General Discussion of Handbook Contents

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Introduction

This section introduces the reader to the general objective, contents, and format of this handbook. Definitions of the physical and mechanical properties are presented as well as pertinent comments on the selected data.

The general objective is to provide an unbiased characterization of alloys of interest to the aerospace designer so that alloy selection for a particular application may be made with a knowledge not only of typical physical and mechanical properties, but especially of those factors which limit the load carrying capacity, whether associated with the service conditions or with the metallurgical history of the alloy.

This handbook contains typical data as contrasted to statistically derived design data presented in MIL-HDBK-5 (Ref. 1). However, specified mechanical properties are frequently presented as derived from AMS, federal, and industrial sources and specifications. Caution should be used when comparing data from different sources because mechanical properties are sensitive to processing history and testing techniques. Data in this handbook are characterized as to source, product form and size, and all pertinent details of thermal-mechanical processing and testing history.

An attempt is made to provide an organized record of important mechanical and selected physical properties. However, it should be realized that a vast amount of information relating to mechanical and physical properties of alloys used in the aerospace and related industries has been and is still being generated. Some of this is confined to specific pieces of hardware and/or applications and has limited general usefulness (e.g., flight spectrum fatigue loading behavior). This type of information is not generally included in this handbook. Also in the case of alloys such as 4340 steel, Ti-6Al-4V, and 2024Al which have been widely used for many years and where design allowables are well established, it is not practical to make a comprehensive record here. Extensive data bases for such alloys exist in industrial and government organizations. For such well characterized alloys this handbook presents an overview with emphasis on those factors limiting load carrying capacity.

With respect to chapter revision and deletion, all chapters are identified by their date of preparation. While it has always been the desire of the editors to update chapters on some regular basis, limited funds have forced concentration on new materials and have restricted revisions to alloys whose characterization is substantially changed by new information. Chapters are deleted when the alloy has had limited use and is no longer in production.

A special problem exists in determining what data to delete when a chapter is revised. A decision is easy to make when there has been a clear change in the composition or the processing practice. On the other hand, some alloys have a rather wide range of accepted compositions and are processed in several ways which have evolved over a period of years. Under these circumstances data are not deleted during a chapter revision unless evidence has been presented that it was, for some reason, obtained from faulty test or analysis procedures. Comments on the significance of data are made on the basis of the most recent information in a particular chapter.

Alloy Classification

The chapters are classified according to specific alloy categories and each category is assigned a code number. Chapters are then numbered serially under their respective codes as they are added to the handbook. The chapter code numbers appear at the bottom of each page along with the page number. An outline of the categories and their numbers is given below.

Ferrous Alloys

Category	Code Series
Carbon and Low Alloy Steels (FeC)	1100
Ultra High Strength Steels (FeUH)	1200
Austenitic Stainless Steels (FeA)	1300
Martensitic Stainless Steels (FeM)	1400
Age Hardening Steels (FeAH)	1500
Nickel Chromium Steels (FeNC)	1600

Non-Ferrous Alloys

Category	Code Series
Aluminum Alloys; Cast (AlC)	3100
Aluminum Alloys; Wrought, Heat Treatable (AlWT)	3200
Aluminum Alloys; Wrought, Not Heat Treatable (AlWN)	3300
Magnesium Alloys; Cast (MgC)	3400
Magnesium Alloys; Wrought, Heat Treatable (MgWT)	3500
Magnesium Alloys; Wrought, Not Heat Treatable (MgWN)	3600
Titanium Alloys (TiW)	3700
Titanium Alloys Cast (TiC)	3800
Nickel Base Alloys (<5% Co) (Ni)	4100
Nickel Base Alloys (>5% Co) (NiCo)	4200
Cobalt Base Alloys (Co)	4300
Beryllium Alloys (Be)	5100
Columbium (Niobium) Alloys (Cb)	5200
Molybdenum Alloys (Mo)	5300
Tantalum Alloys (Ta)	5400
Tungsten Alloys (W)	5500
Vanadium Alloys (V)	5600
Zirconium Alloys (Zr)	5700

Alloy Identification

Alloys are identified by their chemical composition. The major elements are listed in decreasing order of their percentage by weight followed by the minor elements listed in the same way. When two or more elements are present in equal quantities they are listed alphabetically. Minor elements are given only when they are intentionally added to yield special mechanical properties. Impurities are neglected. The only exception to this practice is for ferritic steels; when carbon is the element having the predominate influence on the mechanical properties, it is listed immediately after iron.

In addition to the above described system of identification, the most commonly used designations (e.g., AISI Code) are given along with the number from the SAE/ASTM Unified Number System (Ref. 2). To facilitate the location of a particular alloy an index is provided in Volume 5 which gives cross-references for alloy category codes and commonly used designations.

Measurement System

The data presented in this handbook are obtained from sources in various countries. The original units of data measurement vary depending on the source. Where practical, mechanical property data are presented in English units (inch, pounds force, seconds, Fahrenheit) which are customarily used by the aerospace industry. Physical property data are generally given in the units used by the source. To assist in converting SI and other units to the customary units a conversion table is presented in Appendix D.

Data Organization

The data for each alloy are presented according to a property code system designed for this handbook. The numbers of the tables and figures that follow each section correspond to their respective paragraphs in the text. An outline of this code follows. (Please note also that the numbering system used in the earlier handbooks has been altered. For example, 1.01 is now 1.1, 2.011 is 2.1.1, and so forth.)

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Data points are generally shown for physical and mechanical properties. Multiple data points for a particular value of the independent variable are averaged to establish the trend curves. Where large data scatter is encountered or where a very large number of data points are reported (e.g., fatigue crack propagation data) a scatter band is shown to represent the upper and lower bounds of the data. However, such bands should not be used to represent lower bound properties for design purposes.

The mechanical properties and, to a lesser extent, the physical properties of metallic alloys are strongly dependent on the processing history of the test material. Where possible the most important features of processing are identified and reported in the data representations. Melting practice, product form, heat treatment, cold work, joining conditions, and related information (such as the testing direction and the specimen location with respect to the surfaces of the part from which they were removed) are included. Unfortunately, such complete characterizations are not available in many cases and, occasionally, so little information of this type is available that the data in question are excluded.

1 General

This section contains a brief general description of the selected alloy including a listing of any different grades, special features of interest to the structural designer relating to the alloy's advantages and limitations, and its typical applications.

1.1 Commercial Designation

The most commonly used designation is given first. This may originate with the alloy producer or from widely used specifications such as the Society of Automotive Engineers - Aerospace Materials Specifications (SAE-AMS). Trade names are generally not used, but in a few cases no other satisfactory designation is available. The reader should be aware of the rules governing the use of trade names.

1.2 Alternate Designations

The alternate designations include proprietary names and others encountered in the literature. No attempt is made to be complete here. A list of alloy names used in the handbook is given in the Index. For further information, see Ref. 3.

1.3 Specifications

This section provides a listing of specifications along with a description of the product forms and related metallurgical conditions. The primary sources are the Aerospace Material Specifications (AMS) issued by the SAE and the ASTM. Military and federal specifications may also be given. In some cases the alloy user may develop a specification for a particular application that also may be reported if it assists in the proper characterization of the data.

1.4 Composition

The SAE-AMS specifications are the primary source of reported chemical composition limits. In cases where an AMS specification has not been published the composition limits given by the producer are reported. It should be realized that for some materials a relatively small variation in composition limits for certain elements may have a substantial influence on the properties. These effects may be discovered as application experience is accumulated. Important compositional influences are discussed in Section 1.9, Special Considerations.

1.5 Heat Treatment

This section defines and discusses the thermal and/or deformation process applied to the alloy to achieve desired properties. A given heat treatment may be designated by either the process or the result. Because a clear understanding of heat treating terms is necessary to properly use material presented in this section, a Glossary of Heat Treating Terms is given in Appendix B.

1.6 Hardness

Hardness, as used herein, refers to an alloy's resistance to permanent deformation by indentation. Several indentation methods of measuring hardness have been standardized by the ASTM, namely Brinell E 10 (Ref. 4), Rockwell E 18 (Ref. 5), Vickers E 92 (Ref. 6) and Microhardness E 384 (Ref. 7). Hardness values reported in this handbook relate to one of these standardized procedures. In general, the hardness is related to the alloy tensile strength; hence, hardness values are often used to delineate the response of an alloy to heat treatment or cold work. This section reports the effect of various variables on the hardness. The depth to which an alloy will harden as a result of heat treatment is an important consideration in structural applications. The load carrying capacity of a component will be reduced if the desired hardness cannot be achieved throughout the cross section. The property that relates to the depth of hardening is called the hardenability. It is strongly dependent on the composition and, to a lesser extent, on the details of heat treatment. In the case of titanium alloys and steels, the higher the hardenability the less rapid the cooling rate from the solution or austenitizing temperature that is required to produce a given hardness level at the center of the cross section. In steels, insufficient hardenability or too slow a quenching rate can produce undesirable transformation products in the microstructure which may embrittle the steel. Hardenability is measured in several different ways. For steels the end quench hardenability test is frequently employed. This test, ASTM Standard A 255 (Ref. 8), consists of water quenching one end face of a steel cylinder and then determining the distribution of hardness along the axis of the cylinder. More complete information is obtained by quenching cylinders of various diameters and measuring the hardness distribution on a diameter. In some cases the depth of hardening is judged by abstracting tensile specimens from different positions in the cross section or from cross sections of different sizes.

1.7 Forms and Conditions Available

The availability of a particular form will change with the market conditions. Current information on availability of forms and conditions should be obtained from the alloy producer.

1.8 Melting and Casting Practice

Melting practice can have a strong influence on the mechanical properties when these are sensitive to impurities. In such cases the details of melting practice are given in this section. Many of the alloys included in this handbook can be cast. However, only a limited number have cast properties which are of interest to the aerospace and related industries. The production of high quality castings requires very careful control of pouring and gating techniques as well as cooling rates in various portions of the cast structure. This section will contain detailed information on such casting techniques for those alloys where high quality castings are of interest to the designer.

1.9 Special Considerations

This section summarizes problems which may be encountered in the production of alloys as well as in their application. Emphasis is placed on those factors which limit the load carrying capacity in intended applications. Included are such factors as hydrogen embrittlement introduced by plating or cleaning processes or resulting from exposure to high pressure hydrogen gas. Where appropriate this section may reference other sections for further information. In addition, this section may include comments on particular advantages possessed by an alloy.

2 Physical Properties and Environmental Effects

A concise presentation of those physical properties of importance to the designer is given rather than a comprehensive compilation. When values of physical properties are reported without a specified test temperature, the values are for room temperature only. In some cases, the determination of the property requires measurements at two or more temperatures (e.g., thermal expansion). These temperatures, unless otherwise indicated, are in the range from room temperature to 212F. Usually the difference in property values for any two temperatures in this range is less than the uncertainty in the values themselves. Frequently the source material does not give the form and the condition of the alloy for which the physical property determination was made. The influence of form and condition may explain some of the differences between published values for the same alloy. For detailed information on physical properties (excluding magnetic properties) the reader is referred to CINDAS/Purdue University, West Lafayette, Indiana 47906.

Environmental effects include the influence of various chemical agents on the mechanical properties and on the general corrosion behavior. The influence of nuclear environments is also covered here. Particular attention is given to the environmental factors that affect the crack propagation characteristics of an alloy.

2.1 Thermal Properties

Thermal properties include the melting range, phase changes, thermal conductivity, thermal expansion, specific heat, and, where available, thermal diffusivity and dimensional changes on heat treating.

2.1.1 Melting Range. The melting range is bound by the solidus temperature on the low end and the liquidus temperature on the high end. These two temperatures are influenced by compositional variations within specified limits. The range reported is generally established by experience with the solidus being set low enough to avoid incipient melting during hot working which could damage the alloy.

2.1.2 Phase Changes. A phase is any physically discrete homogeneous portion of an alloy system. In some cases a phase change refers to a change in the crystal structure of the major alloying element. This can be observed in low alloy steels where face centered cubic austenite transforms to a body centered cubic structure on cooling below a certain critical temperature. However, precipitations of intermetallic compounds from solid solution also constitute phase changes. Phase changes may be caused or accelerated by cold work. Phase changes may be beneficial or detrimental with respect to the load carrying capacity of a part. For example, creep resistance may be increased by precipitations occurring during heat treatment or during the creep process. On the other hand, when quenching steels from the austenitizing temperature, too slow a cooling rate (slack quenching) may produce embrittling constituents in the microstructure. In welded components, phase changes may result in dimensional changes which can give rise to residual stresses. A detailed discussion of phase changes and transformation structures may be found in Ref. 9.

2.1.2.1 Time-temperature transformation diagrams. These are also referred to as isothermal transformation diagrams or T-T-T diagrams and enable the user to estimate how an alloy will respond to cooling through a range of temperatures where phase transformations take place. Where appropriate, continuous cooling transformation diagrams are shown.

2.1.3 Thermal Conductivity. This quantity, more properly called the coefficient of thermal conductivity K, proportions the heat flow rate H over a conducting distance x to the area of the conductor A and the temperature difference ΔT over the conducting distance. K is given by the following expression:

$$K = \frac{Hx}{A\Delta T}$$

A variety of units is used to report the thermal conductivity in the literature. This handbook uses Btu-ft per (hr sq ft F). The Btu is defined in several different ways; however, for the present purposes, the difference in thermal conductivity depending on the definition is negligible.

2.1.4 Thermal Expansion. This section reports the mean coefficient of linear expansion defined as

$$\alpha = \frac{\Delta L}{L_0} \frac{1}{\Delta T}$$

where α is the coefficient and ΔL the change in original length L due to a temperature $\Delta T = T - T_0$. In this handbook room temperature is used as the reference temperature T_0. Units for the coefficient are in. per in. per F.

2.1.5 Specific Heat. The specific heat at a specified temperature is the amount of heat necessary to raise a unit mass of a substance one degree in temperature divided by that necessary to raise a unit mass of water one degree at the same temperature. For engineering purposes the specific heat of metallic alloys may be taken equal to their heat capacity. The heat capacity of alloys will vary with temperature. Unless the reference temperature is specified the values of specific heat given in this handbook refer to room temperature.

2.1.6 Thermal Diffusivity. This quantity is the thermal conductivity divided by the density and the heat capacity at constant pressure. The units used here are sq ft per hr.

2.2 Other Physical Properties

2.2.1 Density. The weight density is reported as either lbs per cu. in. or as gms per cu. cm.

2.2.2 Electrical Properties. This section reports the electrical resistivity on a volume basis (sometimes referred to as the "volume resistivity"), which proportions the electrical resistance to the dimensions of the conductor according to the expression

$$R = \frac{\rho l}{A}$$

where R is the resistance, ρ the resistivity, l the length, and A the cross sectional area of the conductor. A variety of units is used for the volume resistivity, the most common being microhm-inch. Conversion factors for several units are given in Appendix D.

2.2.3 Magnetic Properties. Materials are classified as paramagnetic, ferromagnetic, or diamagnetic. Bars of paramagnetic and ferromagnetic materials align their long dimensions in the flux direction in a magnetic field, while diamagnetic materials align their long dimensions normal to the field. For the purposes of electrical engineering, ferromagnetic materials are of the greatest interest. A number of magnetic properties for ferromagnetic materials can be derived from the normal induction curve or from the normal hysteresis loop. Standard methods for determining these curves are given in ASTM A 34 (Ref. 10).

In non-magnetic media any change in the magnetizing force H measured in oersteds is accompanied by an equal change in magnetic induction B measured in gauss. However, in ferromagnetic materials the relation between H and B is non-linear and a plot of B vs H is known as the normal induction curve. This is illustrated by the heavy line in Figure 2.2.3.1. Increasing H beyond a certain value produces only a small further increase in B. The limiting value of B is designated as the saturation induction B_s. The ratio of B to H at any point on the normal induction curve is known as the normal permeability μ.

The units of permeability are gauss per oersted. However, it is usual to report a dimensionless quantity which is the ratio of the normal permeability described above to that of a vacuum which is unity in the cgs system but $4\pi \times 10^{-7}$ in the SI system. This number is known as the relative permeability μ_r. The normal permeability has a maximum value μ_m near the knee of the induction curve and is represented by the slope of a line passing through the origin and tangent to the induction curve. The slope of the induction curve at the origin is known as the initial permeability μ_o. Other values of permeability are sometimes reported being representative of the B/H ratio at some particular value of the magnetizing force. It should be noted that the permeability of paramagnetic materials is slightly greater than unity, essentially independent of the magnetizing force, and that diamagnetic materials have permeabilities slightly less than unity. For diamagnetic materials it is common to report the susceptibility K. The relation between μ and K in the cgs system is

$$\mu = 1 + 4\pi K$$

Referring to Figure 2.2.3.1, if the value of H is reduced from any point on the induction curve, hysteresis is evident and it is necessary to reverse the magnetizing force to produce a condition of zero induction. The result is a hysteresis loop. There are two quantities of special interest that can be derived from the hysteresis loop, namely, the residual induction B_r remaining after H has been reduced to zero and H_c which is the negative value of H necessary to reduce B to zero. If the normal hysteresis loop is representative of a condition where the peak magnetizing force was sufficiently high to produce saturation induction (as in Figure 2.2.3.1), the B_r is designated as the retentivity B_{rs} and H_c is designated as the coercivity H_{cs}. The details of magnetic measurements are discussed in Refs. 11 and 12.

2.2.3.1 *[Figure]* Normal induction curve and hysteresis loop for ferromagnetic materials.

2.2.4 Emittance. The hemispherical emittance is the ratio of the radiance of a body to the radiance of a black body at the same temperature. The radiance is the rate of radiant energy emission from a unit area of the source in all radial directions of the overspreading hemisphere. If measurements are made normal to the surface, the quantity determined is called the normal emittance. When the measurements are made at a specific wave length, the result is designated as spectral emittance. Emittance is a dimensionless quantity with values less than unity. For further information the reader is referred to Ref. 13.

2.2.5 Damping Capacity. If the excitation is removed from a metal specimen subjected to torsional or bending vibrations the amplitude will decay due to internal friction which results in the dissipation of energy. The higher the damping the larger the rate of amplitude decay. Various measures have been proposed for damping and these are reviewed in Ref. 14. One that is frequently used in engineering is the damping capacity or specific damping energy measured as energy dissipated per unit volume per cycle.

2.3 Chemical Environments

This section includes information concerning the resistance of an alloy to various environments which can degrade its load carrying capacity by chemical reaction with its surface or interior. While a large number of corrosion tests have been standardized none of these give information which can directly be related to the degradation in load carrying capacity of a structural component. However, valuable comparative information can be obtained by selecting tests which represent the service environment. Corrosion tests can be divided into two generally recognized categories, namely, general corrosion and stress corrosion. This distinction is somewhat blurred by the influence of residual stresses which can affect the results of a general corrosion test. When corrosion data are reported, reference is made to an applicable ASTM or other standard for the test method and data evaluation. However, as pointed out in ASTM G 31 (Ref. 15), it is not possible to rigorously standardize corrosion testing because of the great variety of factors, many of which can not be well controlled.

2.3.1 General Corrosion. Smooth specimens are exposed to a variety of environments for various lengths of time. For example, specimens may be exposed to a seacoast or an industrial atmosphere, to a salt spray, to continuous immersion, or to alternate immersion in a salt solution (e.g., 3.5% NaCl). Tests of this type are commonly applied to aluminum and magnesium alloys and to high strength steels. The specimen surface is periodically examined for evidence of pitting and/or exfoliation and the observed surface conditions may be graded according to photographs contained in appropriate standards. In some cases, weight loss is determined and the result expressed as a time rate, or the result is converted to a dimensional loss rate (e.g., mils per year). Aluminum and magnesium alloys are quite susceptible to increased corrosion when electrically coupled in a corrosive media to a more noble alloy (e.g., Mg to steel in a salt solution). This galvanic corrosion is dependent on many variables and is not treated in this handbook. Some guidelines on predicting the behavior of galvanic coupled metals are given in ASTM G 82 (Ref. 16).

Some alloys (e.g., stainless steels and Ni-rich Cr-bearing high temperature alloys) when improperly heat treated are susceptible to intergranular corrosion. Accelerated test methods for evaluating the susceptibility of such alloys have been developed. The results may be expressed in terms of weight change or by bending the specimen and examining the tension surface for cracks related to intergranular attack.

2.3.2 Stress Corrosion. Most alloys are rendered more susceptible to corrosive attack if subjected to a stress in the aggressive environment. Stress corrosion tests are designed to measure the resistance to this type of behavior. A large number of tests have been standardized which make use of smooth specimens generally subjected to some fraction of the yield strength (e.g., tension specimens ASTM G 49 [Ref. 17] and C ring specimens ASTM G 38 [Ref. 18]). Specimens may be continuously exposed or alternately exposed to the environment and then to air. After an incubation time, cracks frequently form due to the adsorption of and diffusion of hydrogen generated by the corrosion reaction. Specimens are examined periodically to determine the presence of stress corrosion cracks. In tests using tension loading, specimens often fracture completely after crack initiation. Failure in tests using bending loads must be established by careful examination of the surface. The results of stress corrosion tests exhibit large scatter due to the difficulty of establishing the time to first cracking, premature fracture resulting from loss of load carrying area associated with general corrosion, and the fact that the cracks represent the behavior of a very localized region of the specimen. Frequently specimens subjected to tensile loading are removed from the aggressive environment and fractured to determine the retained load carrying capacity. This type of data has qualitative value in establishing the degeneration of load carrying capacity due to the aggressive environment.

To establish the structural load carrying capacity of a material, fracture mechanics tests can be used to obtain a measure of the effect of an aggressive environment. Sustained load tests on cracked specimens are used to establish a value of applied stress intensity factor K below which cracks will not grow in a particular aggressive environment. This value is known as K_{Iscc} and may be well below K_{Ic}. (K and K_{Ic} are defined in ASTM E 399 [Ref. 19].) At present there are no standardized tests for K_{Iscc}; when such values are reported herein the test conditions are described. If the application involves alternating loads, the K threshold below which cracks will not grow in an aggressive environment may be below K_{Iscc}.

2.4 Nuclear Environments

This section includes information concerning the resistance of metallic alloys to neutron radiation such as may be encountered in power generating reactors. Neutron radiation can result in large changes in mechanical properties and it is these changes that are emphasized in this section. The mechanical properties are represented as a function of the integrated neutron flux multiplied by the exposure time. This product is called the fluence, often designated as nvt. The neutron energy is also reported in millions of electron volts (Mev).

3 Mechanical Properties

The properties treated in these sections include those conventionally used in design as well as properties derived from special tests such as those from notch or precracked specimens. Information on mechanical properties is given concerning the effects of composition, heat treatment, and processing methods. Emphasis is on commercial practice. However, results obtained from experimental procedures are reported where these contribute to a better understanding of the effects of the variables influencing the mechanical properties.

While it is general practice to put all mechanical properties under these sections, where appropriate, mechanical properties may also be located in Section 1.5 on Heat Treatment, Section 1.9 on Special Considerations, and in Section 4 on Fabrication.

3.1 Specified Mechanical Properties

The specified mechanical properties reported in this section should not be taken as design values. Design values are given in MIL-HDBK-5 and the reader should obtain that handbook as a companion volume. It should be remembered that specifications are sometimes subject to frequent change, especially in the case of new alloys.

Room temperature mechanical properties form the core of most specifications. However, for heat resistant alloys, elevated temperature mechanical properties are sometimes specified. Specifications generally give minimum values of strength and ductility properties although occasionally maximum values are given. Forming limits in terms of minimum bend radii are specified in certain cases but this type of information is usually not included in the handbook.

3.2 Mechanical Properties at Room Temperature

This section includes data on conventional mechanical properties determined at room temperature with the exception of creep, fatigue, and elastic properties which are covered in separate sections. Used in the present sense, room temperature is a common but loose way of defining a test temperature. In this handbook it refers to the temperature range between 60 and 90F. In this range there is negligible time dependent flow (creep) for the great majority of structural alloys. Room temperature data will also be found in Section 3.3 where it appears as one of a series of values at various temperatures.

3.2.1 Tension Stress-strain Diagrams and Tensile Properties. Unless otherwise stated, stress is based on the original cross-section area. Elongation and reduction of area refer to percent changes from an original dimension. Occasionally, true stress and true strain are reported where the stress and strains are related to instantaneous values. Stress-strain curves generally encompass the range between zero and one percent strain. Such curves are useful in determining the static modulus and the yield strength. The tensile strength F_{tu} is the stress at maximum load. The yield strength F_{ty}, sometimes called proof stress, is the stress at a specified amount of plastic strain. In the United States this is generally 0.2 percent. The deformation values, elongation e and the reduction of area RA, are also reported. A standard method for measuring these strength and deformation values at room temperature is given in ASTM E 8 (Ref. 20). The tensile strength of brittle materials is influenced by any bending stresses introduced by the loading and gripping devices. These bending stresses may vary from test to test and result in substantial scatter of the strength values (ASTM E 1012, Ref. 21). It should be appreciated that the elongation of an alloy exhibiting necking before fracture may vary with the gage length. Neither elongation nor reduction of area are satisfactory predictors of fracture toughness (Ref. 22).

3.2.2 Compression Stress-strain Diagrams and Compression Properties. As in tension the stress and strain refer to the original dimension of the specimen and the compression yield strength F_{cy} is analogous to the tensile yield strength. Compression loads are influenced by friction at the interface between the anvils of the test machine and the specimen ends. Various means have been used to overcome these effects (e.g., large length to diameter ratios and/or lubrication; see ASTM E 9, Ref. 23). Unfortunately, information on specimen dimensions and means to minimize friction are seldom reported with compression data. In the absence of frictional effects the compression yield strength for most materials is essentially equal to the tensile yield strength.

3.2.3 Impact, see Section 3.3.3.

3.2.4 Bending. This section reports data from slow (as distinct from impact) bend tests on smooth specimens. These types of tests are sometimes used to evaluate the ability of welds to resist cracking at high deformations (ASTM E 290, Ref. 24). They are also used to determine the modulus of elasticity and yield strength in bending (ASTM E 855, Ref. 25). The yield strength so determined may not be equal to the yield strength in pure tension. The strength and deformation capacity of very brittle materials are frequently evaluated in three point bend tests commonly called modulus of rupture tests (ASTM B 406, Ref. 26). These tests have limited application in evaluation of aerospace alloys.

3.2.5 Torsion and Shear. The property reported here is the ultimate strength in shear (F_{su}) as determined from a torsion test or from one of a number of special shear tests.

3.2.6 Bearing. Bearing tests measure the yield (F_{bry}) and ultimate strength (F_{bru}) of a material when subjected to bearing loads. In a pinned or riveted joint the effective bearing area is the product of the hole diameter and the thickness of the bearing member. Specimen geometry must be considered when evaluating the results from these tests. Pin type bearing tests of metallic materials have been standardized and are described in ASTM E 238 (Ref. 27).

3.2.7 Stress Concentration, see Section 3.3.7.

3.2.7.1 Notch properties, see Section 3.3.7.1.

3.2.7.2 Fracture toughness, see Section 3.3.7.2.

3.2.8 Combined Loading (formerly Combined Properties). This section reports data from tests involving combinations of static loads such as combined bending and tension or multiaxial stress tests. Tests of this nature have not been standardized and only a limited amount of data from such tests is reported in this handbook.

3.3 Mechanical Properties at Various Temperatures (see also Section 3.2).

This section includes only the so-called short-time properties determined in conventional tests. The rate of deformation can influence the strength values at temperatures where time dependent flow occurs. At sufficiently high temperatures the time necessary to stabilize the specimen temperature may be sufficiently long to cause metallurgical changes in the material. For these reasons the scatter observed in elevated temperature mechanical properties is sometimes considerably larger than in the room or low temperature properties. At cryogenic temperatures some alloys become quite brittle and may break before the yield strength is reached. Under such circumstances the ultimate strength values may exhibit considerable scatter.

3.3.1 Tension Stress-strain Diagrams and Tensile Properties, see also Section 3.2.1. Methods recommended for conducting high temperature tensile tests are described in ASTM E21 (Ref. 28). This recommended practice emphasizes the importance of loading rate effects which depend on the testing techniques used.

3.3.2 Compression Stress-strain Diagrams and Compression Properties, see also Section 3.2.2. Compression properties, like tension properties, are sensitive to loading and heating rate effects at sufficiently high temperatures. ASTM E 209 (Ref. 29) gives recommended practices for conducting compression tests at elevated temperatures for conventional or rapid heating rates and strain rates.

3.3.3 Impact. Impact tests provide a measure of toughness in terms of an alloy's resistance to fracture when the load is applied at relatively high rates. Such tests do not directly provide a result that can be used in determining structural load carrying capacity. However, they are useful for ranking alloys in terms of their resistance to impact loading and in some cases may provide safe temperature limits for avoiding brittle fracture. Various types of impact tests have been described in the literature and several have been standardized. This handbook will report data only from standard test methods (Refs. 30, 31, 32, 33). These methods are listed in Table 3.3.3 which identifies the test method, the specimen type, and the indices of toughness reported. The standardized impact tests fall into two general classes, namely, those employing small specimens (Charpy and Izod) and those employing large specimens (NDT, Drop Weight Tear, and Dynamic Tear). The Charpy and Izod tests have been used for many years in the evaluation of a variety of alloys. The most widely used Charpy specimen has a V notch with a 0.01 in. radius. Charpy specimens without a notch and those with mild notches (Keyhole and U) have limited applications to special situations where the relatively sharp V notch is considered undesirable. The large specimens are designed to bring the test conditions more in line with structural applications. In general, the larger the specimen and the sharper the notch the greater is the sensitivity to factors producing brittle behavior. Consequently, the results of impact tests from different types of specimens should not be co-mingled. The trend of the impact energy with test temperature is strongly dependent on crystallographic structure, composition, and heat treatment. Body center cubic structures are particularly sensitive to temperature. Ferritic steels and beta titanium alloys generally show a marked decrease in impact energy within a relatively narrow temperature range. The center temperature of this range is the transition temperature. At temperatures outside this range the impact energy tends to level out. At temperatures above the transition range the nearly level value of impact energy is known as the upper shelf value and has been given special significance in defining tough behavior. At sufficiently high temperatures the impact energy will decrease due to loss of strength. At subtransition temperatures the impact energy may fall to a few ft-lbs indicating very brittle behavior. Heat treated high strength steels do not exhibit strong transitional behavior and the impact energy is a less useful quantity than for the ferritic steels. The impact energy values may be supplemented by measurement of the lateral expansion and/or percent shear. Lateral expansion refers to a measurement of the maximum thickness increase after fracture which results from the development of shear lips. The percent shear refers to percentage of the fracture projected area consumed by shear lips. This measurement procedure is necessarily arbitrary because the shear zone generally varies as the crack progresses through the specimen. Fracture appearance measurements are likely to be more easily determined from large specimens. Both lateral expansion and percent shear generally follow the same temperature trend as the impact energy with the brittle conditions exhibiting very low values. The NDT and Drop Weight Tear tests do not require measurement of an energy value. The NDT test is designed to determine the highest temperature where a specimen breaks when subjected to a small deflection (approximating yield point loading) in the presence of cleavage crack originating in a brittle weld bead. This temperature is defined as the nil ductility temperature. The Drop Weight Tear test is designed to determine the fracture appearance in terms of percent shear as a function of test temperature for impact values at least sufficient to completely fracture the specimen.

3.3.3.1 *[Table]* Summary of ASTM selected standard impact texts.

3.3.4 Bending, see Section 3.2.4.

3.3.5 Torsion and Shear, see Section 3.2.5.

3.3.6 Bearing, see Section 3.2.6.

3.3.7 Stress Concentration. This section is concerned with the effects of stress concentrations on the static strength of alloys. Stress concentrations are of special concern when high strength alloys are being used in severe service. In these circumstances large losses in load carrying capacity can accompany the presence of high stress concentrations. The majority of tests used to investigate the effect of stress concentrations may be classified either as notch tests or crack tests. Detailed discussion of both types of these tests may be found in Appendix C: Fracture Properties (under revision). The effect of stress concentrations on the static strength can be strongly influenced by the metallurgical structure as determined by the fabrication history and heat treatment, as well as by the external environment.

3.3.7.1 Notch properties. The results from notch tests are generally presented in terms of the notch strength computed from the maximum load and the original dimensions of the notched section (e.g., ASTM E 602, Ref. 34). Occasionally the strength reported is based on the unnotched section dimensions and in such cases the strength value is referred to as the residual strength. Strength values determined from notched specimens are dependent on the geometry of the notch and specimen size. For this reason it is not possible to compare data from different sources unless the specimen geometry and sizes are identical. Results from notch specimen tests reported in this handbook are accompanied by information concerning the notch geometry and pertinent specimen dimensions.

3.3.7.2 Fracture toughness. Fracture toughness in this context is concerned with the influence of cracks on the strength of alloys. Evaluation of fracture toughness requires the use of specimens containing so called "natural cracks." These are generally produced by fatigue loading of specimens provided with sharp notch crack starters. Results from such tests may be reported as crack strength, analogous to the notch strength, or as an index of fracture toughness which can be used to give an indication of structural load carrying capacity in the presence of cracks or crack-like flaws. Various indices have been developed and test methods for defining several of them have been standardized, namely, K_{Ic} (ASTM E 399, Ref. 19), J_{Ic} (ASTM E 813, Ref. 35), and CTOD (ASTM E 1290, Ref. 36). These methods are primarily concerned with determining critical values corresponding to crack initiation under static loading. Each method contains certain criteria which must be met to qualify the test result as a valid value. Invalid results are frequently published as indicators of toughness trends (e.g., changes in toughness with tempering temperature). Such values have dubious value for this purpose (Ref. 22) and should be used with caution. The plane strain fracture toughness K_{Ic} is considered to be a lower bound of fracture toughness where crack initation is primarily controlled by the linear elastic stress field at the crack tip. It has special significance for predicting the fracture behavior of high strength materials under highly constrained loading (e.g., thick sections). The J_{Ic} and CTOD indices of fracture toughness are designed to characterize materials where crack initiation is accompanied by an amount of plastic flow sufficient to invalidate the determination of K_{Ic}. CTOD tests have proven useful in cases where bursts of cleavage crack extension are observed in the test records. This type of behavior is commonly observed in ferritic steels. Under dynamic loads the fracture toughness may be well below the value determined from the static tests. This effect of rapid loading is most pronounced in ferritic steels but has also been observed in heat treated low alloy steels (Ref. 37). There appears to be a limiting value of the stress intensity factor below which increases in loading rate produce no further decrease in toughness. Thus, a fast running crack would arrest if the K level falls below this value. The arrest value K_{Ia} is determined according to ASTM E 1221 (Ref. 38) which relates specifically to ferritic steels.

Stable crack growth resistance under static loads following initiation can be determined in terms of K (ASTM E 561, Ref. 39) or in terms of J (ASTM E 1152, Ref. 40). The resistance is expressed as a curve relating K or J to crack extension. The K resistance curves are dependent on material thickness and criteria are provided to ensure that the uncracked ligament is always predominantly elastic. The J resistance curves are presumably independent of thickness if the validity criteria of the method are met. Resistance curves can be used to estimate the amount of stable crack growth (tearing) which precedes unstable fracture in very ductile alloys.

Other types of tests have been proposed to measure fracture toughness either directly or by correlations with valid values from K_{Ic}, J_{Ic}, or CTOD tests. The chevron notch specimen (ASTM E 1304, Ref. 41) measures a plane strain toughness quantity K_{Iv} which may be equal to K_{Ic} for materials of low toughness but will overestimate K_{Ic} for materials having a rising crack growth resistance curve (e.g., most aluminum alloys, Ref. 42). Fracture toughness values from Chevron notch specimens are reported only when valid K_{Ic} or J_{Ic} values are not available. An equivalent energy method (ASTM E 992, Ref. 43) yields a K-EE value from invalid ASTM E 399 tests. However, the equivalent energy method does not transform invalid K_{Ic} values to valid values. K-EE values are useful only in restricted circumstances and are not reported in this handbook.

Many attempts have been made to correlate Charpy V impact test results with K_{Ic}. A review of these (Ref. 44) indicates that there is no general relation which can be applied to a wide range of alloys. An example of this lack of generality is shown in Ref. 22 for a variety of steels where valid K_{Ic} values were available. The difficulty of establishing general relationships is not surprising considering the differences in strain rate and notch acuity in the two types of tests. The slow bend precracked Charpy test (ASTM E 812, Ref. 45) has been used to establish correlations between K_{Ic} and the crack strength of the Charpy specimens. These correlations are limited by plastic yielding in the small Charpy specimen (Ref. 46) and should never be extrapolated.

3.3.8 Combined Loading (formerly Combined Properties), see Section 3.2.8.

3.4 Creep and Creep Rupture Properties

In most cases, creep tests are performed in tension with temperature and the applied load held constant. Stress values generally are based on the original area of the specimen. In creep rupture tests the deformation is not reported and the data are represented as stress vs time to failure (rupture). ASTM E 139 (Ref. 47) gives recommended practices for creep and creep-rupture tests which are followed by most investigators. A wide variety of specimen sizes are employed and, except for very brittle materials or for tests on notched specimens, the size has little effect on the results. On the other hand, the atmosphere in contact with the specimen can have a substantial influence on the results depending on the surface reactions which may occur. Since most tests are carried out in air, caution should be used in applying such data to situations where the environment may be more or less aggressive.

Creep data are reported in terms of either total strain or as only the plastic component of the strain. The basic data are represented as strain as a function of time for various applied stress levels at a constant temperature. Creep deformation curves of this type usually give more information than is needed for practical applications and the data are often replotted in different ways using the normal stress as an independent variable but plotting it on the ordinate: (a) stress vs time with strain and temperature held constant, (b) stress vs minimum creep rate at a constant temperature, (c) stress for a specified creep strain as a function of temperature with time constant, and (d) isochronous stress vs strain curves at constant temperature. To obtain an isochronous curve the total creep strain or the plastic portion of the strain is plotted as the abscissa with the stress necessary to obtain that strain as an ordinate. Time is then the parameter. The plastic portion of the creep strain is obtained by subtracting the elastic part from the total strain. This procedure is somewhat indefinite because of the uncertainty regarding the modulus of elasticity which is indicated by the tangent at the origin of the isochronous curve. In graphical representation of creep data, logarithmic stress and time scales are generally used although no special physical significance is attributed to the trends of the data on log-log representations. If the data are very limited or cover only a small range of the variables, tabular representations may be employed. The creep rupture strength of notched specimens is sensitive to the time-temperature dependent embrittlement that develops in many high temperature alloys. These embrittlements are frequently associated with microstructural changes, some of which enhance the smooth creep strength. Generally, the sensitivity to embrittling reactions increases with increasing notch sharpness. For this reason creep tests using very sharp notches or cracks have special significance in the selection of materials for use in critical components which operate at elevated temperatures for extended periods of time (e.g., steam and gas turbines). The notch rupture strength is calculated on the basis of the initial area of the notched section and, to be a useful indicator of embrittlement, must be compared with the smooth strength at the corresponding rupture time.

For some applications (e.g., steam and gas turbine components) it is desired to characterize alloy behavior for service times of many years. Very long time creep or creep rupture tests are very expensive and subject to interruptions due to power failure or equipment breakdown. It has been recognized for many years that it would be advantageous to substitute temperature for time in such a way that the long time behavior could be predicted from time-temperature parameters. One of the first and simplest proposed is the Larson-Miller parameter (Ref. 48). Many others followed having increased complexity. It is not yet clear which, if any, have general applicability and none have been standardized. This handbook prefers to present creep and rupture directly and will report data in terms of a time-temperature parameter only if no direct data is available. Time-temperature parameters should be used with caution particularly when extrapolation outside the data range is attempted.

3.5 Fatigue Properties

This section presents the effects of repeated loading on the strength and deformation properties. In some cases the temperature may vary as well as the load. For the purposes of this discussion the information on fatigue properties may be divided into (1) conventional high-cycle fatigue, (2) low-cycle fatigue, and (3) fatigue crack propagation. In conventional fatigue the strains throughout the test are predominantly elastic and consequently the stresses are relatively low and the number of cycles to failure large. In low-cycle fatigue the plastic component of the total strain is larger than the elastic component, the stresses are relatively high, and the cycles to failure relatively short. Both conventional high-cycle and low-cycle fatigue tests are concerned with total life including the crack initiation and propagation phases, and in some cases data are reported for each phase. Fatigue-crack growth is most commonly obtained from specimens with pre-existing cracks.

3.5.1 Conventional High-cycle Fatigue. The basic types of tests used are (1) rotating beam where a specimen of circular cross-section rotates under an applied bending moment, (2) reverse bending where a specimen generally of rectangular crossection is subjected to alternating bending, and (3) axial load in which the alternating load is parallel to the specimen axis. Both smooth and notched specimens are employed in these tests. Generally the load is allowed to fluctuate between two definite limits although random load spectrum tests are frequently employed in the design of a particular component. Random load test data have limited application and are not reported in this handbook. The stresses are calculated by conventional elastic formulae. The maximum stress is referred to as F_{max} and the minimum stress as F_{min}. The stress ratio R is defined as follows:

$$R = F_{min}/F_{max}$$

Another definition of the stress relationship is the A ratio defined as follows:

$$A = F_{alt}/F_{mf}$$

where $F_{alt} = \frac{1}{2}(F_{max} - F_{min})$ is the alternating stress and where $F_{mf} = \frac{1}{2}(F_{max} + F_{min})$ is the mean stress. The stress range is 2 F_{alt}. Where only one stress ratio is involved, it is common to report this ratio and plot the fatigue strength as a function of the number of cycles to failure. Where more than one stress ratio is used the data may be presented in the form of a stress range diagram. Each curve in this diagram gives the alternating stress as a function of the mean stress for a given number of cycles to failure. The fatigue strength is derived from these diagrams by the following relation:

$$F_{max} = F_{mf} + F_{alt}$$

When reporting the results of notch fatigue tests an attempt is made to give the dimensions of the notch specimen as well as the stress concentration factor K_t. It should be noted that the fatigue strength of a notched specimen will, in some cases, be dependent on the absolute size of the specimen while the elastic stress concentration factor will be independent of size providing the proportions remain unchanged. For both smooth and notched specimens, the fatigue properties will be dependent on the type of loading, specimen type, stress ratio and, in many cases, the surface condition of the specimen.

Two types of behavior are noted in high-cycle fatigue tests at room temperature. In one case a definite fatigue or endurance limit exists. Stresses below this limit produce no failure in an extreme number of cycles.

This behavior is most clearly noted in ferritic steels and is less pronounced in heat treated low alloy steels. In the other case no definite limit is observed. This type of behavior characterizes aluminum alloys and other face center cubic materials. In this case the fatigue limit is arbitrarily assigned, usually at 10^6 or 10^7 cycles.

3.5.2 Low-cycle Fatigue. The most commonly used low-cycle fatigue tests employ cylindrical specimens subjected to axial loads. Attention is focused primarily on the strain and strain range rather than on the stress and stress range. Tests are generally carried out between fixed strain limits. It is important to recognize that under these conditions the alloy may either cyclically harden or soften. When hardening occurs, progressively higher stresses are produced under a constant strain range. If strain softening occurs, the stresses will progressively decrease under a constant strain range. In order to simplify the material characterization it is common to express the strain range in terms of the stress range developed at the half-life (half the cycles to failure) point. Such a plot of strain vs stress at a given number of cycles is called the cyclic stress-strain curve. For cyclically strain hardening materials, the cyclic stress-strain curve is above the monotonic curve; for cyclically softening materials it is below the conventional stress-strain curve. Cyclic stress-strain curves are more useful in design against low-cycle fatigue than are the conventional monotonic curves. A simple criterion for establishing whether the material is cyclically strain hardening or softening (Ref. 49) is the ratio F_{tu}/F_{ty}. When this ratio is greater than 1.4 the material is likely to be cyclically strain hardening; if less than 1.2, the material is likely to be strain softening. Ratios between 1.2 and 1.4 do not clearly identify either strain hardening or strain softening. A more complex and somewhat more accurate criterion for determining whether softening or hardening takes place under cyclic loading is given in Ref. 50. The basic relation between fatigue life and plastic strain in the absence of creep, first formulated by Manson (Ref. 51) and Coffin (Ref. 52), is

$$\Delta\varepsilon_p = MN_f^z$$

where ε_p is the plastic component of the cyclic strain, N_f is the number of cyles to failure, and M and z are material constants. Thus, the low-cycle fatigue behavior of a material is often characterized by a plot of plastic strain vs cyclic life on log-log coordinates. According to the Manson-Coffin relation such a plot should be a straight line; however, curvature is sometimes noted in the high-cycle range.

General relationships. The fatigue limit generally increases with tensile strength and sometimes is estimated as one-half the tensile strength. However, at best, this relationship is a very rough approximation. Steels heat treated to hardness above about 40 RC can not be characterized by such a simple relation (Ref. 53), probably because at high hardness levels steels become very sensitive to crack initiation at surface irregularities and/or inclusions. Much more useful estimates of fatigue lives from tensile properties have been made by developing relationships based on the total strain (elastic plus plastic). The following relation has been proposed (Ref. 54) for estimating the fatigue life in terms of the total strain and the tensile properties.

$$\Delta\varepsilon = (N_f/D)^{-0.6} + 3.5(F_{tu}/E)N_f^{-0.12}$$

where D is the true diametrical strain = ln(1 - RA), where RA is the reduction in area at fracture and N_f is the fatigue life at a total strain range of $\Delta\varepsilon$. For most materials this relation gives useful results in the range between 10 and 10^7 cycles.

At elevated temperatures creep may be superimposed on fatigue and the interpretation of the data becomes rather complicated. Frequency of cycling is an important variable under these circumstances. If temperature and mean stress are sufficiently high, creep rupture becomes the primary mode of failure and the times to failure are often reported rather than the number of cycles to failure. For much of the elevated temperature fatigue test data, it is not possible to clearly classify the information as conventional high-cycle or as low-cycle fatigue.

3.5.3 Fatigue Crack Propagation. This section contains information on propagation of so-called natural cracks under cyclic loading. With few exceptions these cracks are produced from a starter notch by fatigue cycling at stress intensity levels well below K_{Ic}. ASTM E 647 (Ref. 59) gives details concerning the preparation of specimens, testing methods, and validity criteria. Logarithmic coordinates are most frequently used to plot crack propagation rates (da/dN) as a function of the stress intensity range ΔK. Such plots often define two major regions of interest: (1) region where the rate is a nearly linear function of the stress intensity range and (2) a value of the stress intensity range, designated as ΔK_{th}, below which fatigue crack propagation presumably will not occur under the test conditions. It is important to realize that the crack propagation rates and the K_{th} value will be a function of the test environment and the mean value of the stress intensity range. In come cases the value of K_{th} will be below K_{Iscc}. At elevated temperatures and in the presence of aggressive environments, the test results can be a function of the cyclic load frequency. Appendix C (under revision) gives further details.

3.6 Elastic Properties

This section includes not only the classical elastic constants but also the tangent and secant moduli which extend into the plastic region. A high degree of sensitivity and precision in strain measurements is required in determining the elastic constants. Values reported in the literature often exhibit considerable scatter due to poor testing techniques. Some annealed alloys have no true proportional limit at room temperature, and at sufficiently high temperature no alloy has a well defined proportional limit. Under these circumstances truly elastic properties do not exist and attempts to determine the elastic constants will result in values which depend strongly on the testing technique.

3.6.1 Poisson's Ratio. Poisson's ratio is the absolute value of the ratio of the transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material. Poisson's ratio is related to the elastic modulus E and shear modulus G as follows:

$$\mu = \frac{E}{2G} - 1$$

ASTM D 132 (Ref. 55) is a standard method for determination of Poisson's ratio at room temperature.

3.6.2 Modulus of Elasticity. For the purposes of this handbook the modulus of elasticity refers to Young's modulus. The static modulus of elasticity is the ratio of the normal stress to the corresponding strain measured at stresses below the proportional limit of the material. The determination may be made in either tension or compression (ASTM E 111, Ref. 56). The tension modulus E is theoretically equal to the compression modulus E_c; however, residual stresses may produce some difference in these values. The modulus may also be determined by resonance methods (Ref. 57) and when so determined is generally referred to as the dynamic modulus. At temperatures where time dependent deformation is absent the static and dynamic moduli are essentially equal with the dynamic value in some materials being slightly lower than the static value. At temperatures where time dependent deformation would occur in static tests the dynamic modulus is useful where vibratory loads accompany creep deformation. The modulus of elasticity decreases with increasing temperature and is much less sensitive to the metallurgical structure than is the flow stress. However, the modulus will depend on the testing direction in cases where a bulk crystallographic anisotropy is present.

3.6.3 Modulus of Rigidity. The modulus of rigidity or the shear modulus is the ratio of the shear stress to the corresponding shear strain for shear stresses below the proportional limit in shear of the material. The modulus of rigidity is related to Young's modulus and Poisson's ratio as follows:

$$G = \frac{E}{2(1+\mu)}$$

ASTM E 143 (Ref. 58) gives a standard method for determining the shear modulus.

3.6.4 Tangent Modulus. The tangent modulus is the slope of the stress strain curve at each stress value considered. Reported values are subject to considerable variation because of the basic difficulty in determining the slope of any curve. The tangent modulus may be determined in either tension or compression.

3.6.5 Secant Modulus. The secant modulus is the slope of a line from the origin to the stress values considered. The secant modulus may be determined in either tension or compression.

4 Fabrication

The term fabrication is used here to mean all of the processes, except heat treatment, which may normally be employed in the manufacture of components from material supplied by the alloy producers. These processes include forming (forging, rolling, drawing, etc.), metal removal (machining, chem milling, etc.), joining (welding, soldering, brazing, etc.), and post fabrication treatments that may be required (cleaning and other surface treatments). In many cases the fabrication process may profoundly alter the mechanical properties of the material through the effect on the microstructure by the introduction of residual stresses or the production of crack like defects. This handbook can devote only a limited amount of space to the very large amount of information that exists on the so-called fabricability of an alloy or the details of recommended fabrication procedures. Emphasis is placed on the effect of fabrication processes which can adversely affect the load carrying capacity in service. In this connection particular attention is given to welding and other joining processes.

4.1 Forming

The information presented in this section relates primarily to the effects of various forming processes on the mechanical properties. Forming includes the processes of permanent metal deformation (e.g., forging, rolling, drawing, etc.). Forging temperatures are reported as the maximum starting and the minimum finishing temperature. These apply to closed die or blacksmith forgings in the weight range from 5 to 1000 lbs. Forging temperatures for small parts are approximately the same; however, for small forgings a great deal of care must be exercised to avoid critical strains which can induce grain growth on reheating for a subsequent operation or during heat treating.

4.2 Machining and Grinding

Only a very limited amount of information on these subjects is presented. The reader is referred to the Machinability Data Center, Metcut Research Associates, Cincinnati, Ohio, for detailed information on the machinability of the alloys in this handbook.

4.3 Joining

The joining processes of welding and brazing and, to a lesser extent, soldering can produce damaged regions in a fabricated component which may severely limit its load carrying capacity. Thus, the deposited filler metal or heat affected zone of the parent metal may contain embrittled regions or cracks. Special attention is given to the effects of welding and brazing parameters on the fracture properties and to recommended procedures which will produce sound joints.

4.4 Surface Treating

Attention here is focused on cleaning procedures or special surface treatments (e.g., case hardening) that could influence the mechanical properties.

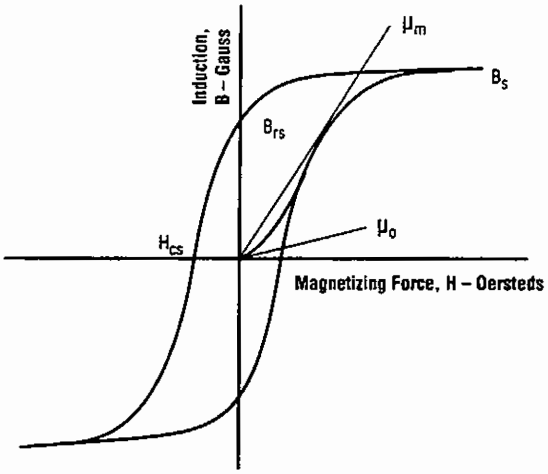

Fig. 2.2.3.1 Normal induction curve and hysteresis loop for ferromagnetic materials

Table 3.3.3 Summary of ASTM selected standard impact tests

Name	Specimen	Notch	Index of Toughness	Reference
Charpy and Izod	Simple Beam	None	Absorbed Energy	ASTM E 23 Ref. 30
Charpy and Izod	Notched Beam 10x10 mm (a)	V, Keyhole or U	Absorbed Energy Lateral Expansion Transition Temp. Fracture Appearance	ASTM E 23 Ref. 30
NDT	Surface Crack Plate	Brittle Weld Crack Starter	Nil Ductility Transition Temp.	ASTM E 208 Ref. 31
Drop Weight Tear	Edge Notch Plate 3x12 in. full thickness	Pressed V R < 0.001 in.	Fracture Appearance	ASTM E 436 Ref. 32
Dynamic Tear	Edge Notch Plate 7x1.6 in. 3/16<t<5/8 in.	Pressed V R < 0.001 in.	Absorbed Energy Fracture Appearance	ASTM E 604 Ref. 33

(a) Subsized Charpy specimens permitted

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