45	6	41		
5056	O	Rolled rod and shapes	75	25	6	41	285	30	205	23	160	21	145	20	140	20	140		
			300	150	1	...	...	22.5	155	17	115	15.5	105	15	105	15	105		
			400	205	1	18.5	130	17	115	12	85	10	70	9	62	8.5	59		
			500	260	1	22	150	15	105	10.5	70	8.5	59	7.5	52	7	48		
	H32	Rolled rod and shapes	75	25	1	43.5	300	32	220	25	170	23	160	22	150	22	150		
			300	150	1	...	...	24	165	19.5	135	17	115	16.5	115	16	110		
			500	260	1	23	160	16.5	115	11.5	80	8	55	6.5	45	6	41		
	H34	Rolled rod and shapes	75	25	1	46.5	320	35	240	27.5	190	24.5	170	23.5	160	23.5	160		
			300	150	1	...	...	27.5	190	20.5	140	17	115	15.5	105	15	105		
			500	260	1	26	180	16.5	115	11	75	8	55	6.5	45	6	41		
5083	O	Plate	75	25	1	40	275	31	215	24	165	22.5	155	22	150	22	150		
			300	150	1	...	...	24	165	18	125	16	110	15	105	14.5	100		
			400	205	1	...	...	21	145	16.5	115	13	90	11.5	80	10.5	70		
			500	260	1	22	150	17.5	120	13	90	9	62	7	48	6.5	45		
	H321	Plate	600	315	1	20	140	15	105	10.5	70	7	48	5.5	38	5.5	38		
			75	25	3	42	290	31	215	25	170	23.5	160	23	160	23	160		
			300	150	1	...	...	26	180	19	130	16	110	14	95	13.5	95		
			400	205	1	...	...	22.5	155	17.5	120	13.5	95	11	75	10.5	70		
			500	260	1	24	165	17	115	12	85	9	62	7	48	6.5	45		
			600	315	1	18.5	130	12.5	85	7.5	52	5.5	38	4.5	31	4.5	31		
5086	O	Rolled rod and shapes, plate	75	25	3	40	275	28.5	195	24	165	22.5	155	22	150	21.5	150		
			300	150	1	26	180	18.5	130	14	95	12.5	85	11.5	80	11.5	80		
			400	205	1	22	150	16	110	11.5	80	10	70	9.5	66	9.5	66		
			500	260	1	19	130	13.5	95	9.5	66	7.5	52	6.5	45	6.5	45		
	H32	Plate	600	315	1	13	90	10	70	7	48	5	34	4.5	31	4	28		
			75	25	1	40	275	28.5	195	24	165	22.5	155	22	150	21.5	150		
			300	150	1	31	215	24	165	19	130	16	110	15.5	105	15	105		
			400	205	1	27	185	20.5	140	15.5	105	13	90	12	85	11	75		
			500	260	1	22.5	155	16	110	11.5	80	9	62	8	55	8	55		
			600	315	1	17	115	11.5	80	7	48	4.5	31	4	28	3.5	24		

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.3 (continued)

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
5154	O	Rolled rod and shapes, plate	75	25	4	39	270	27	185	20.5	140	18	125	17.5	120	17	115		
			300	150	2	27	185	19.5	135	14.5	100	12	85	11.5	80	11	75		
			400	205	1	24	165	17.5	120	13	90	10.5	70	10	70	10	70		
			500	260	1	19	130	14	95	10	70	8	55	7	48	6.5	45		
	H34	Rolled rod and shapes, plate	75	25	4	39	270	29	200	23	160	21	145	20	140	20	140		
			300	150	3	...	...	24	165	18	125	16	110	14.5	100	14	95		
			400	205	2	...	...	20	140	14.5	100	11.5	80	10.5	70	10	70		
			500	260	2	23.5	160	15	105	10	70	8	55	7	48	6.5	45		
	H38	Rolled rod and shapes	75	25	2	44	305	32	220	26	180	24	165	23	160	22	150		
			300	150	2	...	...	26	180	20.5	140	17.5	120	15.5	105	14.5	100		
			400	205	1	...	...	21.5	150	15	105	12.5	85	11.5	80	11	75		
			500	260	2	...	...	15	105	10	70	8	55	7	48	6.5	45		
5356	O	Rolled rod and shapes, plate	75	25	2	41	285	30	205	22	150	19	130	18	125	18	125		
			300	150	1	30	205	22	150	18	125	16	110	15.5	105	15	105		
			500	260	1	21	145	15	105	11	75	8.5	59	7.5	52	7	48		
			75	25	1	44	305	32	220	24	165	21	145	20	140	20	140		
	H32	Rolled rod and shapes	300	150	1	...	...	25.5	175	20	138	17.5	120	16	110	16	110		
			500	260	1	22.5	155	16	110	11	75	8	55	7	48	6.5	45		
			75	25	1	44	305	32	220	24	165	21	145	20	140	20	140		
			300	150	1	...	...	25.5	175	18	125	15.5	105	15	105	14.5	100		
	H34	Rolled rod and shapes	500	260	1	23.5	160	17	115	10.5	72	8	55	7.5	52	7.5	52		
			75	25	1	44	305	32	220	24	165	21	145	20	140	20	140		
			300	150	1	...	...	25.5	175	18	125	15.5	105	15	105	14.5	100		
			500	260	1	23.5	160	17	115	10.5	72	8	55	7.5	52	7.5	52		
5454	O	Rolled rod and shapes, plate	75	25	5	33	230	26	180	22	150	21	145	20	140	20	140		
			300	150	2	25	170	19.5	134	14.5	100	12	85	11	75	11	75		
			400	205	2	23	160	17.5	120	13	90	11	75	10	70	9	62		
			500	260	1	22	150	17	115	12.5	85	10	70	9	62	8.5	59		
	H32	Plate	600	315	1	19	130	14	95	9.5	66	7	48	5.5	38	5	34		
			75	25	1	36	250	28	195	22	150	21	145	20	140	20	140		
			300	150	1	28	195	21.5	150	17	115	15	105	14	95	13	90		
			400	205	1	26	180	20	140	15	105	13	90	12	85	12	85		
	H34	Rolled rod and shapes, plate	500	260	1	24	165	19	130	14	95	11	75	9	62	9	62		
			600	315	1	21	145	14.5	100	9.5	66	6.5	45	5.5	38	5	34		
			75	25	3	36	250	28	195	23	160	22	150	21	145	21	145		
			300	150	1	31	215	24	165	17.5	120	14	95	13	90	12.5	85		
5456	O	Rolled rod and shapes, plate	400	205	1	28	195	22	150	15.5	105	12	85	10.5	70	9.5	66		
			75	25	5	42	290	32	220	25	170	23	160	22.5	155	22.5	155		
			300	150	1	31	215	24	165	20	140	17.5	120	16	110	15.5	105		
			400	205	1	27	185	21	145	15.5	105	12	85	10.5	70	10	70		
	H321	Plate	500	260	1	24	165	18	125	13	90	10	70	9	62	9	62		
			600	315	1	21	145	14.5	100	9.5	66	6.5	45	6	41	5.5	38		
			75	25	6	44	305	34	235	26	180	24	165	23.5	160	23	160		
			300	150	1	...	...	25.5	175	19.5	135	16.5	115	14.5	100	14	95		
	H321	Plate	400	205	1	29	200	23	160	17	115	12.5	85	10.5	70	10.5	70		
			500	260	1	25	170	17	115	11.5	80	8.5	59	6.5	45	6	41		
			600	315	1	21	145	13.5	95	9.5	66	7.5	52	5.5	38	5	34		

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.3 (continued)

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa				
6061	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	18	44	305	31	215	23	160	17	115	15	105	13.5	95		
6063	O	Cast tube	300	150	1			31	215	22.5	155	16.5	115	13	90	12	85		
		Extrusions	75	25	1	11.5	80	10	70	9	62	8	55	7.5	52	7.5	52		
			300	150	1	8.5	59	7	48	6	41	5.5	38	5	34	4.5	31		
			400	205	1	7	48	6	41	5	34	4.5	31	3.5	24	3	21		
	T42	Extrusions	75	25	1	26.5	185	19.5	135	16	110	13.5	95	11	75	10	70		
			300	150	1	...	...	19	130	12.5	85	9	62	6.5	45	6	41		
			400	205	1	22	150	16.5	115	10.5	70	7.5	52	5	34	4.5	31		
			500	260	1	16.5	115	12	85	8	55	5	34	3.5	24	3	21		
	T5	Extrusions	75	25	1	28	195	20.5	140	15.5	105	12	85	10.5	70	10	70		
			300	150	1	22	150	17.5	120	11.5	80	8.5	59	7	48	6.5	45		
			400	205	1	22	150	16.5	115	11.5	80	7.5	52	5	34	4.5	31		
			500	260	1	16.5	115	12	85	8	55	4.5	31	3	21	2.5	17		
	T6	Extrusions	75	25	1	34	235	23.5	160	16.5	115	13.5	95	11	75	10	70		
			300	150	1	27	185	17.5	120	11.5	80	8.5	59	7	48	6.5	45		
			400	205	1	22	150	16.5	115	11.5	80	7.5	52	5	34	4.5	31		
			500	260	...	16.5	115	12	85	8	55	4.5	31	3	21	2.5	17		
6151	T6	Rolled rod and shapes, forgings	75	25	5	43	295	30	205	22	150	17	115	13	90	12	85		
6201	T81	Forgings	300	150	1	...	...	26	180	19.5	135	13.5	95	10	70	9	62		
			350	177	2	...	...	23	160	16.5	115	11.5	80	8	55	7	48		
			400	205	2	...	...	22	150	16	110	10.5	70	7.5	52	7	48		
			500	260	1	...	...	17.5	120	12.5	85	8	55	4	28	3	21		
		Rolled rod and shapes	75	25	1	...	...	29	200	22	150	18	125	16	110	15	105		
			212	100	1	...	...	28	195	21	145	16	110	11	75	8.5	59		
			300	150	1	...	...	25	170	17.5	120	11	75	6.5	45	5	34		
			7073	T6	Plate, forgings	75	25	2	...	...	...	...	26	180	20	140	16	110	15
7073	T6	Forgings	350	177	1	...	...	...	...	18	125	13.5	95	9.5	66	8	55		
			400	205	1	...	...	...	...	14	95	10	70	7	48	5.5	38		
			500	260	1	...	...	16	110	10	70	6.5	45	4.5	31	4	28		
		7074	T6	Rolled rod and shapes, forgings, extrusions	75	25	4	...	...	40	275	30	205	26	180	22	150	21	145
7075	T6	Extrusions	300	150	1	...	...	...	...	...	...	21	145	17.5	120	17	115		
			400	205	1	...	...	...	...	...	...	15.5	105	10	70	9	62		
			500	260	1	20	140	16.5	115	13	90	10	70	7	48	6.5	45		
		Rolled rod and shapes, plate, forgings, extrusions	75	25	59	55	380	40	275	29	200	24	165	22	150	22	150		
			Rolled rod and shapes	300	150	2	...	...	40	275	29	200	24	165	19.5	135	17.5	120	
				400	205	2	44	305	33	230	22	150	16.5	115	12.5	85	11	75	
			500	260	2	25	170	18	125	14	95	10.5	70	8.5	59	8	55		
			600	315	1	17	115	14	95	11	75	9	62	7	48	6	41		

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.3 (continued)

Alloy	Temper	Product form	Testing temperature		No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
						ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
7075	T651	Rolled rod and shapes, plate	75	25	8	55	380	40	275	29	200	24	165	22	150	22	150		
		Rolled rod and shapes	300	150	1	...	...	40	275	29	200	24	165	19.5	135	17.5	120		
			400	240	1	44	305	33	230	22	150	16.5	115	12.5	85	11	75		
			500	260	1	25	170	18	125	14	95	10.5	70	8.5	59	8	55		
			600	315	1	17	115	14	95	11	75	9	62	7	48	6	41		
7076	T6	Rolled rod and shapes, forgings	75	25	28	...	...	38	260	29	200	24	165	22	150	21	145		
		Forgings	300	150	1	...	...	...	...	25	170	20	140	17	115	15	105		
			400	205	1	...	...	24.5	170	19	130	13.5	95	10	70	7.5	52		
			500	260	1	...	...	17.5	120	12.5	85	8	55	6	41	5.5	38		
7079(a)	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	26	54	370	40	275	29	200	24	165	22	150	22	150		
		Rolled rod and shapes, forgings	300	150	3	...	...	31	215	25.5	175	21.5	150	18.5	130	18	125		
			400	205	3	41	285	27	185	21.5	150	16.5	115	13.5	95	12.5	85		
		T651	Rolled rod and shapes, plate	75	25	8	54	370	40	275	29	200	24	165	22	150	22	150	
			Rolled rod and shapes	300	150	1	...	...	31	215	25.5	175	21.5	150	18.5	130	18	125	
7177	T6		400	205	1	41	285	28	195	21.5	150	16.5	115	13.5	95	12.5	85		
		Rolled rod and shapes	75	25	1	...	...	42	290	31	215	27	185	24	165	23	160		
			300	150	1	...	...	30	205	24.5	170	21.5	150	19.5	135	19	130		
7178	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	9	59	405	47	325	36	250	29	200	25.5	175	24.5	170		
		Rolled rod and shapes	300	150	1	...	...	39	270	28	195	22.5	155	18.5	130	16	110		
			400	205	1	41	285	31	215	22	150	16	110	11.5	80	10.5	70		
		T651	Rolled rod and shapes, plate	75	25	4	...	...	47	325	36	250	29	200	25	170	23	160	
			300	150	1	...	...	39	270	28	195	22.5	155	18.5	130	16	110		
7179(a)	T6		400	205	1	41	285	31	215	22	150	16	110	11.5	80	10.5	70		
		Forgings	75	25	1	36	250	26	180	23	160	23	160	22	150	...	...		
		Castings	300	150	1	...	...	37	255	26	180	21	145	18	125	...	...		
7370	T6	Rolled rod and shapes, forgings	75	25	2	...	...	33	230	26	180	22.5	155	21	145	20	140		
			300	150	1	...	...	27	185	21	145	16.5	115	15.5	105	15	105		
			400	205	1	...	...	22.5	155	17	115	12	85	7.5	52	7	48		
			500	260	1	21.5	150	15	105	10.5	70	7.5	52	5.5	38	5	34		

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle subjecting the specimen to completely reversed loading. Specimens held at testing temperature 0.5 h before applying load. Testing speed = 3450 cpm. Values at room temperature 75 °F (25 °C) from rotating-beam tests. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Elevated temperature cantilever-beam fatigue tests after long-time stabilization at the test temperature. Tests were made of specimens of the type in Fig. A5.2 in accordance with ASTM standard test methods in existence at the time. Test temperatures ranging from 75 to 600 °F (25 to 315 °C) were used. The tests were started immediately after the specimens reached the test temperature (about 1/2 h), but the specimens had previously been soaked in furnaces, not under stress, for the indicated time at the test temperature to represent service exposure. The bending stress in such specimens was completely reversed ($R = -1.0$). Test speeds were about 3450 rpm. The tests were made over the period from about 1950 through about 1980. There was no atmospheric control in the testing laboratories.

In general, each fatigue curve was generated from tests of 10 to 15 specimens, a number of which were used to identify the highest

stress that would not cause failure in 10 million cycles. An average fatigue curve was drawn through the completed data set, usually with appropriate extrapolation to 500 million cycles which was identified as the endurance limit. The table entries are the intersections of the average line with the respective cyclic lives.

The metric/SI units shown in the table were calculated by multiplying the fatigue strength values measured in engineering units by the conversion factor of 1 MPa = 6.897 ksi, and then rounded by the aluminum industry standard to the nearest 5 MPa, except in the case of values less than 10 ksi, for which the converted value was not rounded.

The results of cantilever-beam rotating-bending fatigue tests made at elevated temperatures after the specimens had been held relatively long times at the test temperatures are presented in Table A5.4.

Table A5.4 Cantilever-beam fatigue strengths of stabilized wrought aluminum alloys at elevated temperatures following stabilization at the test temperature

Alloy	Temper	Product form	Testing temperature		Holding time, days	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles		
			°F	°C			10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles						
							ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa			
1100	H18	Rolled rod and shapes	75	25	...	2	22	150	16.5	115	13.5	95	11	75	10	70	9	62			
			300	150	60	1	...	...	11.5	80	7	48	4.5	31	3.5	24	3	21			
			400	205	60	1	...	...	8.5	59	5.5	38	4	28	3	21	2.5	17			
			500	260	7	1	...	...	3	21	2.5	17	2.5	17	2	14	2	14			
2011	T3	Rolled rod and shapes	75	25	...	2	46	315	35	240	26.5	185	22.5	155	19.5	135	18	125			
			300	150	300	1	25	170	19	130	14.5	100	11.5	80	9	62	7.5	52			
			400	205	207	1	17.5	120	13.5	95	10.5	70	8	55	6	41	5	34			
			500	260	100	1	10	70	8	55	6	41	4	28	3	21	3	21			
2014	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	...	54	52	360	39	270	30	205	24	165	19	130	18	125			
			300	150	365	1	28	195	23	160	18	125	15	105	13	90	12	85			
			400	205	250	1	17	115	14	95	12	85	10	70	8.5	59	8	55			
			500	260	242–600	2	12	85	10	70	8.5	59	7	48	5.5	38	5	34			
2017	T4	Extrusions	600	315	169	1	10.5	70	8.5	59	7	48	5.5	38	5	34	4.5	31			
			75	25	...	6	...	...	40	275	32	220	24	165	19	130	18	125			
			300	150	1534	1	...	...	32	220	26	180	21	145	17.5	120	16.5	115			
			400	205	1534	1	...	...	26	180	20	140	15	105	12	85	10.5	70			
			500	260	242	1	26	180	20	140	15	105	10.5	70	7.5	52	6.5	45			
			600	315	169	1	16.5	115	13.5	95	10.5	70	9	62	7	48	6	41			
			2018	T61	Rolled rod and shapes, forgings	75	25	...	7	53	365	42	290	29	200	23	160	19.5	135	17	115
			300			150	700	1	...	...	27	185	19.5	135	14.5	100	11	75	10	70	
300	150	300	2			...	...	27	185	19.5	135	14.5	100	12.5	85	11	75				
400	205	300	2			...	...	18	125	13.5	95	10	70	7.5	52	6.5	45				
			400	205	200	1	22	150	18	125	13.5	95	10	70	7.5	52	6.5	45			
			500	260	300	2	...	...	11.5	80	9	62	7	48	5.5	38	5	34			
			2024	T4	Forgings	500	260	25	1	15.5	105	11.5	80	9	62	7	48	5.5	38	5	34
			75			25	...	20	56	385	43	295	31	215	24	165	21	145	20	140	
300	150	659	1			...	...	24	165	20	140	17	115	15	105	14	95				
400	205	659	1			...	...	20	140	16	110	13	90	10	70	9.5	66				
			500	260	242	1	14	95	11.5	80	9.5	66	8	55	7.5	52	7.5	52			
			500	260	40	1	...	...	14	95	11	75	8.5	59	7	48	6	41			
			600	315	169	1	12	85	10	70	8	55	6.5	45	6.5	45	6.5	45			
			2025	T6	Rolled rod and shapes, forgings, extrusions	75	25	...	27	...	...	35	240	26	180	21	145	17	115	15	105
300	150	200	2			...	...	19	130	14.5	100	12	85	10.5	70	10	70				
400	205	80	2			18	125	14	95	11	75	8.5	59	7.5	52	7	48				
500	260	80	2			12	85	9.5	66	7	48	5.5	38	4.5	31	4.5	31				

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle, subjecting the specimen to completely reversed loading. Specimens machined from materials held at testing temperature as noted. Test speed = 3450 cpm. Values at 75 °F (25 °C) from rotating-beam tests on material as fabricated. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.4 (continued)

Alloy	Temper	Product form	Testing temperature		Holding time, days	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C			10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
			ksi	MPa			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa				
2027	T6	Rolled rod and shapes	75	25	...	1	...	...	...	...	27	185	20	140	15	105	13	90		
			300	150	151	1	...	...	...	...	19.5	135	16	110	12.5	85	10.5	70		
			400	205	102	1	...	...	14.5	100	12	85	10	70	8.5	59	8	55		
			500	260	102	1	...	...	...	...	5.5	38	5	34	4	28	4	28		
2218	T61	Rolled rod and shapes, forgings	75	25	...	4	50	345	40	275	32	220	26	180	21	145	19	130		
			300	150	700	1	...	...	...	...	20	140	15.5	105	11	75	10	70		
			400	205	200	1	18.5	130	15.5	105	12.5	85	10	70	8	55	7.5	52		
			500	260	25	1	14	95	11.5	80	9.5	66	7.5	52	6	41	5.5	38		
3003	H18	Rolled rod and shapes	75	25	...	3	28	195	19	130	14	95	11.5	80	10.5	70	10	70		
			300	150	7	1	...	...	15.5	105	11	75	8.5	59	7.5	52	7.5	52		
			400	205	7	1	18	125	12	85	8.5	59	6.5	45	5	34	5	34		
			500	260	7	1	12.5	85	9	62	6	41	4.5	31	3.5	24	3.5	24		
3004	H38	Rolled rod and shapes	75	25	...	2	34	235	28.5	195	23	160	20.5	140	19	130	18	125		
			300	150	215	1	...	...	21	145	16	110	11.5	80	9.5	66	9	62		
			400	205	92	1	...	...	18.5	130	12	85	9	62	7.5	52	7	48		
			500	260	31	1	...	...	11	75	8	55	6	41	5.5	38	5	34		
4032	T6	Rolled rod and shapes	75	25	...	2	42	290	38	260	30	205	24	165	18	125	16.5	115		
			300	150	369	1	...	...	21	145	17	115	13	90	10	70	9	62		
			400	205	250	2	19	130	13	90	10.5	70	8.5	59	7	48	6.5	45		
			500	260	151	2	...	...	9.5	66	7.5	52	6	41	4.5	31	4	28		
5052	H36	Rolled rod and shapes	75	25	...	1	39	270	28	195	22	150	20	140	19	130	19	130		
			300	150	120	1	...	...	22.5	155	16.5	115	13	90	12.5	85	12.5	85		
			400	205	60	1	...	...	19.5	135	13.5	95	10.5	70	9.5	66	9.5	66		
			500	260	60	1	...	...	12	83	8.5	59	7	48	6	41	6	41		
6051	T6	Rolled rod and shapes	75	25	...	2	...	...	...	...	21	145	15	105	12	85	11	75		
			300	150	300	1	...	...	17.5	120	12.5	85	9.5	66	7.5	52	7	48		
			400	205	240	1	14.5	100	11	75	8.5	59	6	41	4.5	31	4	28		
			500	260	60	1	4.5	31	4	28	4	28	3	21	2.5	17	2	14		
6053	H16	Rolled rod and shapes	75	25	...	1	23.5	160	19	130	15	105	13.5	95	12	85	11	75		
			300	150	201	1	...	...	13	90	9	62	6	41	5	34	5	34		
			400	205	200	1	14.5	100	10	70	6.5	45	4.5	31	4	28	3.5	24		
			500	260	104	1	...	...	6.5	45	4.5	31	3.5	24	3	21	2.5	17		
6061	T6	Rolled rod and shapes, extrusions	75	25	...	3	36.5	250	29	200	22	150	17.5	120	14.5	100	13	90		
			300	150	260	2	...	...	20	140	15	105	11.5	80	9.5	66	9	62		
			400	205	260	2	15.5	105	12.5	85	9.5	66	7.5	52	6.5	45	6	41		
			500	260	100	1	8.5	59	7.5	52	6	41	5.5	38	4.5	31	4.5	31		
6061	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	...	18	44	305	31	215	23	160	17	115	15	105	14	95		
			300	150	300	1	...	...	24	165	18	125	14	95	11	75	11	75		
			400	205	200	1	24	165	19	130	15	105	11	75	8.5	59	7.5	52		
			500	260	100	1	8.5	59	7.5	52	6	41	5.5	38	4.5	31	4.5	31		
6151	T6	Rolled rod and shapes, forgings	75	25	...	5	43	295	30	205	22	150	17	115	13	90	12	85		
			300	150	450–700	2	...	...	21	145	16	110	11	75	9	62	8.5	59		
			400	205	200	2	14	95	11	75	8	55	6	41	5	34	4.5	31		
			500	260	7–27	2	9	62	6.5	45	5.5	38	4.5	31	4	28	3.5	24		

(continued)

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle, subjecting the specimen to completely reversed loading. Specimens machined from materials held at testing temperature as noted. Test speed = 3450 cpm. Values at 75 °F (25 °C) from rotating-beam tests on material as fabricated. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.4 (continued)

Alloy	Temper	Product form	Testing temperature		Holding time, days	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			°F	°C			10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles					
							ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
7070(a)	T6	Rolled rod and shapes, forgings	75	25	...	2	...	...	...	...	26	180	24	165	22	150	21	145		
			300	150	200	1	...	...	17.5	120	13.5	95	11.5	80	10	70	9.5	66		
		Rolled rod and shapes	400	205	200	1	12.5	85	10.5	70	8.5	59	7	48	6	41	6	41		
			500	260	100	1	...	...	7.5	52	6	41	5	34	4.5	31	4.5	31		
7075	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	...	59	55	380	40	275	29	200	24	165	22	150	22	150		
			300	150	365	1	21	145	18	125	15	105	13	90	12	85	12	85		
		Rolled rod and shapes	400	205	171	1	16	110	13	90	11	75	9.5	66	8.5	59	8.5	59		
			500	260	60	1	14	95	12	85	9.5	66	8	55	7.5	52	7	48		

Tests at elevated temperatures made in cantilever-beam machines in which one end of the specimen is deflected in the path of a circle, subjecting the specimen to completely reversed loading. Specimens machined from materials held at testing temperature as noted. Test speed = 3450 cpm. Values at 75 °F (25 °C) from rotating-beam tests on material as fabricated. Approximate completely reversed flexural stresses. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.5 Cantilever-beam rotating-beam reversed-bending fatigue strengths of cast aluminum alloys at elevated temperatures

Fatigue strengths determined from reserved-bending tests of 0.330 in. (8.38 mm) diam specimens in R.R. Moore or cantilever-beam rotating-beam machines

Alloy	Temper	Test temperature		Fatigue strength at indicated cycles										Endurance limit at 5 × 10 ⁸ cycles	
		°F	°C	10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles		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
242.0	T77	600	315	...	...	14.0	97	9.5	66	7.0	48	5.5	38	5.0	34
		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
249.0	T7	600	315	...	...	11.5	79	8.5	59	6.0	41	4.0	28	3.5	24
		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
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
333.0	T5	600	315	18.0	124	13.0	90	8.5	59	5.5	38	4.0	28	3.5	24
		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
	T7	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
		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
336.0	T551	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
		RT	RT	...	...	21.0	145	18.0	124	16.0	110	14.5	100	13.5	93
	T6	300	150	...	...	19.5	134	15.0	103	13.0	90	11.0	76	10.5	72
		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
		RT	RT	50.0	345	40.0	276	31.0	214	25.5	176	21.0	145	19.5	134
354.0	T6	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	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	...	...
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

(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 A5.5 (continued)

		Test temperature		Fatigue strength at indicated cycles										Endurance limit at 5 × 10 ⁸ cycles	
				10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
Alloy	Temper	°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
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

Flexural fatigue data tests were made of specimens (Fig. A5.3) in sheet flexure-fatigue machines in accordance with ASTM standard test methods in existence at the time. The bending stress in such specimens was uniform across the test section and completely reversed ($R = -1.0$). Test speeds were about 3500 rpm. The tests were made over the period from about 1950 through about 1985. There was no atmospheric control in the testing laboratories.

In general, each fatigue curve was generated from tests of 10 to 15 specimens, sometimes from several samples (lots), a number of which were used to identify the highest stress that would not cause failure in 10 million cycles. An average fatigue curve was drawn through the completed data set, usually with appropriate extrapolation to 500 million cycles which was identified as the endurance limit, and the table entries are the intersections of the average line with the respective cyclic lives.

The metric/SI units shown in the table were calculated by multiplying the fatigue strength values measured in engineering units by the conversion factor of 1 MPa = 6.897 ksi, and then rounded by the aluminum industry standard to the nearest 5 MPa, except in

the case of values less than 10 ksi, for which the converted value was not rounded.

The alloys are presented in Table A5.6 in numeric order.

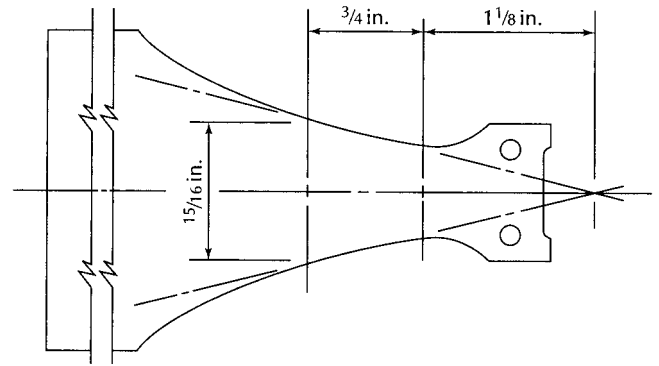


Fig. A5.3 Flat sheet, flexural fatigue specimen

Table A5.6 Average flexural fatigue strengths for aluminum alloy flat sheet under completely reversed flexure at room temperature

Alloy	Temper	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
			10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1100	O	1	...	...	...	...	8	55	6.5	45	5.5	38	5	34	5	34
	H18	1	...	...	...	...	16.5	115	12.5	85	10	70	9	62	8	55
1160	H14	1	21	145	15	105	10.5	70	7	48	6	41	5.5	38	5.5	38
2014	T3	...	...	...	...	...	35	240	25	170	20	140	19	130	18	125
Alclad 2014	T6	1	...	...	...	...	35	240	25	170	20	140	19	130	18	125
	T3	1	...	...	...	...	31	215	20	140	17	115	15	105	15	105
	T6	2	...	...	...	...	31	215	20	140	17	115	15	105	15	105
2017	T3	1	...	...	...	...	...	...	24	165	20	140	18	125	17	115
Alclad 2017	T3	1	...	...	...	...	25	170	18	125	14	95	13	90	12	85
2020	O	1	...	...	23	160	18	125	14.5	100	12.5	85	12	85	11.5	80
Alclad 2020	T4	1	...	...	...	...	31	215	21	145	17.5	120	16.5	115	16	110
	T6	4	...	...	...	...	32	220	24	165	20	140	19	130	18	125
	T6	2	...	...	...	...	26	180	14	95	12	85	11.5	80	11	75
2024	T3	6	...	...	...	...	34	235	26	180	21	145	18	125	18	125
Alclad 2024	T36	2	...	...	...	...	37	255	29	200	22	150	19	130	19	130
	T6	2	...	...	...	...	37	255	26	180	21	145	18	125	18	125
	T81	3	...	...	...	...	34	235	26	180	21	145	18	125	18	125
	T86	3	...	...	...	...	34	235	26	180	21	145	18	125	18	125
	T3	7	...	...	...	...	31	215	19	130	15	105	13	90	13	90
	T36	2	...	...	...	...	31	215	19	130	15	105	13	90	13	90

(continued)

Average strengths. Values determined using specimens taken from flat sheet with as-rolled surfaces, subjected to reversed-bending stresses in either constant-load or constant-deflection fatigue testing machines. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.6 (continued)

			Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
Alloy	Temper	No. of samples	10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
			ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Alclad 2024	T81	3	...	...	...	...	31	215	19	130	15	105	13	90	13	90
	T86	2	...	...	...	...	31	215	19	130	15	105	13	90	13	90
2219	T6	1	...	...	...	...	30	205	20	140	17	115	16	110	15	105
	T62	2	...	...	...	...	30	205	20	140	17	115	16	110	15	105
Alclad 2219	T6	1	...	...	...	...	23	160	13	90	11	75	10	70	10	70
	T62	2	...	...	...	...	23	160	13	90	11	75	10	70	10	70
2618	T6	1	...	...	...	...	34	235	24	165	20	140	18	125	17.5	120
3003	O	2	...	...	18	125	11	75	8	55	7	48	6	41	6	41
	H14	2	...	...	26	180	18	125	14	95	13	90	12	85	11	75
Alclad 3003	H14	1	...	...	22	150	15	105	11	75	9	62	8	55	8	55
3004	O	1	...	...	...	...	16	110	14	95	13	90	12.5	85	12	85
	H18	1	...	...	...	...	30	205	22	150	20	140	18.5	130	18	125
Alclad 3004	H16	1	...	...	27	185	20	140	15	105	13.5	95	13	90	13	90
	H291	1	...	...	...	...	26	180	16	110	13	90	12.5	85	12	85
3105	H14	1	...	...	...	...	24	165	18	125	17	115	16	110	15	105
Alclad 3105	H14	1	...	...	...	...	19	130	14	95	12	85	11	75	10	70
5050	O	1	...	...	30	205	20	140	14	95	12	85	11	75	10.5	70
	H34	1	40	275	31	215	23	160	17	115	14	95	13.5	95	13	90
	H35	1	...	...	37	255	26	180	18.5	130	17	115	16	110	15	105
5052	O	1	...	...	...	...	22	150	18	125	16	110	15.5	105	15	105
	H291	1	...	...	...	...	32	220	23	160	20	140	19	130	18.5	130
	H34	1	...	...	...	...	27	185	22.5	155	19	130	18.5	130	18	125
5083	O	1	...	...	40	275	28	195	22	150	19	130	17	115	16	110
	H24	1	...	...	...	...	31	215	24	165	23	160	22	150	21	145
	H34	1	...	...	...	...	31	215	24	165	23	160	22	150	21	145
5086	O	2	...	...	40	275	26	180	20	140	17.5	120	16.5	115	16	110
	H34	2	...	...	41	285	30	205	23	160	21	145	20	140	19.5	135
5154	O	2	...	...	...	...	27	185	18	125	15	105	14	95	13.5	95
	H34	2	...	...	...	...	29	200	21	145	18	125	17.5	120	17	115
	H38	2	...	...	...	...	31	215	22	150	19	130	18.5	130	18	125
Alclad 5155	H38	3	...	...	...	...	28	195	15	105	13	90	12.5	85	12	85
5456	O	3	...	...	40	275	29	200	22	150	20	140	19	130	18	125
	H14	1	...	...	...	...	34	235	25	170	23	160	22	150	22	150
	H18	1	...	...	...	...	34	235	27	185	24	165	23	160	23	160
	H24	1	...	...	...	...	34	235	25	170	23	160	22	150	22	150
	H34	2	...	...	...	...	34	235	25	170	23	160	22	150	22	150
6053	O	1	...	...	...	...	9	62	8	55	7.5	52	7	48	7	48
	T4	1	...	...	...	...	...	...	21	145	15.5	105	14	95	14	95
	T6	1	...	...	...	...	...	...	19	130	16	110	14	95	13	90
6061	T6	5	...	...	...	...	30	205	22	150	17	115	16	110	15	105
Alclad 6061	T6	1	...	...	...	...	23	160	13	90	10	70	9	62	8.5	59
6062	O	1	...	...	20	140	15	105	11	75	9.5	66	9	62	8.5	59
	T4	1	47	325	37	255	28	195	20	140	15	105	14	95	13.5	95
	T6	1	...	...	46	315	32	220	22	150	16	110	14	95	13.5	95
6071	T6	2	...	...	...	...	31	215	21	145	16.5	115	15.5	105	15	105
7002(a)	T6	1	...	...	...	...	35	240	22	150	19	130	17.5	120	17	115
7005	T63	1	...	...	...	...	...	...	21	145	17	115	16	110	15.5	105
7006(a)	T6	...	...	...	...	...	35	240	23	160	19	130	18	125	16.5	115
	T63	2	...	...	...	...	35	240	23	160	19	130	18	125	16.5	115
7039	T6E86	1	...	...	...	...	33	230	23	160	18.5	130	17	115	16	110
7071	T4	1	...	...	...	...	27	185	20	140	18	125	17	115	17	115
	T6	1	...	...	...	...	...	...	20	140	18	125	17	115	17	115
7074	T6	1	...	...	...	...	37	255	26	180	21	145	20	140	20	140
Alclad 7074	T6	3	...	...	...	...	31	215	19	130	15	105	13	90	13	90
7075	T6	5	...	...	...	...	37	255	26	180	21	145	20	140	20	140
	T73	4	...	...	...	...	37	255	26	180	21	145	20	140	20	140
Alclad 7075	T6	2	...	...	...	...	31	215	19	130	15	105	13	90	13	90
7079	T6	2	...	...	...	...	32	220	23	160	19	130	18	125	18	125
Alclad 7079(a)	T6	1	...	...	...	...	26	180	17	115	15	105	14	95	14	95
Alclad 7106(a)	T6	3	...	...	...	...	33	230	23	160	18.5	130	16	110	16	110
Alclad 7139(a)	T6	1	...	...	...	...	34	235	24	165	18.5	130	16	110	15	105
7175	T6	1	...	...	...	...	37	255	26	180	21	145	20	140	20	140
Alclad 7175	T6	1	...	...	...	...	31	215	19	130	15	105	13	90	13	90
7178	T6	2	...	...	...	...	37	255	26	180	21	145	20	140	20	140
	T76	2	...	...	...	...	33	230	24	165	20	140	18	125	17	115
Alclad 7178	T6	3	...	...	...	...	24	165	15	105	13	90	12	85	12	85
7277	T6	1	...	...	51	350	35	240	24	165	20	140	19	130	18	125

Average strengths. Values determined using specimens taken from flat sheet with as-rolled surfaces, subjected to reversed-bending stresses in either constant-load or constant-deflection fatigue testing machines. (a) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Axial-stress fatigue data tests were made of specimens of the type in Fig. A5.4 in accordance with then current ASTM standard test methods. The tests were made over a period from about 1950 through about 1985. There was no atmospheric control in the testing laboratories.

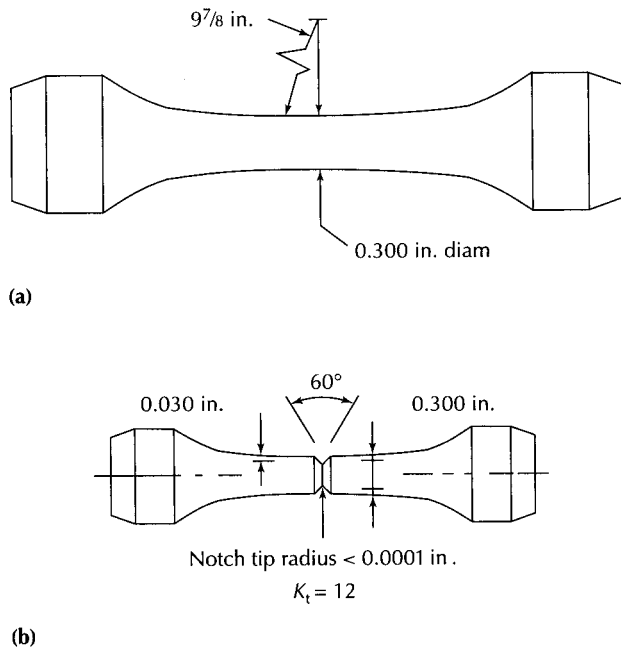


Fig. A5.4 (a) Smooth and (b) notched axial-stress fatigue specimens

Test speeds ranged from about 1750 to 3500 rpm (no speed of testing effect was ever noted over this range). In general, each fatigue curve was generated from tests of 10 to 15 specimens, representing several samples (i.e., several commercial lots and compositions), a number of which were used to identify the highest stress that would not cause failure in 10 million cycles. An average fatigue curve was drawn through the completed data set, usually with appropriate extrapolation to 500 million cycles which was identified as the endurance limit, and the table entries are the intersections of the average line with the respective cyclic lives.

The metric/SI units shown in the table were calculated by multiplying the fatigue strength values measured in engineering units by the conversion factor of 1 MPa = 6.897 ksi, and then rounded by the aluminum industry standard to the nearest 5 MPa, except in the case of values less than 10 ksi, for which the converted value was not rounded.

Fatigue strengths from axial-stress fatigue tests at various stress ratios are shown in Table A5.7 for wrought aluminum alloys and Table A5.8 for cast aluminum alloys.

Table A5.7 Axial-stress fatigue strength at various stress ratios

Temper	Product form	Stress ratio(a), <i>R</i>	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
				10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles		ksi	MPa
				ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
1350 smooth specimens																	
H18	Rolled rod and shapes	0	1	...	...	...	...	+23	+160	+17	+115	+15	+105	+14.5	+100	+14.5	+100
		-1	1	...	...	...	...	+11.5	+80	+8.5	+59	+7	+48	+6.5	+45	+6.5	+45
2014 smooth specimens																	
T6	Rolled rod and shapes, forgings, extrusions	+0.5	3	+71	+490	+70	+485	+68	+470	+59	+405	+56	+385	+55	+380	+55	+380
	Extrusions	+0.2	1	+75	+515	+74	+510	+60	+415	+51	+350	+48	+330	+46	+315	+46	+315
	Rolled rod and shapes, plate, forgings, extrusions	0	14	+71	+490	+66	+455	+54	+370	+43	+295	+37	+255	+33	+230	+30	+205
	Extrusions	-0.33	1	+69	+475	+63	+435	+49	+340	+39	+270	+34	+235	+30	+205	+28	+195
	Forgings	-0.5	1			+56	+385	+42	+290	+33	+230	+26	+180	+22	+150	+20	+140
	Rolled rod and shapes, forgings, extrusions	-1	4	+53	+365	+48	+330	+35	+240	+28	+195	+21	+145	+17	+115	+15	+105
	Forgings	-2	1	...	...	...	...	+22	+150	+17	+115	+13	+90	+11	+75	+10	+70
		$-\infty$	1	-71(b)	-490(b)	-70(b)	-485(b)	-63(b)	-435(b)	-49(b)	-340(b)	-40(b)	-275(b)	33(b)	-230(b)	-30(b)	-205(b)
2014 notched specimens(c)																	
T6	Forgings	0	1	...	...	+27	+185	+20	+140	+15	+105	+12.5	+85	+10.5	+70	+10	+70
	Rolled rod and shapes, forgings	-1	2	...	...	+20	+140	+13	+90	+8	+55	+6.5	+45	+6	+41	+6	+41
2017 smooth specimens																	
T4	Rolled rod and shapes	+0.75	1	...	...	...	...	...	...	+62	+425	+61	+420	+60	+415	+59	+405
		+0.5	3	...	...	...	...	+56	+385	+47	+325	+44	+305	+43	+295	+42	+290
		0	2	+59	+405	+57	+395	+45	+310	+38	+260	+31	+215	+26	+180	+24	+165
		-0.5	2	...	...	...	...	+37	+255	+30	+205	+24	+165	+19.5	+135	+18	+125
		-1	3	...	...	+45	+310	+32	+220	+25	+170	+20	+140	+16.5	+115	+15	+105
		-2	2	...	...	...	...	+20	+140	+16	+110	+13	+90	+11	+75	+10	+70
		$-\infty$	2	...	...	...	...	-47(b)	-325(b)	-43(b)	-295(b)	-41(b)	-285(b)	-39.5(b)	-270(b)	-39(b)	-270(b)
2020 smooth specimens																	
T6	Plate	+0.5	1	...	...	...	...	+71	+490	+58	+400	+51	+350	...	...	...	...
	Plate, sheet	0	3	...	...	...	...	+47	+325	+34	+235	+31	+215	+30	+205	+30	+205
	Plate	-1	1	...	...	+58	+400	+35	+240	+23	+160	+21	+145	...	...	...	...
T651	Plate	0	1	+76	+525	+71	+490	+58	+400	+45	+310	+38	+260	+35	+240	+34	+235
2020 notched specimens(c)																	
T6	Plate	+0.5	1	...	...	...	...	+27	+185	+18	+125	+14	+95	+12.5	+85	...	...
		0	1	...	...	+30	+205	+20	+140	+14	+95	+12	+85	...	...	...	...
		-1	1	...	...	+21	+145	+14	+95	+9.5	+66	+6.5	+45	...	...	...	...
2021 smooth specimens																	
T8	Plate	0	1	...	...	+67	+460	+47.5	+330	+31.5	+215	+27	+185	+26	+180	...	...
2024 smooth specimens																	
T4	Extrusions	+0.5	2	...	...	+81	+560	+66	+455	+57	+395	+53	+365	+51.5	+355	+51	+350
		+0.3	1	...	...	+74	+510	+59	+405	+47.5	+330	+41	+285	...	...	...	...
	Rolled rod and shapes, extrusions	0	8	+80	+550	+67	+460	+55	+380	+44	+305	+37	+255	+34	+235	+33	+230

(continued)

Positive value (+) indicates tension; minus (-) indicates compression.

(a) Stress ratio (R) = (minimum stress)/(maximum stress). (b) Minimum stress in each cycle (maximum stress is zero). (c) Notched specimens; values determined using specimens containing a single 60° sharp V-notch, 0.03 in. (0.762 mm) deep with root diameter of 0.300 in. (7.62 mm) and a root radius at base of notch less than 0.0005 in. (0.0125 mm) ($K_t > 12$). (d) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.7 (continued)

Temper	Product form	Stress ratio(a), <i>R</i>	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
				10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles		ksi	MPa
				ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
	Extrusions	−0.33	1	...	...	+64	+440	+48	+330	+37	+255	+30	+205	...	...	...	...
	Rolled rod and shapes	−0.5	1	...	...	...	...	+43	+295	+33	+230	+27	+185	+24	+165	+23	+160
	Rolled rod and shapes, extrusions	−1	2	...	...	+51	+350	+35	+240	+26	+180	+21	+145	+18	+125	+17	+115
	Rolled rod and shapes	−2	1	...	...	...	...	+24	+165	+18	+125	+14	+95	+12	+85	+11	+75
		−∞	1	...	...	...	...	...	...	−51(b)	−350(b)	−41(b)	−285(b)	−36(b)	−250(b)	−34(b)	−235(b)
T6	Forgings	−1	2	...	...	...	...	...	...	+29	+200	+22	+150	...	...	...	...
T81	Plate	0	1	...	...	+68	+470	+43	+295	+38	+260	+35	+240	+34	+235	...	...
T851	Sheet, plate	0	3	...	...	+68	+470	+43	+295	+34	+235	+31	+215	+30	+205	...	...
T86	Plate	+0.5	1	...	...	...	...	+66	+455	+53	+365	+50	+345	...	...	...	...
		0	2	+76.5	+527	+68	+470	+43	+295	+32	+220	+28	+195	+25	+170	...	...
		−1	1	...	...	...	...	+31	+215	+20	+140	+16	+110	...	...	...	...
2024 notched specimens(c)																	
T851	Plate	0	1	...	...	+29	+200	+19	+130	+12.5	+85	+10.5	+70	+9.5	+66	...	...
T86	Plate	+0.5	1	...	...	...	...	+21.5	+150	+15.5	+105	+12.5	+85	...	...	...	...
		0	1	...	...	...	...	+16	+110	+10.5	+70	+8.5	+59	...	...	...	...
		−1	1	...	...	+23	+160	+12.5	+85	+7	+48	+5	+34	...	...	...	...
2025 smooth specimens																	
T6	Rolled rod and shapes	0	1	...	...	...	...	+41	+285	+35	+240	+30.5	+210	+26.5	+185	+24.5	+170
		−0.5	1	...	...	...	...	+34	+235	+29	+200	+24.5	+170	+20.5	+140	+20	+140
	Rolled rod and shapes, forgings	−1	2	...	...	...	...	+30	+205	+25	+170	+20	+140	+17.5	+120	+16	+110
	Rolled rod and shapes	−2	1	...	...	...	...	...	...	+16.5	+115	+12.5	+85	+10.5	+70	+10.5	+70
		−∞	1	...	...	...	...	−47(b)	−325(b)	−40.5(b)	−280(b)	−35(b)	−240(b)	−31(b)	−215(b)	−29(b)	−200(b)
2025 notched specimens(c)																	
T6	Extrusions	−1	1	...	...	+19	+130	+11	+75	+6.5	+45	+5.5	+38	+5	+34	...	...
2027 smooth specimens																	
T6	Rolled rod and shapes	+0.5	2	...	...	...	...	+56	+385	+49.5	+340	+43.5	+300	+38.5	+265	+36	+250
		0	2	...	...	...	...	+45.5	+314	+37	+255	+30	+205	+24	+165	+22.5	+155
		−0.5	1	...	...	...	...	+36	+250	+28	+195	+21	+145	+17	+115	+16	+110
		−1	2	...	...	...	...	+27	+185	+21	+145	+16	+110	+13	+90	+12.5	+85
		−2	1	...	...	...	...	+18	+125	+14.5	+100	+11	+75	+9.5	+66	+8.5	+59
		−∞	1	...	...	...	...	...	...	−40(b)	−275(b)	−33(b)	−230(b)	−27.5(b)	−190(b)	...	...
2219 smooth specimens																	
T81	Plate	0	1	+66	+455	+60	+415	+46	+315	+38.5	+265	+33	+230	+29.5	+205	+28	+195
T851	Plate	+0.5	1	...	...	...	...	+58	+400	+49.5	+340	+47	+325	+46	+315	+45.5	+314
		0	1	...	...	...	...	+46	+315	+38.5	+265	+33	+230	+29.5	+205	+28	+195
		−1	1	...	...	...	...	+36	+250	+26	+180	+20	+140	+17	+115	+16	+110
T852	Forgings	0	1	+52	+360	+49	+340	+37	+255	+30	+205	+27	+185	+24	+165	+23	+160
T87	Plate	+0.5	1	...	...	...	...	+60	+415	+49	+340	+45	+310	+43	+295	+42	+290
		0	1	...	...	+66	+455	+47	+325	+35.5	+245	+30	+205	+26	+180	+25	+170
		−1	1	...	...	...	...	+30	+205	+20	+140	+16	+110	+14	+95	...	...
2219 notched specimens(c)																	
T81	Plate	0	1	...	...	+24	+165	+13	+90	+7	+48	+5.5	+38	+5	+34	+5	+34
T851	Plate	+0.5	1	...	...	...	...	...	...	+11	+75	+8.5	+59	...	...	...	...
		0	1	...	...	...	...	+15	+105	+8	+55	+7.5	+52	...	...	...	...
		−1	1	...	...	...	...	+11.5	+80	+7	+48	+5.5	+38	+5	+34	...	...

(continued)

Positive value (+) indicates tension; minus (−) indicates compression.

(a) Stress ratio (*R*) = (minimum stress)/(maximum stress). (b) Minimum stress in each cycle (maximum stress is zero). (c) Notched specimens; values determined using specimens containing a single 60° sharp V-notch, 0.03 in. (0.762 mm) deep with root diameter of 0.300 in. (7.62 mm) and a root radius at base of notch less than 0.0005 in. (0.0125 mm) ($K_t > 12$). (d) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.7 (continued)

Temper	Product form	Stress ratio(a), <i>R</i>	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
				10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles		ksi	MPa
				ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
T87	Plate	+0.5	1	...	...	...	...	+20	+140	+13	+90	+10.5	+70	+9.5	+66	...	...
		0	1	...	...	...	...	+13.5	+95	+9.5	+66	+8	+55	+7	+48	...	...
		-1	1	...	...	+20.5	+140	+10	+70	+6	+41	+4.5	+31	+4.5	+31	...	...
2618 smooth specimens																	
T651	Plate	+0.5	1	...	...	...	...	+58	+400	+52.5	+362	+48	+330	+44	+305	+41.5	+286
		0	1	...	...	+63	+435	+50.5	+350	+39	+270	+31	+215	+27	+185	...	...
		-1	1	...	...	...	...	+32	+220	+24	+165	+19	+130	+14.5	+100	...	...
2618 notched specimens(c)																	
T651	Plate	0	1	...	...	...	...	+13.5	+95	...	...	...	...	...	...	...	...
		-1	1	...	...	+19.5	+135	+11.5	+80	...	...	...	...	...	...	...	...
3004 smooth specimens																	
O	Rolled rod and shapes	-1	1	+20	+140	+17	+115	+14.5	+100	+12.5	+85	+10.5	+70	+10	+70	+10	+70
5052 smooth specimens																	
H36	Rolled rod and shapes	0	1	...	...	...	...	+35	+240	+33	+230	+31	+215	+30	+205	+29	+200
		-0.5	1	...	...	...	...	+27	+185	+24.5	+170	+22	+150	+21	+145	+20.5	+140
		-1	1	...	...	...	...	+22	+150	+18	+125	+15.5	+105	+15	+105	+15	+105
		-2	1	...	...	...	...	+14.5	+100	+12	+85	+10.5	+70	+10	+70	+10	+70
5083 smooth specimens																	
H112	Extrusions	0	1	...	...	...	...	+38	+260	+31	+215	+30	+205	+30	+205	...	...
H113	Plate	0	1	...	...	+50	+345	+39	+270	+33	+230	+32	+220	+32	+220	+32	+220
5086 smooth specimens																	
O	Plate	+0.5	1	...	...	+41.5	+286	+41.5	+286	+39	+270	+36.5	+250	+35	+240	+34.5	+238
		0	1	...	...	...	...	+38	+260	+26	+180	+25	+170	+24.5	+170	+24	+165
		-1	1	...	...	+29	+200	+23	+160	+19.5	+135	+17.5	+120	+15.5	+105	+15	+105
H112	Plate	0	1	...	...	...	...	+39	+270	+31	+215	+30.5	+210	+30	+205	+29.5	+205
H32	Plate	0	1	+45	+310	+45	+310	+40	+275	+34	+235	+33.5	+231	+33	+230	+33	+230
5154 smooth specimens																	
O	Plate	+0.5	1	...	...	+35	+240	+35	+240	+32.5	+224	+29	+200	+28.5	+195	...	...
		0	1	...	...	+35	+240	+33	+230	+22	+150	+19	+130	...	...	...	...
		-0.5	1	...	...	+34	+235	+26.5	+188	+18	+125	+15.5	+105	+14.5	+100	...	...
		-1	1	...	...	+32	+220	+21.5	+150	+16	+110	+14.5	+100	+14	+95	+13.5	+95
5454 smooth specimens																	
O	Plate	+0.5	1	+36	+250	+36	+250	+36	+250	+35.5	+245	+34.5	+238	+34	+235	+34	+235
		0	1	+36	+250	+36	+250	+34	+235	+26.5	+185	+25	+170	+24.5	+170	+24	+165
		-1	1	+34	+235	+27	+185	+21.5	+150	+18.5	+130	+17	+115	+16.5	+115	+16	+110
H112	Rolled rod and shapes	0	1	...	...	...	...	+34	+235	...	...	...	...	...	...	...	...
H311	Rolled rod and shapes	0	1	...	...	...	...	+34	+235	...	...	...	...	...	...	...	...
H32	Plate	0	1	+40	+275	+40	+275	+39.5	+272	+31	+215	+30	+205	+30	+205	+30	+205
5456 smooth specimens																	
O	Plate	+0.5	1	+49	+340	+49	+340	+48	+330	+38	+260	+36.5	+250	+36	+250	+36	+250
		0	1	+49	+340	+49	+340	+35	+240	+26	+180	+25	+170	+24.5	+170	+24	+165
		-0.5	1	+49	+340	+43	+295	+29.5	+205	+23.5	+160	+22	+150	+21.5	+150	+21	+145
		-1	1	...	...	+34	+235	+25	+170	+20.5	+140	+19.5	+135	+19	+130	+19	+130
H112	Rolled rod and shapes	0	1	+52.5	+360	+52	+360	+38	+260	+29	+200	+27.5	+190	+27	+185	+27	+185
H311	Rolled rod and shapes	0	1	+52.5	+360	+52	+360	+38	+260	+29	+200	+27.5	+190	+27	+185	+27	+185
H321	Plate	0	2	+53	+365	+53	+365	+41	+285	+35	+240	+34	+235	+33.5	+230	+33	+230

(continued)

Positive value (+) indicates tension; minus (-) indicates compression.

(a) Stress ratio (*R*) = (minimum stress)/(maximum stress). (b) Minimum stress in each cycle (maximum stress is zero). (c) Notched specimens; values determined using specimens containing a single 60° sharp V-notch, 0.03 in. (0.762 mm) deep with root diameter of 0.300 in. (7.62 mm) and a root radius at base of notch less than 0.0005 in. (0.0125 mm) ($K_t > 12$). (d) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.7 (continued)

Temper	Product form	Stress ratio(a), <i>R</i>	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5 × 10 ⁸ cycles	
				10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
				ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
6053 smooth specimens																	
T6	Rolled rod and shapes	+0.5	1	+38	+260	+38	+260	+35	+240	+33.5	+230	+32.5	+224	+31.5	+217	+31	+215
		0	3	+35	+240	+38	+260	+32.5	+224	+27	+185	+23.5	+160	+20.5	+140	+19.5	+135
		−0.5	1	...	...	...	...	+24.5	+170	+19.5	+135	+16	+110	+14.5	+100	+13.5	+95
		−1	4	+38	+260	+30	+205	+21.5	+150	+17	+115	+13.5	+95	+11	+75	+10	+70
		−2	1	...	...	...	...	+13	+90	+10.5	+70	+9	+62	+7.5	+52	+7	+48
		−∞	1	...	...	...	...	...	...	...	...	−27.5(b)	−190(b)	−24(b)	−165(b)	...	...
6061 smooth specimens																	
T6	Rolled rod and shapes	+0.5	3	+45	+310	+45	+310	+44	+305	+41	+285	+38	+260	+37	+255	+36	+250
		+0.1	2	...	...	...	...	+44	+305	+39.5	+270	+35.5	+245	+34	+235	...	...
		0	5	...	...	+44	+305	+37.5	+259	+31	+215	+26	+180	+23	+160	+22	+150
		−0.5	1	...	...	+39	+270	+31	+215	+24	+165	+19	+130	+16	+110	+15	+105
		−1	2	+39	+270	+33	+230	+25	+170	+19	+130	+15	+105	+13	+90	+12	+85
		−2	1	...	...	+24	+165	+18	+125	+13	+90	+10.5	+70	+9	+62	+8	+55
		−∞	1	...	...	...	...	...	...	−40(b)	−275(b)	−33(b)	−230(b)	−29(b)	−200(b)	−27(b)	−185(b)
6062 smooth specimens																	
T6	Extrusions	+0.1	2	...	...	...	...	+39	+270	+34	+235	+28	+195	+26	+180	...	...
		0	3	...	...	+44	+305	+37.5	+259	+31	+215	+26	+180	+23	+160	+22	+150
		−1	2	...	...	+33	+230	+25	+170	+19	+130	+15	+105	+13	+90	+12	+85
6070 smooth specimens																	
T6	Extrusions	0	1	...	...	+61	+420	+48	+330	+40	+275	+34	+235	+29	+200	...	...
6070 notched specimens(c)																	
T6	Extrusions	0	1	...	...	+28	+195	+20	+140	+12.5	+85	+8.5	+59	+6.5	+45	+6	+41
6071 smooth specimens																	
T6	Extrusions	+0.5	1	...	...	...	...	+47	+325	+41.5	+286	+37	+255	...	...	...	...
	Sheet	0	2	...	...	...	...	+42	+290	+34	+235	+27.5	+190	+25.5	+175	...	...
6262 smooth specimens																	
T9	Rolled rod and shapes	0	11	...	...	...	...	+46	+315	+30	+205	+22	+150	+19	+130	+17.5	+120
7001 smooth specimens(d)																	
T75	Plate	0	3	...	...	+65.5	+450	+46	+315	+38	+260	+35.5	+245	...	...	...	...
X7002 smooth specimens(d)																	
T6	Sheet	0	1	...	...	+60	+415	+42	+290	+35.5	+245	+33	+230	+32	+220	...	...
7006 smooth specimens(d)																	
T6	Rolled rod and shapes	0	5	...	...	...	...	+41	+285	+33.5	+231	+30	+205	+28.5	+195	...	...
T63	Sheet	0	1	...	...	...	...	+41	+285	+33.5	+231	+30	+205	+28.5	+195	...	...
X7007 smooth specimens(d)																	
T6E	Plate	0	1	...	...	+66	+455	+48	+330	+37	+255	+33	+230	+30.5	+210	...	...
7039 smooth specimens(d)																	
T6	Sheet	0	1	...	...	...	...	+45	+310	+38	+260	+35	+240	+34	+235	...	...
7075 smooth specimens																	
T6	Rolled rod and shapes, extrusions	+0.5	3	+88	+605	+82	+565	+75	+515	+63	+435	+58	+400	+56	+385	+55	+380
	Extrusions	+0.2	1	...	...	+88	+605	+66	+455	+54	+370	+48	+330	+44	+305	...	...
	Rolled rod and shapes, forgings, extrusions, sheet	0	15	+88	+605	+75	+515	+57	+395	+45	+310	+38	+260	+36	+250	+35	+240

(continued)

Positive value (+) indicates tension; minus (-) indicates compression.

(a) Stress ratio (*R*) = (minimum stress)/(maximum stress). (b) Minimum stress in each cycle (maximum stress is zero). (c) Notched specimens; values determined using specimens containing a single 60° sharp V-notch, 0.03 in. (0.762 mm) deep with root diameter of 0.300 in. (7.62 mm) and a root radius at base of notch less than 0.0005 in. (0.0125 mm) ($K_t > 12$). (d) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.7 (continued)

Temper	Product form	Stress ratio(a), <i>R</i>	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
				10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles		ksi	MPa
				ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa		
T6	Extrusions	-0.33	1	...	...	...	...	+53	+365	+42	+290	+36	+250	+33	+230	...	...
	Rolled rod and shapes	-0.5	2	...	...	+64	+440	+46	+315	+35	+240	+29	+200	+27	+185	+25	+170
		-1	3	+76	+525	+53	+365	+38	+260	+28	+195	+23	+160	+21	+145	+20	+140
		-2	2	...	...	+40	+275	+28	+195	+20	+140	+16	+110	+15	+105	+14	+95
		$-\infty$	...	...	...	...	...	...	...	...	...	-54(b)	-370(b)	-50(b)	-345(b)	-48(b)	-330(b)
T651	Rolled rod and shapes, plate	0	5	...	...	+74	+510	+53	+365	+40.5	+280	+33.5	+230	+30	+205	+29	+200
T73	Rolled rod and shapes	+0.5	2	+75	+515	+74.5	+515	+67	+460	+59	+405	+53.5	+370	+49	+340	+45	+310
	Rolled rod and shapes, plate, forgings, sheet	0	10	+75	+515	+68	+470	+50	+345	+41	+285	+36	+250	+32	+220	+31	+215
	Rolled rod and shapes	-1	2	...	...	+47	+325	+35.5	+245	+27	+185	+20.5	+140	+16	+110	+13.5	+95
T7351	Plate	0	2	...	...	...	...	+54	+370	+46	+315	...	...	...	...	...	...
T7352	Forgings	0	1	...	...	+55	+380	+42.5	+295	+34.5	+240	+29	+200	+25.5	+175	...	...
7075 notched specimens(c)																	
T6	Rolled rod and shapes	+0.5	1	+70	+485	+39	+270	+21	+145	+14	+95	+12	+85	+12	+85	+12	+85
		0	1	+50	+345	+29	+200	+17	+115	+12	+85	+10.5	+70	+10	+70	+10	+70
		-1	1	+34	+235	+19	+130	+11	+75	+8	+55	+6.5	+45	+6	+41	+6	+41
7076 smooth specimens																	
T6		+0.5	...	...	...	...	...	...	...	+60.5	+415	+57.5	+396	+56	+385	+55	+380
		0	...	...	...	...	...	+49	+340	+43.5	+300	+38.5	+265	+34.5	+240	+32.5	+225
		-0.5	...	...	...	...	...	+38	+260	+33	+230	+28	+195	+24.5	+170	+23	+160
		-1	...	...	...	...	...	+31	+215	+26.5	+185	+22	+150	+19	+130	+18	+125
		-2	...	...	...	...	...	+22.5	+155	+19	+130	+16	+110	+13.5	+95	+12.5	+85
T61	Forgings	-1	1	...	...	...	...	+39	+270	+33.5	+230	+29	+200	+25	+170	...	...
7076 notched specimens(c)																	
T61	Forgings	-1	1	...	...	+21	+145	+14.5	+100	+10	+70	+8	+55	+7	+48	+6.5	+45
7079 smooth specimens(d)																	
T6	Rolled rod and shapes	0	1	...	...	...	...	+55	+380	+41	+285	+34	+235	+30	+205	...	...
T651	Rolled rod and shapes, plate	0	7	...	...	+69	+475	+47.5	+330	+35	+240	+28	+195	+25.5	+175	+25	+170
7079 notched specimens(c)(d)																	
T6	Rolled rod and shapes	0	1	...	...	+29	+200	+18	+125	+12	+85	+10.5	+70	+10	+70	+10	+70
T651	Rolled rod and shapes, plate	0	4	...	...	+23	+160	+12	+85	+8.5	+59	+6.5	+45	+5.5	+38	+5.5	+38
7080 smooth specimens(b)																	
T7	Forgings	0	1	...	...	...	...	+61	+420	+50.5	+350	+42.5	+293	+39	+270	+38	+260
7106 smooth specimens(d)																	
T6	Sheet	0	2	...	...	...	...	...	...	+45.5	+315	+37.5	+260	+31.5	+215	+30	+205
7175 smooth specimens																	
T7352	Forgings	0	1	...	...	+54	+370	+45.5	+315	+39.5	+270	+34	+235	+29	+200	...	...
7175 notched specimens(c)																	
T7352	Forgings	0	1	...	...	+24.5	+170	+16	+110	+10.5	+70	+10	+70	...	...	...	...

(continued)

Positive value (+) indicates tension; minus (-) indicates compression.

(a) Stress ratio (*R*) = (minimum stress)/(maximum stress). (b) Minimum stress in each cycle (maximum stress is zero). (c) Notched specimens; values determined using specimens containing a single 60° sharp V-notch, 0.03 in. (0.762 mm) deep with root diameter of 0.300 in. (7.62 mm) and a root radius at base of notch less than 0.0005 in. (0.0125 mm) ($K_t > 12$). (d) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.7 (continued)

Temper	Product form	Stress ratio(a), <i>R</i>	No. of samples	Fatigue strengths at indicated cycles												Endurance limit at 5×10^8 cycles	
				10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
				ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
7178 smooth specimens																	
T6	Rolled rod and shapes	0	1	...	...	...	...	+57	+395	+47	+325	+40	+275	+33.5	+230	...	...
T651	Rolled rod and shapes, plate	0	2	...	...	+78	+540	+55	+380	+41	+285	+36.5	+250	+33.5	+230	+32	+220
T76	Plate	0	1	...	...	+67	+460	+48	+330	+37	+255	+33.5	+230	+32	+220	...	...
7178 notched specimens(c)																	
T6	Rolled rod and shapes	0	1	...	...	+25	+170	+16.5	+115	+13.5	+95	+12	+85	+12	+85	...	...
T651	Rolled rod and shapes, plate	0	2	...	...	+24	+165	+14	+95	+10.5	+70	+8.5	+59	+7.5	+52	+7	+48

Positive value (+) indicates tension; minus (−) indicates compression.

(a) Stress ratio (*R*) = (minimum stress)/(maximum stress). (b) Minimum stress in each cycle (maximum stress is zero). (c) Notched specimens; values determined using specimens containing a single 60° sharp V-notch, 0.03 in. (0.762 mm) deep with root diameter of 0.300 in. (7.62 mm) and a root radius at base of notch less than 0.0005 in. (0.0125 mm) ($K_t > 12$). (d) Obsolete alloy. Source data are in English units; metric values are converted and rounded.

Table A5.8 Axial-stress fatigue strengths of cast aluminum alloys

Alloy	Temper	Figure No.	Type of casting	Type of specimen(a)	Stress ratio, <i>R</i> (b)	No. of lots	Fatigue strengths at indicated cycles(c,d)												Endurance limit at 5 × 10 ⁸ cycles	
							10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
							ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
295.0	T6	295.AS01	Sand	Smooth (<i>K</i> _t = 1)	+0.5	1	...	...	...	...	26.0	179	18.0	124	13.5	93	12.0	83	12.0	83
					0.0		...	...	...	...	20.0	138	12.5	86	9.0	62	7.5	52	7.5	52
					−0.5		...	...	...	...	18.0	124	10.5	72	7.0	48	5.5	38	5.5	38
					−1.0		...	...	...	...	16.0	110	9.5	66	5.5	38	4.5	31	4.5	31
					−2.0		...	...	...	...	14.5	100	8.0	55	4.5	31	3.5	24	3.5	24
355.0	T51	355.AS01	Sand	Smooth (<i>K</i> _t = 1)	+0.5	1	...	...	27.0	186	22.0	152	15.5	107	13.5	93	13.0	90	13.0	90
					0.0		...	...	23.0	159	16.0	110	10.5	72	9.0	62	8.5	59	8.5	59
					−0.5		...	...	21.0	145	14.5	100	9.5	66	8.0	55	7.5	52	7.5	52
					−1.0		...	...	19.0	131	12.5	86	8.0	55	6.0	41	5.5	38	5.5	38
					−2.0		...	...	17.0	117	11.0	76	6.0	41	5.0	34	4.5	31	4.5	31
355.0	T6	355.AS02	Sand	Smooth (<i>K</i> _t = 1)	+0.5	...	...	...	32.5	224	28.5	197	20.0	138	14.5	100	13.0	90	13.0	90
					0.0		...	...	30.0	207	23.5	162	15.0	103	11.0	76	10.0	69	10.0	69
					−0.5		...	...	28.0	193	20.0	138	12.0	83	8.5	59	7.0	48	6.5	45
					−1.0		...	...	25.5	176	17.0	117	10.0	69	6.5	45	5.5	38	5.0	34
					−2.0		...	...	23.0	159	14.5	100	8.0	55	5.0	34	4.5	31	3.5	24
A357.0	T62	A357.AS01	Permanent mold	Smooth (<i>K</i> _t = 1)	0.0	...	...	...	39.0	269	27.0	186	17.5	121	15.0	103	...	...	...	...
380.0	F	380.AS01	Die cast	Smooth (<i>K</i> _t = 1)	+0.5	...	...	...	40.0	276	31.0	214	27.0	186	26.5	183	26.0	179	26.0	179
					0.0		...	...	34.0	234	24.0	166	20.0	138	19.0	131	19.0	131	19.0	131
					−0.5		...	...	29.0	200	21.0	145	18.0	124	17.0	117	16.0	110	16.0	110
					−1.0		...	...	26.0	179	19.0	131	16.0	110	15.0	103	15.0	103	15.0	103
					−2.0		...	...	20.0	138	15.0	103	13.0	90	12.5	86	12.0	83	12.0	83
		380.AS02		Notched (<i>K</i> _t = 3)	+0.5		...	...	23.0	159	16.0	110	12.0	83	10.5	72	10.0	69	10.0	69
					0.0		24.0	165	17.0	117	11.0	76	7.5	52	7.0	48	7.0	48	7.0	48
					−0.5		20.0	138	14.5	100	10.0	69	6.5	45	6.0	41	6.0	41	6.0	41
					−1.0		16.0	110	11.5	79	8.0	55	5.5	38	5.0	34	6.0	41	6.0	41
					−2.0		11.5	79	8.0	55	5.5	38	3.5	24	3.0	21	3.0	21	3.0	21
		380.AS03		Notched (<i>K</i> _t = 12)	+0.5		...	...	21.0	145	15.0	103	11.5	79	10.5	72	10.0	69	10.0	69
					0.0		22.0	145	17.0	117	12.0	83	9.5	66	8.5	59	8.0	55	8.0	55
					−0.5		19.5	134	14.5	100	10.5	72	8.0	55	7.0	48	6.0	41	6.0	41
					−1.0		17.5	121	13.0	90	9.0	62	7.0	48	6.0	41	5.0	34	5.0	34
					−2.0		11.0	76	8.0	55	6.0	41	4.5	31	4.0	28	3.5	24	3.0	21
443.0	F	443.AS01	Sand	Smooth (<i>K</i> _t = 1)	+0.5	...	18.5	128	18.5	128	17.0	117	13.5	93	11.5	79	11.0	76	11.0	76
					0.0		17.5	121	17.0	117	14.0	97	8.5	59	7.5	52	7.0	48	8.5	45
					−0.5		16.5	114	15.5	107	11.5	79	8.0	55	6.5	45	5.5	38	5.5	34
					−1.0		14.5	100	13.0	90	11.0	76	7.5	52	5.5	38	4.5	31	4.0	28
					−2.0		...	...	...	...	10.0	69	6.5	45	4.5	31	4.0	28	2.5	17
514.0	F	514.AS01	Sand	Smooth (<i>K</i> _t = 1)	+0.5	...	26.0	179	25.5	176	21.0	145	15.0	103	11.5	79	...	...	...	...
					0.0		24.0	165	20.5	141	16.5	114	12.0	83	8.0	55	8.5	59	8.0	55
					−0.5		23.0	159	19.5	134	13.5	93	8.5	59	7.0	48	6.5	45	6.5	45
					−1.0		20.0	138	15.5	107	11.0	76	7.0	48	5.0	34	4.5	31	5.0	34
					−2.0		...	...	...	...	...	...	6.5	45	3.0	21	3.0	21	4.0	28

(continued)

(a) Smooth specimens according to A5.4(a); notched specimens according to A5.4(b). (b) Stress ratio, R = ratio of minimum stress to the maximum stress in each cycle. (c) Fatigue strengths in ksi to the nearest 0.5 ksi; in MPa, converted by calculation to nearest MPa. (d) All fatigue strength are positive values.

Table A5.8 (continued)

Alloy	Temper	Figure No.	Type of casting	Type of specimen(a)	Stress ratio, R (b)	No. of lots	Fatigue strengths at indicated cycles(c,d)												Endurance limit at 5×10^8 cycles	
							10 ³ cycles		10 ⁴ cycles		10 ⁵ cycles		10 ⁶ cycles		10 ⁷ cycles		10 ⁸ cycles			
							ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
518.0	F	518.AS01	Die cast	Smooth ($K_t = 1$)	+0.5	...	...	43.0	296	35.0	241	28.0	193	28.5	197	28.0	193	28.0	193	
					0.0	...	...	38.0	262	30.0	207	24.0	166	22.5	155	24.0	166	24.0	166	
					-0.5	...	...	32.0	220	24.0	166	19.0	131	17.5	121	17.0	117	17.0	117	
					-1.0	...	...	26.5	183	20.0	138	15.5	107	14.5	100	14.0	97	14.0	97	
					-2.0	...	...	20.0	138	15.0	103	11.5	79	10.5	72	10.0	69	10.0	69	
		518.AS02		Notched ($K_t = 3$)	+0.5	...	...	31.5	217	19.5	134	13.0	90	11.0	76	11.0	76	11.0	76	
					0.0	...	...	22.0	152	12.5	86	9.0	62	7.5	52	7.5	52	7.5	52	
					-0.5	...	...	17.5	121	11.0	76	8.0	55	6.5	45	6.5	45	6.5	45	
					-1.0	...	...	13.0	90	10.0	69	7.0	48	6.0	41	6.0	41	6.0	41	
					-2.0	...	...	11.5	79	7.0	48	5.0	34	4.0	28	3.5	24	3.5	24	
		518.AS03		Notched ($K_t \geq 12$)	+0.5	31.0	214	22.0	152	13.5	93	10.0	69	9.0	62	8.5	59	8.5	59	
					0.0	25.0	172	17.0	117	10.5	72	7.5	52	6.5	45	6.5	45	6.5	45	
					-0.5	19.0	131	13.0	90	9.0	62	6.5	45	5.5	38	5.5	38	5.5	38	
					-1.0	17.5	121	12.0	83	8.0	55	6.0	41	5.0	34	5.0	34	5.0	34	
					-2.0	13.0	90	10.5	72	6.0	41	4.5	31	4.0	28	3.5	24	3.5	24	
520.0	F	520.AS01	Sand	Smooth ($K_t = 1$)	+0.5	...	...	...	...	27.5	190	20.0	138	16.5	114	16.0	110	16.0	110	
					0.0	...	...	...	...	20.5	141	13.5	93	10.5	72	10.0	69	10.0	69	
					-0.5	...	...	...	...	17	117	11.0	76	8.5	59	7.5	52	7.0	48	
					-1.0	...	...	...	...	14	97	8.5	59	7.5	52	5.5	38	5.0	34	
					-2.0	...	...	...	...	12	83	7.0	48	5.0	34	4.5	31	4.0	28	
		520.AS02		Notched ($K_t \geq 12$)	0.5	...	...	...	...	18.5	128	12.5	86	10.0	69	9.5	66	9.0	62	
					0.0	...	...	...	...	13.5	93	10.0	69	8.0	55	7.5	52	7.0	48	
					-1.0	...	...	...	...	10.5	72	7.5	52	6.5	45	5.5	38	5.5	38	

(a) Smooth specimens according to A5.4(a); notched specimens according to A5.4(b). (b) Stress ratio, R = ratio of minimum stress to the maximum stress in each cycle. (c) Fatigue strengths in ksi to the nearest 0.5 ksi; in MPa, converted by calculation to nearest MPa. (d) All fatigue strength are positive values.

Torsional fatigue tests were made of specimens of the type in Fig. A5.5, in accordance with ASTM standard test methods in existence at the time. The tests were made over a period from about 1950 through 1985. There was no atmospheric control in the testing laboratories.

The results of torsional fatigue tests of some wrought aluminum alloys are presented in Table A5.9. Only endurance limits at three stress ratios are included in Table A5.9. Generally, these were determined from tests of ten to fifteen specimens, several of which

were utilized to obtain the best measure of the life at 500 million cycles.

The metric/SI units shown in the table were calculated by multiplying the fatigue strength values measured in engineering units by the conversion factor of 1 MPa = 6.897 ksi, and then rounded by the aluminum industry standard to the nearest 5 MPa, except in the case of values less than 10 ksi, for which the converted value was not rounded.

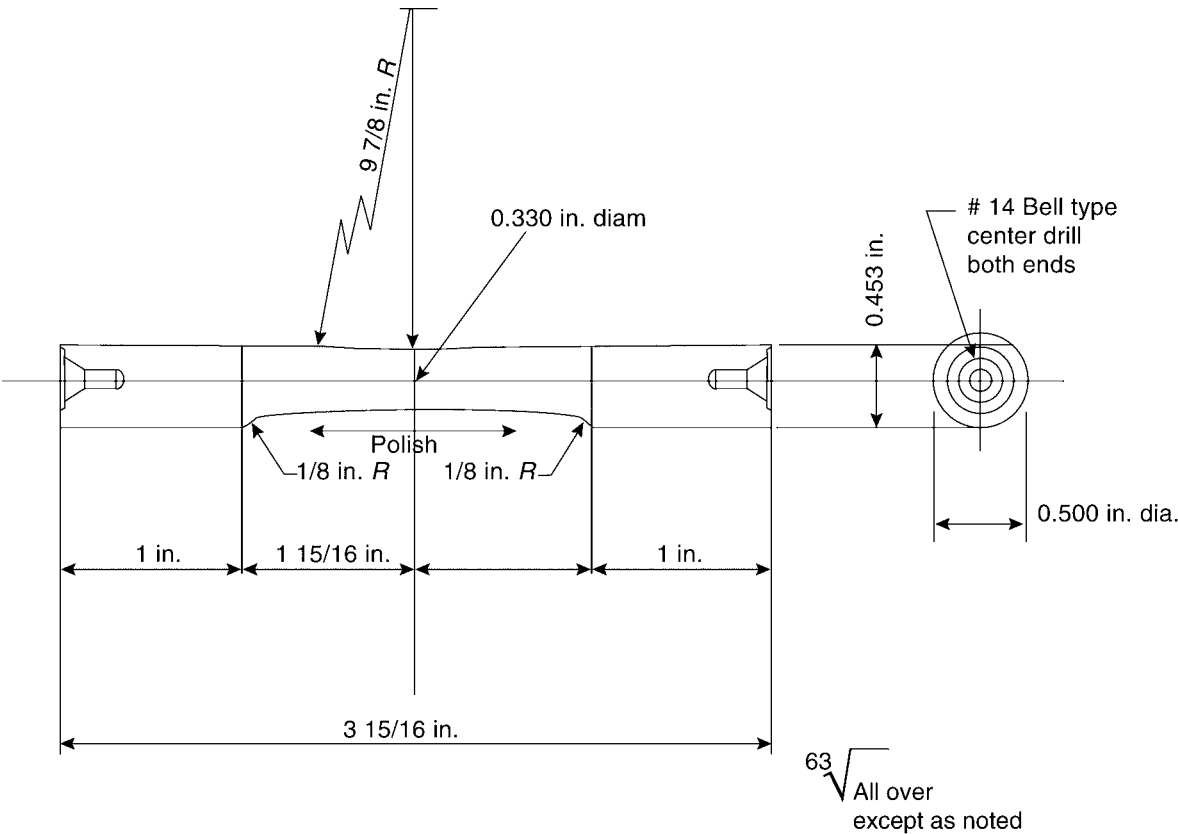


Fig. A5.5 Torsional fatigue specimen

Table A5.9 Torsional fatigue test summary for fatigue endurance limits of wrought alloys at three stress ratios (*R*)

Alloy and temper	Figure No.	Product form	Endurance limit(a)					
			<i>R</i> = +0.5		<i>R</i> = 0.0		<i>R</i> = −1.0	
			ksi	MPa	ksi	MPa	ksi	MPa
2014-T6	2014.TR01	Rolled and drawn rod	37.0	255	20.0	140	10.0	70
2017-T4	2017.TR01	Rolled and drawn rod	39.0	270	22.0	150	11.0	75
2024-T4	2024.TR01	Rolled and drawn rod	34.0	235	19.5	135	10.0	70
2027-T6	2027.TR01	Rolled and drawn rod	25.0	170	15.0	105	7.5	51
5052-H16	5052.TR01	Rolled and drawn rod	27.5	190	20.0	140	10.5	70
5052-H36	5052.TR02	Rolled and drawn rod	27.5	190	19.5	135	10.5	70
5456-H321	5456.TR01	Plate	...	...	25.0	170	15.0	105
6053-T6	6053.TR01	Rolled and drawn rod	25.0	170	17.5	120	7.5	51
6061-T6	6061.TR01	Rolled and drawn rod	25.5	175	14.0	95	8.0	55
7075-T6	7075.TR01	Rolled and drawn rod	38.0	260	16.0	110	4.0	28
7075-T6	7075.TR02	Extrusion	36.5(b)	250(b)	22.5(b)	155(b)	12(b)	85(b)

(a) Endurance limit (EL) defined as fatigue strength at 5×10^8 cycles. Stress ratio (*R*), the ratio of minimum stress in each cycle to the maximum stress. (b) EL not determined; value at 10^7 cycles reported.

APPENDIX 6

Fatigue Test Specimen Drawings

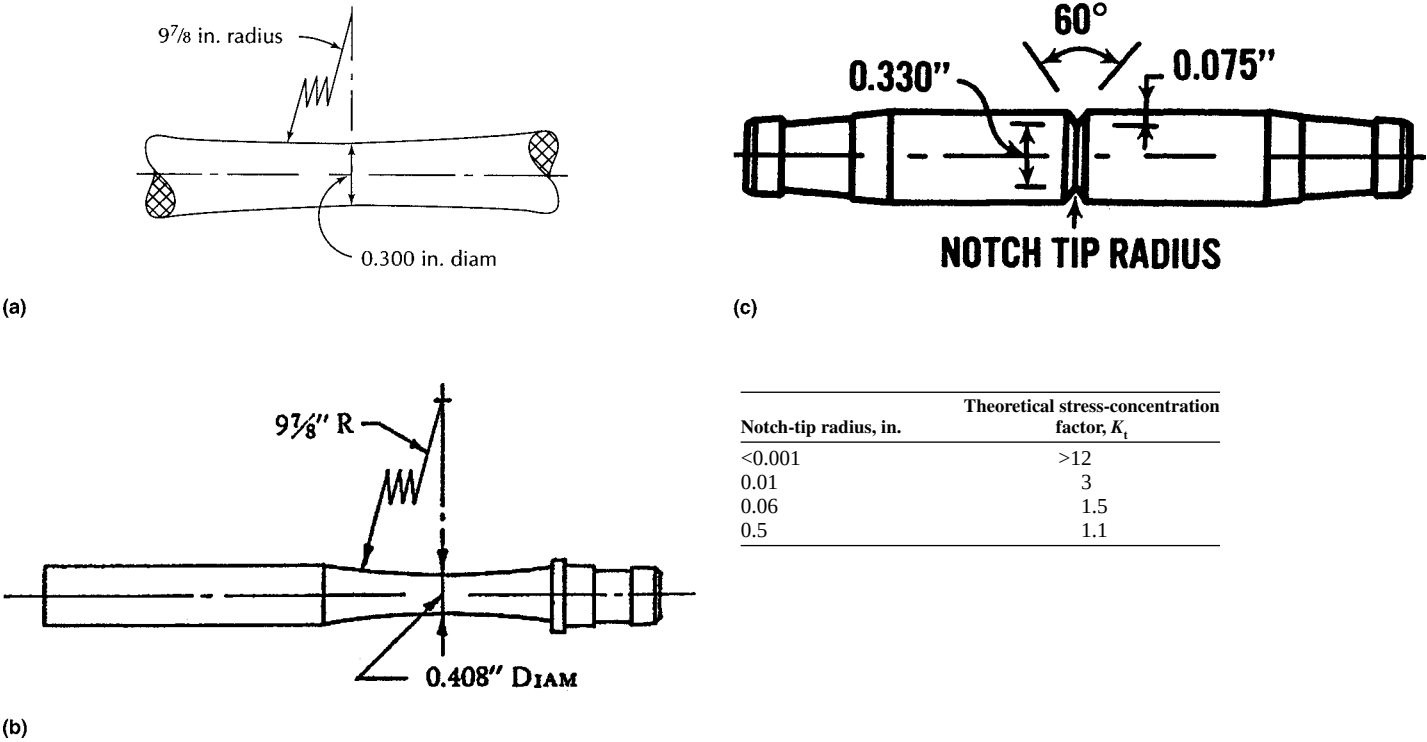


Fig. A6.1 Rotating-bending fatigue specimens. (a) Room-temperature rotating-beam smooth specimen. (b) Elevated-temperature rotating-bending smooth specimen. (c) Rotating-bending fatigue notched specimens. Dimensions in inches

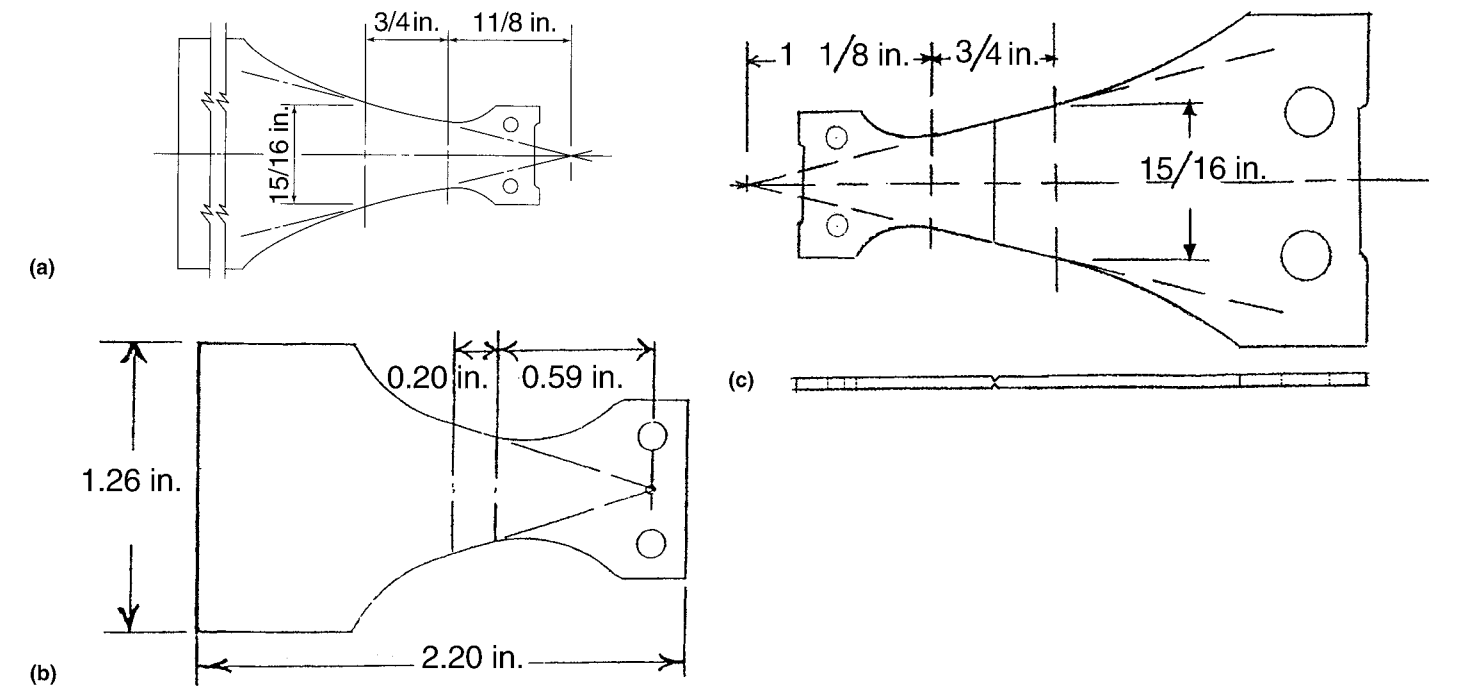


Fig. A6.2 Sheet flexural fatigue specimen. (a) Standard specimen. (b) Shortened specimen. (c) Notched specimen. 60° sharp notch, root radius ~0.0002 in. (0.005 mm), depth equal to ~0.0016 in. (0.041 mm). All dimensions in inches

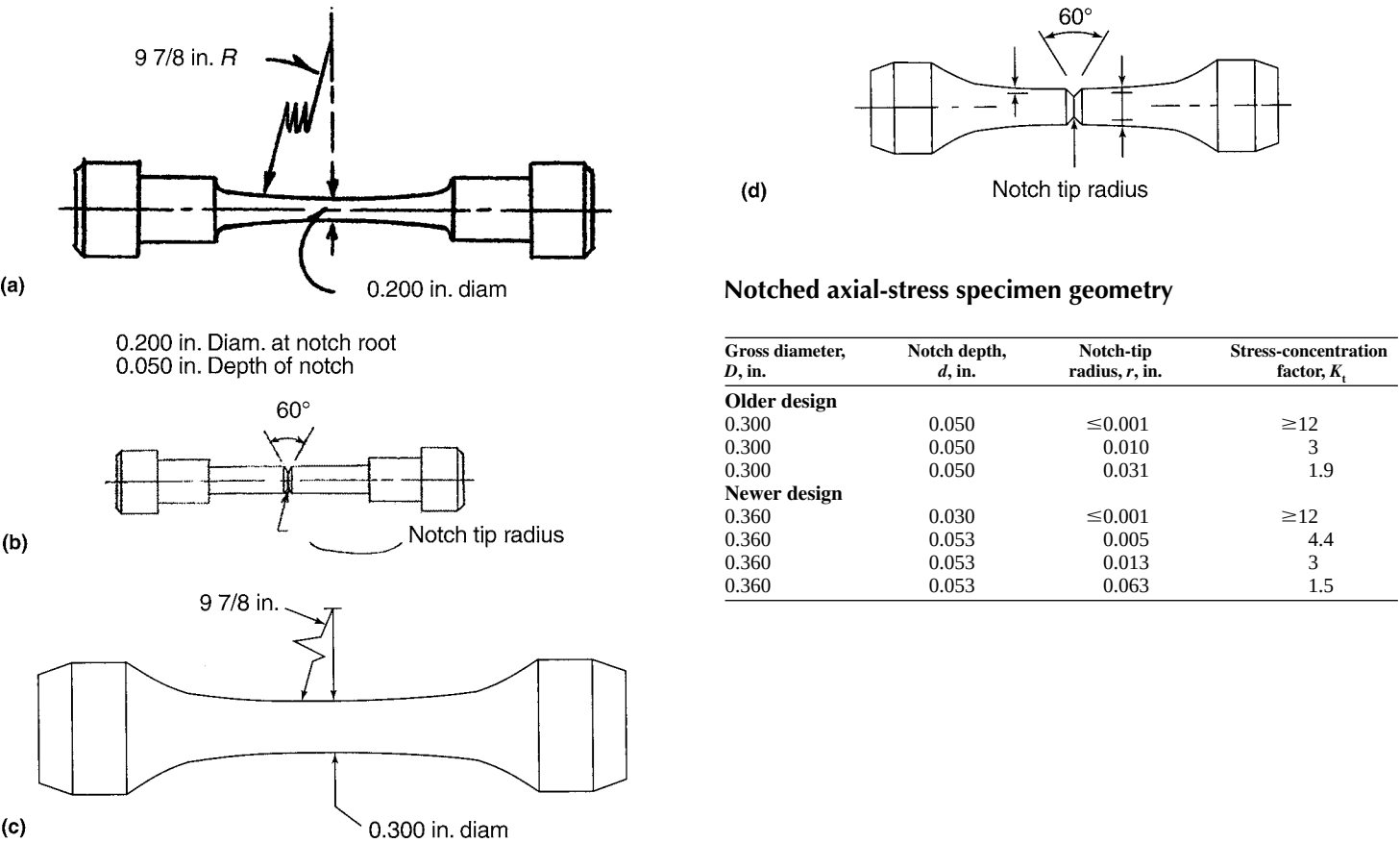


Fig. A6.3 Axial-stress fatigue specimens. (a) Older style. (b) Older style notched design. (c) Newer smooth design. (d) Newer notched design. All dimensions in inches

Notched axial-stress specimen geometry

Gross diameter, D , in.	Notch depth, d , in.	Notch-tip radius, r , in.	Stress-concentration factor, K_t
Older design			
0.300	0.050	≤ 0.001	≥ 12
0.300	0.050	0.010	3
0.300	0.050	0.031	1.9
Newer design			
0.360	0.030	≤ 0.001	≥ 12
0.360	0.053	0.005	4.4
0.360	0.053	0.013	3
0.360	0.053	0.063	1.5

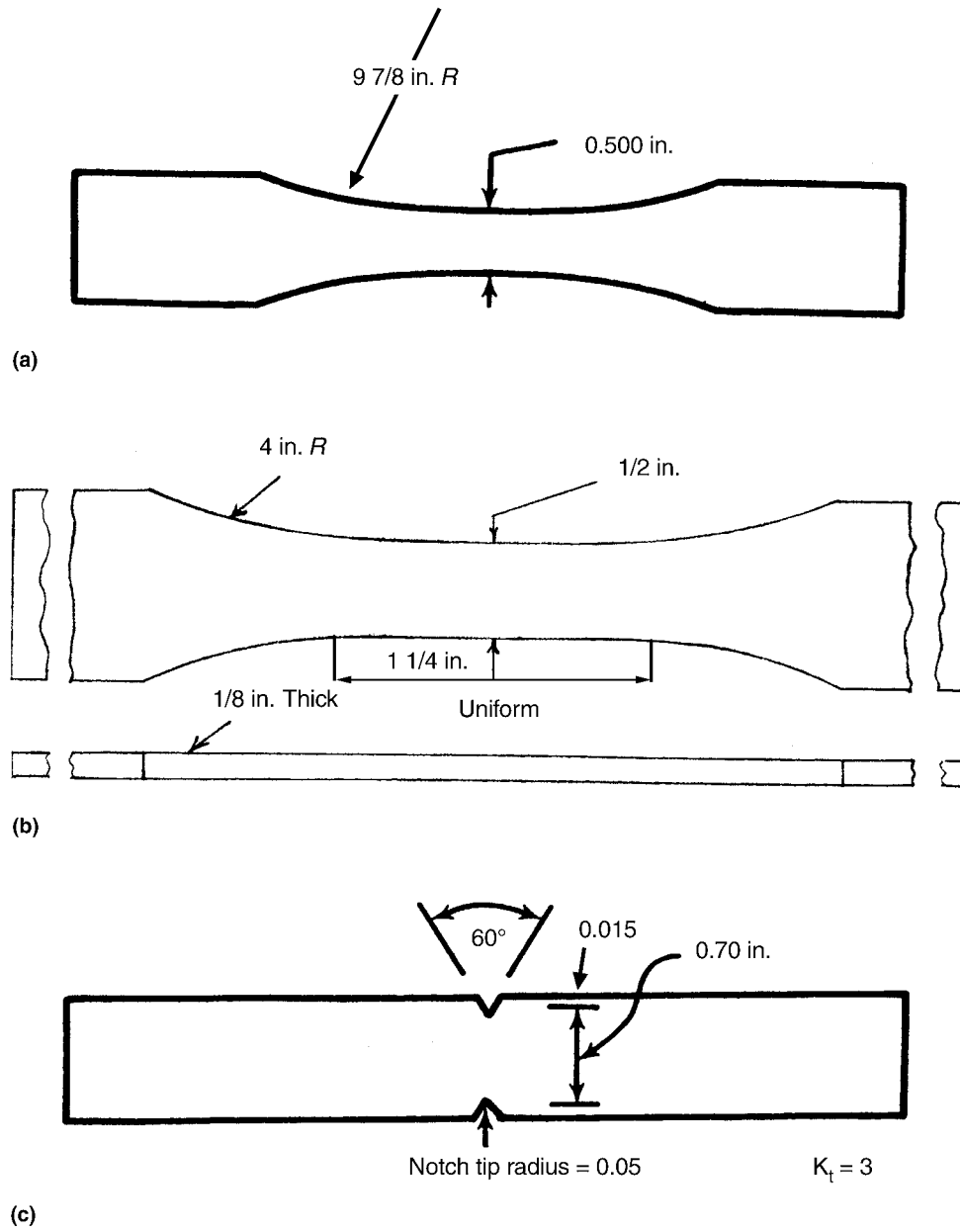


Fig. A6.4 Axial-stress sheet-type fatigue specimens. (a) Smooth, type A. (b) Smooth, type B. (c) Notched

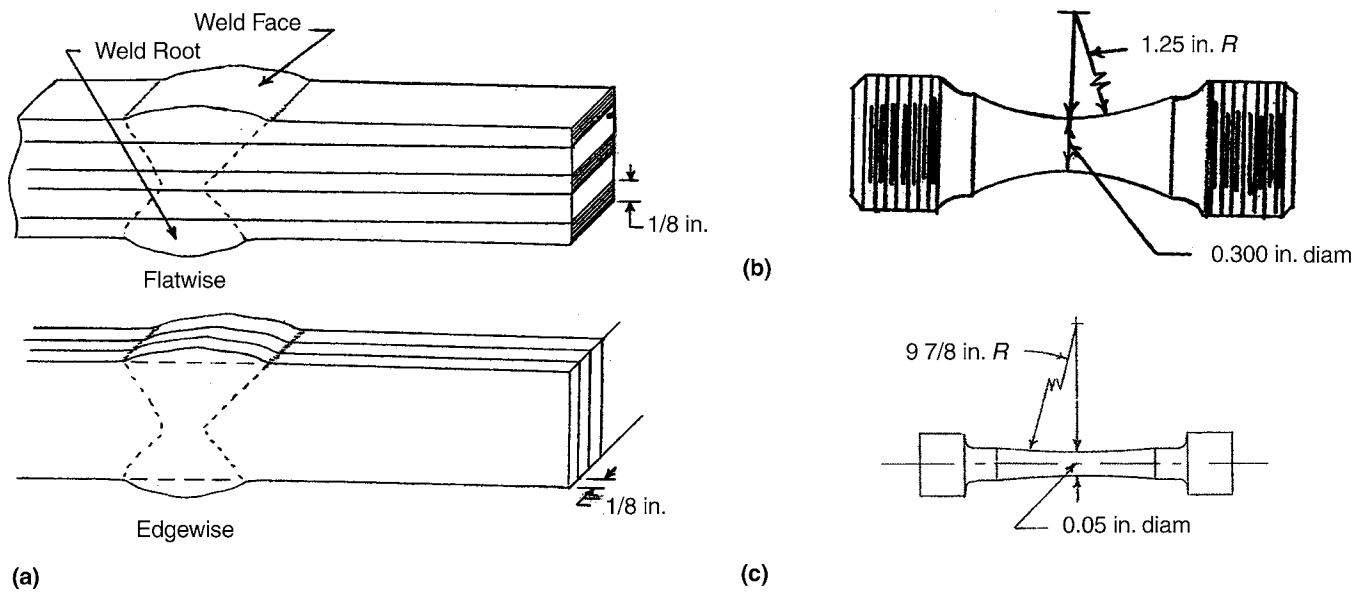


Fig. A6.5 Special axial-stress fatigue specimens. (a) Welded sheet flatwise and edgewise. (b) Short axial-stress cylindrical smooth specimen for short-transverse tests. (c) Special 0.05 in. (1.27 mm) diameter specimen

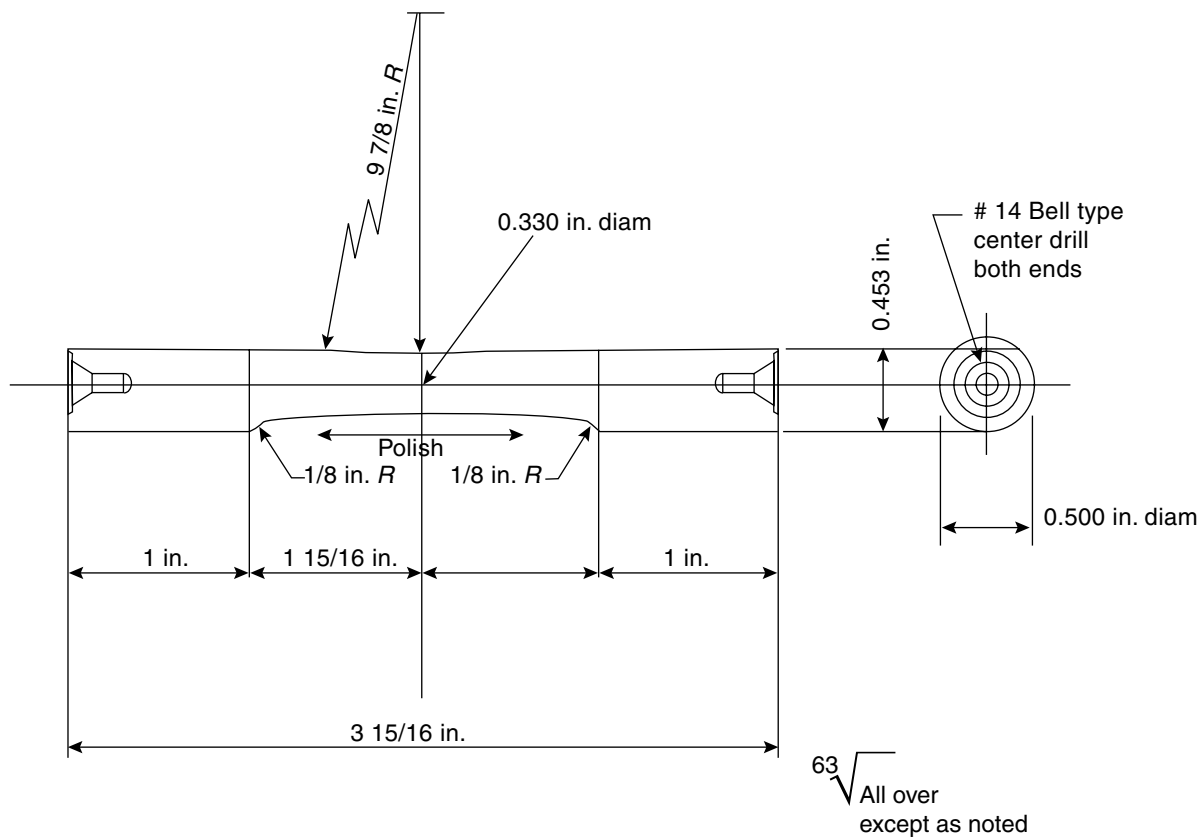


Fig. A6.6 Torsional fatigue specimen

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