CHAPTER A3

PIPING MATERIALS

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The selection of materials for piping applications is a process that requires consideration of material characteristics appropriate for the required service. Material selected must be suitable for the flow medium and the given operating conditions of temperature and pressure safely during the intended design life of the product. Mechanical strength must be appropriate for long-term service, and resist operational variables such as thermal or mechanical cycling. Extremes in application temperature can raise issues with material capabilities ranging from brittle fracture toughness at low temperatures to adequacy of creep strength and oxidation resistance at the other end of the temperature spectrum.

In addition, the operating environment surrounding the pipe or piping component must be considered. Degradation of material properties or loss of effective load-carrying cross section can occur through corrosion, erosion, or a combination of the two. The nature of the substances that are contained by the piping is also an important factor.

The fabricability characteristics of the materials being considered must also be taken into account. The ability to be bent or formed, suitability for welding or other methods of joining, ease of heat treatment, and uniformity and stability of the resultant microstructure and properties all of a given piping material contribute toward or detract from its attractiveness and economy. The selection process should lead to the most economical material that meets the requirements of the service conditions and codes and standards that apply.

Applicable design and construction codes such as the ASME Boiler and Pressure Vessel Code and the ASME B31 Pressure Piping Code identify acceptable materials for piping systems within their jurisdiction. These codes specify the design rules, allowable design stresses, and other properties required to accomplish the design task. However, the information supplied is generally only adequate and intended to assure safe operation under the thermal and mechanical conditions expected under steady-state and sometimes (as in nuclear construction) cyclic operation. These codes do not directly and explicitly address the many other environmental and material degradation issues that should be considered by design and materials engineers in arriving at a piping system that is not only safe to operate but will offer long-term, reliable service and function. Thus, simply designing to "the Code" when selecting materials can sometimes lead to premature end-of-life of piping system components.

This chapter will attempt to identify the important metallurgical characteristics of piping materials and how they can affect or be affected by operation of all of the other materials available to the engineer. Carbon and low-alloy steels come closest to being the ideal construction material. Due to the fact that the majority of piping applications employ iron-based metals, these will be emphasized in this chapter.

MATERIAL PROPERTIES OF PIPING MATERIALS

The behavior of piping material can be understood and predicted by studying a number of properties of the material. Appreciation of how a material will perform must extend all the way down to the atomic components of the material. Metals are crystalline in structure, composed of atoms in precise locations within a space lattice.

The smallest component of the crystalline structure is called a *unit cell,* the smallest repeating building block of the material. For example, iron and iron-based alloys exist in two unit cell forms, the body-centered cubic (BCC) and the face-centered cubic (FCC) structure, shown in Fig. A3.1. They are differentiated in the way the atoms are arranged in repeating patterns. The body-centered cubic structure is represented by a cube with atoms at all eight corners, and one atom in the center of the cube. The face-centered lattice is represented by atoms at the eight corners of the cube, plus one atom located at the center of each of the cube's six faces. The crystal structure naturally assumed by a material dictates some of the fundamental properties of the material. For example, FCC materials are generally more ductile than BCC materials. This is basically because FCC crystals are the most tightly packed of metallic structures and, as such, allow for more planes of atoms to slide across one another with the least amount of resistance (the fundamental atomic motion involved in what is called *plasticity*).

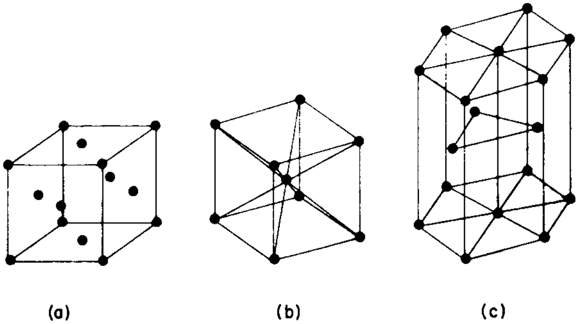


FIGURE A3.1 The three most common crystal structures in metals and alloys. (*a*) Face-centered cubic (FCC); (*b*) body-centered cubic (BCC); (*c*) hexagonal close-packed (HCP).

Metallic materials consist of these and other ordered crystal structures. Some metals, most notably iron, change their crystal structure as temperature varies.

Structure may also change as certain other elements are added in the form of alloying additions. These changes are used to advantage by metallurgists and are the basis for developing and manipulating important material behavior, such as the heat treatability of carbon and low alloy steels.

Plastics may be defined as synthetic materials whose chief component is a resin or resin equivalent. The term *plastic* covers a very broad range of materials that contain, as an essential ingredient, one or more organic polymetic substances. They possess large molecular weight, formed by the chemical combination of carbon-hydrogen atom chains (monomers to polymers). The atomic structure is thus ordered and predictable, but dissimilar from that of metals. Many plastics have greater strength per unit weight than metal, but suffer due to lower impact strength, chemical stability, and thermal and aging stability. However, plastics fill an important niche in the piping engineer's repertoire.

Ceramic materials are composed of the oxides of metal arranged in ordered atomic structures similar to that of metals. The atomic constituents are electronically different, resulting in rigid, predictable behavior, but with an inherent lack of plasticity compared to metals.

Glasses form the other extreme of the atomic structure spectrum. Their atomic makeup is essentially that of a liquid; the structure is actually a solid with no ordered arrangement of atoms.

These atomic characteristics (i.e., the natural arrangement of the atoms, as well as the specific elements involved and their electronic characteristics) establish the fundamental properties of engineering materials. The properties that a engineer requires to design and construct a piping system are a manifestation of the longer-range effects of atomic structure. These properties fall into three categories: chemical, mechanical, and physical.

Chemical Properties of Metals

Chemical properties are herein defined as those material characteristics that are dictated by the elemental constituency of the solid. This is usually measured by the relative atomic weight percent of the various elements (metals or nonmetals) or compounds within the material.

Metals are are not usually used in their pure form. Rather, secondary elements are purposely added to improve or modify their behavior. This addition of secondary elements is called *alloying*, and the elements added fall into two categories, based on the relative size of the atoms. Atoms significantly smaller than those of the parent metal matrix fit into spaces between the atoms in the lattices' interstices and are called *interstitial alloying elements*. Carbon added to iron, creating steel, is the most common example. Larger-sized atoms will substitute for parent metal atoms in their matrix locations, thus the name *substitutional alloying elements*. Examples of this include zinc substituting for copper atoms in copper, creating brass; and tin substituting for copper atoms, creating bronze alloys.

Pure metals possess relatively low strength. Adding an alloying element will increase the strength of a metal's atomic matrix because the atomic lattice is strained locally by the foreign atom, creating a larger impediment for the sliding of planes of atoms across one another during plastic flow. This is true whether the alloying element is interstitial or substitutional; however, the former generally serve as better lattice strengtheners. Strength properties are often improved to the detriment of ductility. Proper alloying, combined with appropriate metal processing and heat treatment, results in optimization of material properties.

Elements are also added to metals to improve or modify their corrosion or oxidation characteristics, or to improve manufacturability (e.g., machineability) and/or electrical properties, among other effects. However, it is important to note that alloying done to optimize one material property may act to the detriment of others.

Carbon steels, the most common of the construction materials, always contain the elements carbon, manganese, phosphorous, sulfur, and silicon in varying amounts. Small amounts of other elements may be found either entering as gases during the steel-making process (hydrogen, oxygen, nitrogen), or introduced through the ores or metal scrap used to make the steel (nickel, copper, molybdenum, chromium, tin, antimony, etc.). The specific effect of each of these elements on steel properties will be addressed later in the chapter. Addition of significant quantities of the interstitial element carbon will result in high strength and hardness—but to the detriment of formability and weldability. A great amount of research has gone into the development of the principal metals used in piping design and construction; thus the specification limits must be vigorously adhered to in order to assure reliability, predictability, and repeatability of material behavior.

The number of elements alloyed with a parent metal, and the acceptable range of content of each, are identified in the material specification (e.g., ASTM, API, ASME). Tests appropriate for determining the elemental constituency of an alloy have been standardized and are also described in ASTM specifications. The material specifications also stipulate whether the chemical analysis of an alloy may be reported by analyzing a sample of the molten metal, or taken from a specimen removed from the final product. The former is commonly referred to as a *ladle* analysis, and the latter as a *product* or *check* analysis. This ''chemistry'' of a construction material is reported on a material test report which may be supplied by the material manufacturer upon request.

Mechanical Properties of Metals

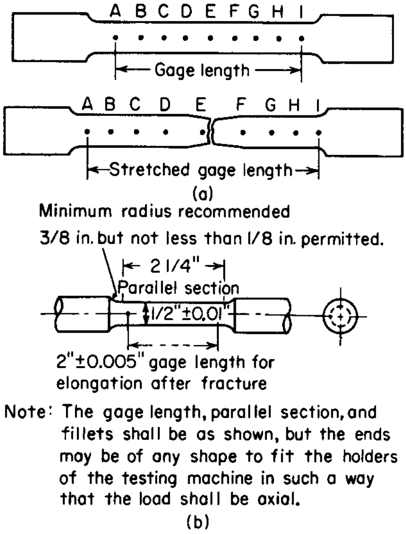
Mechanical properties are critically important to the design process. They are defined as the characteristic response of a material to applied force. The standardized test methods for measuring these properties are described in ASTM specifications.

Properties fall into two general categories, strength and ductility. Some properties, such as material toughness, are dependent on both strength and ductility. The most widely known and used material properties, as defined by ASTM, are described in the following paragraphs.[1]

Modulus of Elasticity (Young's Modulus). The modulus of elasticity is the ratio of normal stress to corresponding strain for tensile or compressive stresses. This ratio is linear through a range of stress, known as Hooke's law. The material behavior in this range is elastic (i.e., if the applied load is released the material will return to its original, unstressed shape). The value of the slope in the elastic range is defined as *Young's Modulus*.

The modulus of elasticity is measured using the tension test, the most widely used test applied to engineering materials. The test consists of applying a gradually increasing load in either tension or compression, in a testing machine, to a standardized test specimen (Fig. A3.2). The applied load is continuously monitored, as is test specimen elongation or contraction under load. These measured quantities are generally represented on a coordinate axis, called a stress-strain curve (Fig. A3.3). The modulus of elasticity and other strength properties are established from this curve. Values of the modulus of elasticity for a number of construction materials are given in Table A3.1

Yield Strength. When a specimen is loaded beyond the point where elastic behavior can be maintained the specimen will begin to deform in a plastic manner. Most materials do not abruptly transform from purely elastic to purely plastic behavior. Rather, a gradual transition occurs as represented by a curve, or *knee*, in the stress-strain curve. Lacking an abrupt and easily definable point representing transition from elastic to plastic behavior, several standardized methods have been defined by ASTM to determine the yield strength used as the engineering property. The most common is termed the *0.2 percent offset method*. In this approach a line is drawn parallel to the elastic portion of the curve anchored to a point displaced 0.2 percent along the strain axis. (Fig. A3.4). The yield strength corresponds to the calculated value of the load indicated at the intersection point of the drawn line, divided by the original cross-sectional area in the gauge length of the tensile specimen. By convention, this test is performed at a constant rate of strain, and is reported as newtons per square meter, or as pounds per square inch of cross section in English units.



Note: The gage length, parallel section, and fillets shall be as shown, but the ends may be of any shape to fit the holders of the testing machine in such a way that the load shall be axial.

FIGURE A3.2 Tension-test specimens. (*a*) Strip specimen showing measurements which are taken to determine elongation; (*b*) standard round specimen with 2-in gauge length.

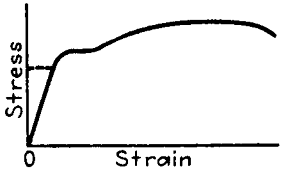


FIGURE A3.3 Stress-strain diagram.

Ultimate Tensile Strength. Upon further increase of applied load under constant strain rate, the specimen will continue to stretch until the loss of load-carrying cross section caused by specimen thinning during the test (due to Poisson's ratio) cannot withstand further load increase. The ultimate tensile strength constitutes the maximum applied load divided by the original specimen cross-sectional area.

Elongation and Reduction of Area. The ductility of the test specimen can be established by measuring its length and minimum diameter before and after testing. Stretch of the specimen is represented as a percent elongation in a given length (usually 2 or 8 in) and is calculated in the following manner:

$$\text{Percent elongation} = \frac{(\text{final length} - \text{original length})}{\text{original length}} \times 100$$

TABLE A3.1 Modulus of Elasticity U.S. Units for Metals*

	E = Modulus of elasticity, msi (millions of psi),[1] at temperature °F[2]																				
Material	−425	−400	−350	−325	−200	−100	70	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
Ferrous metals																					
Gray cast iron	. . .	. . .	. . .	. . .	. . .	. . .	13.4	13.2	12.9	12.6	12.2	11.7	11.0	10.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Carbon steels, C ≤ 0.3%	31.9	. . .	. . .	31.4	30.8	30.2	29.5	28.8	28.3	27.7	27.3	26.7	25.5	24.2	22.4	20.4	18.0	. . .	. . .	. . .	. . .
Carbon steels, C > 0.3%	31.7	. . .	. . .	31.2	30.6	30.0	29.3	28.6	28.1	27.5	27.1	26.5	25.3	24.0	22.2	20.2	17.9	15.4	. . .	. . .	. . .
Carbon-moly steels	31.7	. . .	. . .	31.1	30.5	29.9	29.2	28.5	28.0	27.4	27.0	26.4	25.3	23.9	22.2	20.1	17.8	15.3	. . .	. . .	. . .
Nickel steels, Ni 2%–9%	30.1	. . .	. . .	29.6	29.1	28.5	27.8	27.1	26.7	26.1	25.7	25.2	24.6	23.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Cr–Mo steels, Cr ½%–2%	32.1	. . .	. . .	31.6	31.0	30.4	29.7	29.0	28.5	27.9	27.5	26.9	26.3	25.5	24.8	23.9	23.0	21.8	20.5	18.9	. . .
Cr–Mo steels, Cr 2¼%–3%	33.1	. . .	. . .	32.6	32.0	31.4	30.6	29.8	29.4	28.8	28.3	27.7	27.1	26.3	25.6	24.6	23.7	22.5	21.1	19.4	. . .
Cr–Mo steels, Cr 5%–9%	33.4	. . .	. . .	32.9	32.3	31.7	30.9	30.1	29.7	29.0	28.6	28.0	27.3	26.1	24.7	22.7	20.4	18.2	15.5	12.7	. . .
Chromium steels, Cr 12%, 17%, 27%	31.8	. . .	. . .	31.2	30.7	30.1	29.2	28.5	27.9	27.3	26.7	26.1	25.6	24.7	23.2	21.5	19.1	16.6	. . .	. . .	. . .
Austenitic steels (TP304, 310, 316, 321, 347)	30.8	. . .	. . .	30.3	29.7	29.1	28.3	27.6	27.0	26.5	25.8	25.3	24.8	24.1	23.5	22.8	22.1	21.2	20.2	19.2	18.1
Copper and Copper Alloys																					
Comp. and leaded–Sn bronze (C83600, C92200)	. . .	. . .	. . .	14.8	14.6	14.4	14.0	13.7	13.4	13.2	12.9	12.5	12.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Naval brass, Si– & Al–bronze (C46400, C65500, C95200, C95400)	. . .	. . .	. . .	15.9	15.6	15.4	15.0	14.6	14.4	14.1	13.8	13.4	12.8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Copper (C11000)	. . .	. . .	. . .	16.9	16.6	16.5	16.0	15.6	15.4	15.0	14.7	14.2	13.7	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Copper, red brass, Al–bronze (C10200, C12000, C12200, C12500, C14200, C23000, C61400)	. . .	. . .	. . .	18.0	17.7	17.5	17.0	16.6	16.3	16.0	15.6	15.1	14.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
90Cu–10Ni (C70600)	. . .	. . .	. . .	19.0	18.7	18.5	18.0	17.6	17.3	16.9	16.6	16.0	15.4	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Leaded Ni–bronze	. . .	. . .	. . .	20.1	19.8	19.6	19.0	18.5	18.2	17.9	17.5	16.9	16.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
80Cu–20Ni (C71000)	. . .	. . .	. . .	21.2	20.8	20.6	20.0	19.5	19.2	18.8	18.4	17.8	17.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
70Cu–30Ni (C71500)	. . .	. . .	. . .	23.3	22.9	22.7	22.0	21.5	21.1	20.7	20.2	19.6	18.8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Nickel and Nickel Alloys																					
Monel 400 (N04400)	28.3	. . .	. . .	27.8	27.3	26.8	26.0	25.4	25.0	24.7	24.3	24.1	23.7	23.1	22.6	22.1	21.7	21.2	. . .	. . .	. . .
Alloys G, G1, 20 Mod. (N06007, N08320)	30.3	. . .	. . .	29.5	29.2	28.6	27.8	27.1	26.7	26.4	26.0	25.7	25.3	24.7	24.2	23.6	23.2	22.7	. . .	. . .	. . .
Alloys 800, 800H, × (N08800, N08810, N06002)	31.1	. . .	. . .	30.5	29.9	29.4	28.5	27.8	27.4	27.1	26.6	26.4	25.9	25.4	24.8	24.2	23.8	23.2	. . .	. . .	. . .
Alloys C–4, C276 (N06455, N10276)	32.5	. . .	. . .	31.6	31.3	30.6	29.8	29.1	28.6	28.3	27.9	27.6	27.1	26.5	25.9	25.3	24.9	24.3	. . .	. . .	. . .
Nickel 200, 201, Alloy 625 (N02200, N02201, N06625)	32.7	. . .	. . .	32.1	31.5	30.9	30.0	29.3	28.8	28.5	28.1	27.8	27.3	26.7	26.1	25.5	25.1	24.5	. . .	. . .	. . .
Alloy 600 (N06600)	33.8	. . .	. . .	33.2	32.6	31.9	31.0	30.2	29.9	29.5	29.0	28.7	28.2	27.6	27.0	26.4	25.9	25.3	. . .	. . .	. . .
Alloy B (N10001)	33.9	. . .	. . .	33.3	32.7	32.0	31.1	30.3	29.9	29.5	29.1	28.8	28.3	27.7	27.1	26.4	26.0	25.3	. . .	. . .	. . .
Alloy B-2 (N10665)	34.2	. . .	. . .	33.3	33.0	32.3	31.4	30.6	30.1	29.8	29.4	29.0	28.6	27.9	27.3	26.7	26.2	25.6	. . .	. . .	. . .
Unalloyed Titanium																					
Grades 1, 2, 3, and 7	. . .	. . .	. . .	. . .	. . .	. . .	15.5	15.0	14.6	14.0	13.3	12.6	11.9	11.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .

* These data are for information, and it is not to be implied that materials are suitable for all the temperatures shown. Data are taken from Code for Pressure Piping, ASME B31.1-1995.

[1] To convert psi into kPa, multiply the tabulated values by 6.895 × 10^6.

[2] To convert °F into °C, divide (tabulated °F − 32) by 1.8.

TABLE A3.1 Modulus of Elasticity* (*Continued*)

Material	E = Modulus of elasticity, msi (millions of psi), at temperature, °F −425	−400	−350	−325	−200	−100	70	200	300	400
Aluminum and Aluminum Alloys										
Grades 443, 1060, 1100, 3003, 3004, 6061, 6063, (A24430, A91060, A91100, A93003, A93004, A96061, A96063)	11.4	...	...	11.1	10.8	10.5	10.0	9.6	9.2	8.7
Grades 5052, 5154, 5454. 5652 (A95052, A95154, A95454, A95652)	11.6	...	...	11.3	11.0	10.7	10.2	9.7	9.4	8.9
Grades 356, 5083, 5086, 5456 (A03560,A95083, A95086, A95456)	11.7	...	...	11.4	11.1	10.8	10.3	9.8	9.5	9.0

The diameter of the test specimen will decrease, or *neck down*, in ductile materials. Another standard measure of ductility is the reduction of area of the specimen, defined as follows:

$$\text{Percent reduction of area} = \frac{(\text{original cross-sectional area} - \text{final area})}{\text{original area}} \times 100 \tag{A3.1}$$

Hardness. This is a measure of the material's ability to resist deformation, usually determined by a standardized test where the surface resistance to indentation is measured. The most common hardness tests are defined by the indentor type and size, and the amount of load applied. The hardness numbers constitute a non-dimensioned, arbitrary scale, with increasing numbers representing harder surfaces. The two most common hardness test methods are Brinell Hardness and Rockwell Hardness, with each representing a standardized test machine with its own unique hardness scales. Hardness loosely correlates with ultimate tensile strength in metals (Fig. A3.5). Approximate hardness conversion numbers for a variety of material types, including steels, can be found in ASTM Specification E140.

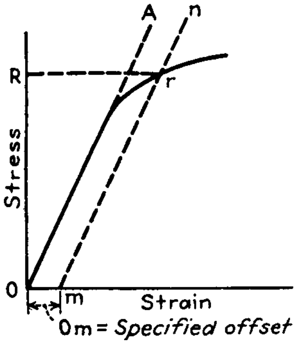


FIGURE A3.4 Offset method of determining yield strength.

Toughness. Sudden fracture, exhibiting little ductility in the vicinity of the break, occurs in certain metals when load is rapidly applied. The capability of a material to resist such a brittle fracture is a measure of its toughness.

Highly ductile materials (those possessing an FCC lattice, for example) exhibit considerable toughness across a full range of temperatures. Other materials, such as BCC-based carbon steels, possess a level of toughness that is dependent on the metal temperature when the load is applied. In these metals, a transition from brittle to ductile behavior occurs over a narrow range of temperatures.

The two most common methods used to measure metal toughness are the Charpy

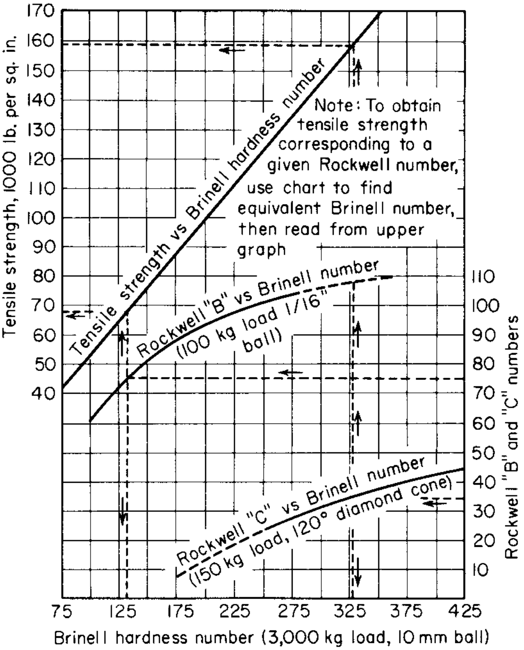


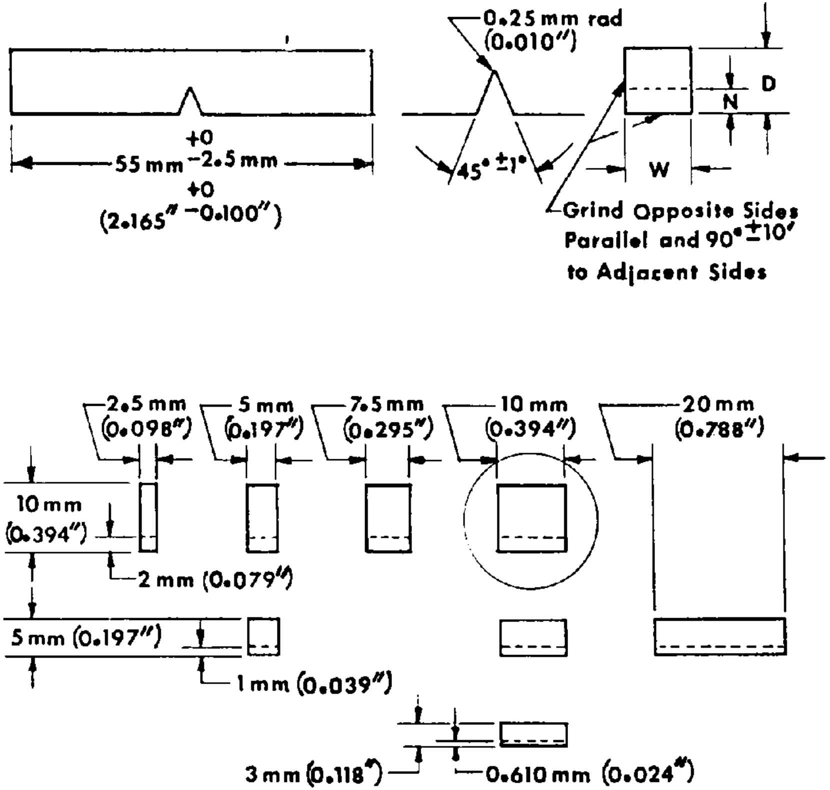
FIGURE A3.5 Conversion chart for Brinell and Rockwell hardness numbers, giving corresponding tensile strength for steel. Based on hardness conversion table. (*SAE Handbook*, 1964.)

Impact test, defined in ASTM specification E 23, and the Drop-Weight test, defined in ASTM E 208. The Charpy test employs a small machined specimen with a machined notch that is struck by a pendulum weight (Fig. A3.6). The energy loss to the pendulum as it passes through and breaks the specimen (Fig. A3.7), measured in kilojoules or ft · lb of force, is a measure of the toughness of the specimen. Typical impact behavior versus test temperature is shown in Fig. A3.8.

The Drop-Weight test is similar in principle but employs a larger specimen with a brittle, notched weld bead used as the crack starter (Fig. A3.9). A weight is dropped from a height onto the specimen, which had been cooled or heated to the desired test temperature. The test determines the *nil-ductility transition temperature* (NDTT), defined as the specimen temperature when, upon striking, the crack propagates across the entire specimen width.

The Charpy brittle transition temperature (sometimes called the *Charpy fix temperature)* and the Drop Weight NDTT are both important design considerations for those materials that can exhibit poor toughness and that may operate in lower temperature regimes. In pressure vessel and piping design codes, limits are placed on material minimum use temperature based on adding an increment of margin over and above the Charpy fix or NDTT. Operating at or above this elevated temperature is then usually sufficient to avoid brittle, catastrophic failure, as for example is the case when at a temperature on the "upper shelf" of the Charpy V-notch toughness-versus-temperature curve.

On subsize specimens the length, notch angle, and notch radius are constant (see Fig. 6); depth (*D*), notch depth (*N*), and width (*W*) vary as indicated below.



NOTE 1—Circled specimen is the standard specimen (see Fig. 6).

NOTE 2—Permissible variations shall be as follows:

Cross-section dimensions	±1 % or ±0.075 mm (0.003 in.), whichever is smaller
Radius of notch	±0.025 mm (0.001 in.)
Depth of notch	±0.025 mm (0.001 in.)
Finish requirements	2 µm (63 µin.) on notched surface and opposite face; 4 µm (125 µin.) on other two surfaces

FIGURE A3.6 Charpy (simple beam) subsize (Type A) impact test specimens. (ASTM Specification E23.)

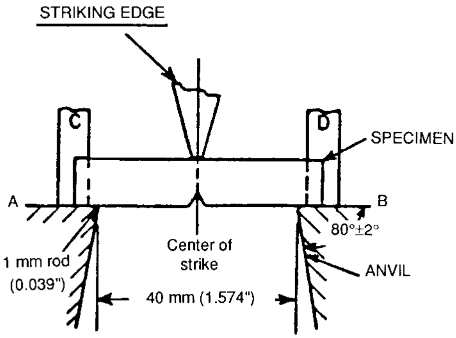


FIGURE A3.7 Charpy V-notch specimen placement during strike by testing anvil. (ASTM Specification E23.)

Fatigue Resistance. The ability of a metal to resist crack initiation and further propagation under repeated cyclic loading is a measure of its fatigue resistance. Several standardized test methods have been developed to test metals, machined to particular geometries, where applying a repeating load range. Loads are generally applied through bending, cantilevered, or push-pull load application in suitably outfitted testing machines. Either constant applied stress or strain ranges can be employed to determine material response.

The most common representation of fatigue test data is an *S-N* curve, relating stress (*S*) required to cause specimen failure in a given number of cycles (*N*) (Fig.

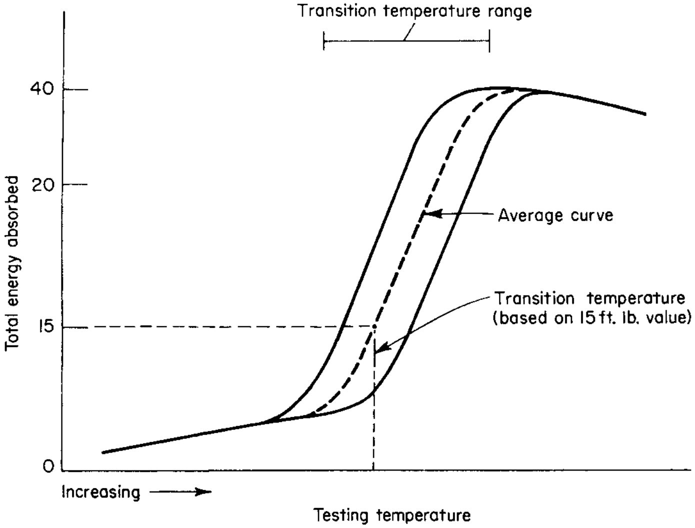


FIGURE A3.8 Transition temperature range and transition temperature in Charpy impact test.

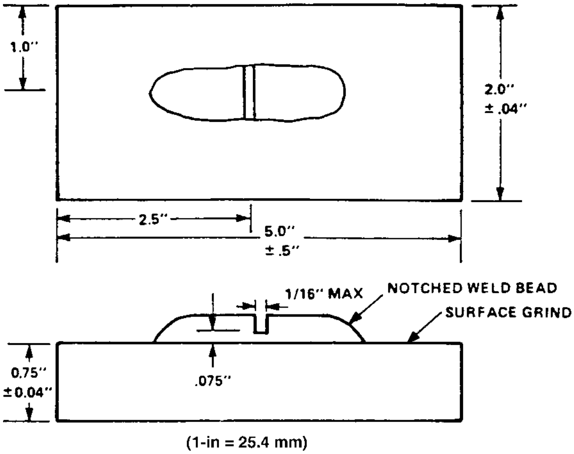


FIGURE A3.9 Drop-weight test specimen with brittle weld deposit on specimen face; machined notch to act as crack starter. Impact load applied from side opposite weld deposit. (ASTM Specification E208.)

A3.10a). These tests are generally performed on smooth specimens, but they can also be run with stress-concentrating mechanisms such as notches machined into the specimen surface. The effect of stress concentrations on fatigue life cycles can also be estimated from the smooth specimen *S-N* curve by calculating the intensified stress due to the particular geometry, and intersecting the curve at that point on the stress axis.

As the applied load range decreases, ferritic steels exhibit a point at which an infinite number of cycles can be absorbed without causing failure. This level of stress is called the *endurance limit.* Many of the other metals do not exhibit this behavior, but rather exhibit an increasing, but finite, number of cycles to failure with decreasing cyclic load (Fig. A3.10b).

The fatigue resistance of a material at a given applied stress or strain range is a function of a number of variables, including material strength and ductility. Results may vary significantly for different surface finishes, product forms of the same material (Fig. A3.11), material internal cleanliness, test specimen orientation, and levels of residual stress, among other factors. Variations in the test environment can also have a profound effect on test results (Fig. A3.12). Therefore, fatigue test results characteristically exhibit significant scatter.

Fatigue design curves are generated from test data by applying large safety margins to the average property curve. In U.S. design codes, the fatigue design curve is commonly generated by taking the lesser of 1⁄20 times the cycles to failure, or ½ of the stress to cause failure. A new curve is constructed taking the lower bound of these two factored curves.

When considering metal fatigue in design, a further safety margin is often also applied against the cycles-to-failure at a given stress amplitude. For example, if a component is continuously cycled over the same stress range, a design limit on allowable cycles may correspond to the cycle life multiplied by a factor such as 0.8. This is a common safety margin employed in vessel and piping design.

As is normally the case, components may experience a wide variety of cyclic

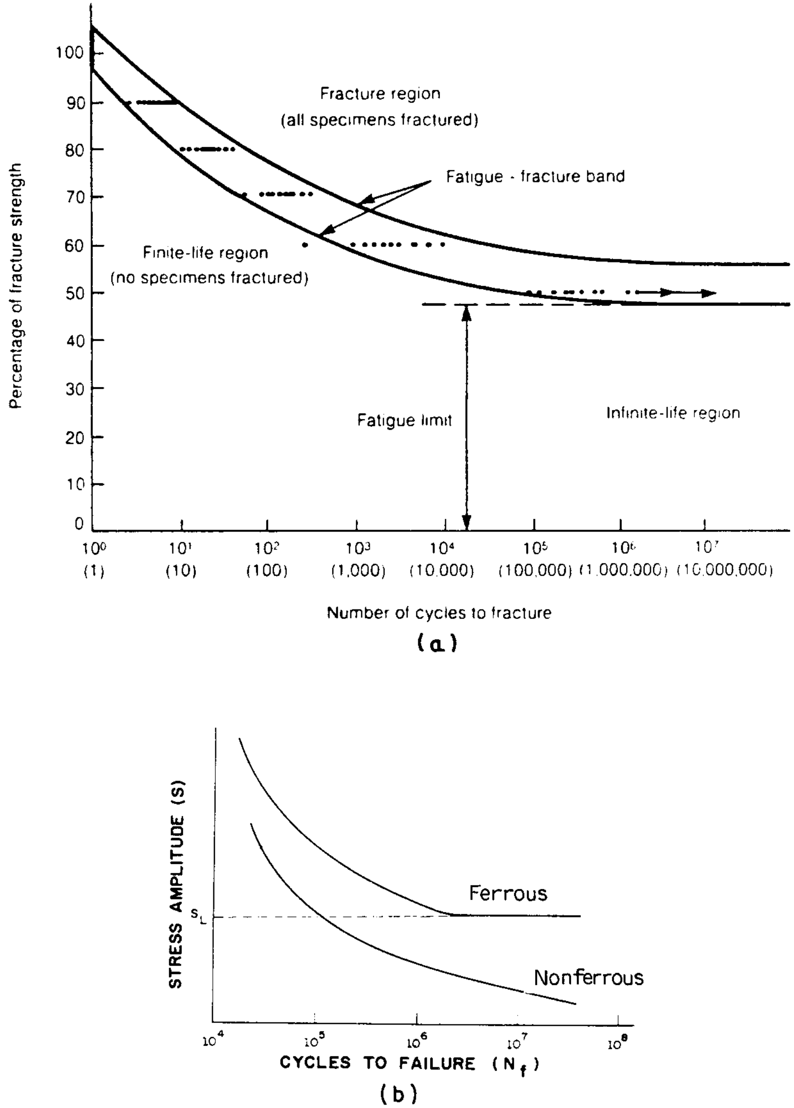


FIGURE A3.10 *S-N* curves that typify fatigue test results (*a*) for testing medium-strength steels and (*b*) showing typical curve shape for ferrous and nonferrous materials. S_L is the endurance limit. (*Atlas of Fatigue Curves*, American Society for Metals, ©1986.)

stress ranges, at various temperatures, over their life. The effect of this array of cyclic parameters on fatigue life can be estimated by an approach referred to as *life fraction summation*. In this design practice, the percentage of life used up in cycling at a certain stress range is calculated, corresponding to the ratio of the number of actual service duty cycles to the total number of cycles to failure at that

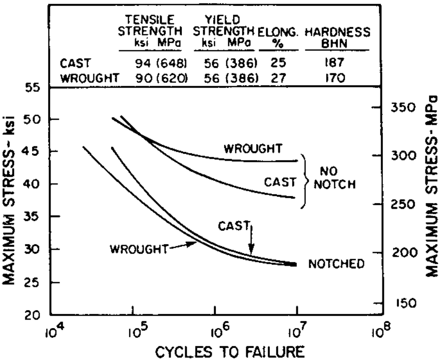


FIGURE A3.11 Fatigue characteristics (*S-N* curve) for cast and wrought 1040 steel in the normalized and tempered condition, both notched and unnotched. R. R. Moore rotating beam tests, K_t = 2.2. (*Atlas of Fatigue Curves*, ASM.)

stress range. This calculation is performed for all of the various stress ranges/duty cycles anticipated. The fractions thereby calculated are summed and compared to the design limit (1.0 with no safety margin, or 0.8 or some other value depending on the design safety factor that applies).

Elevated Temperature Tensile and Creep Strength. Tensile tests are performed at elevated temperatures to characterize the material's yield and ultimate tensile

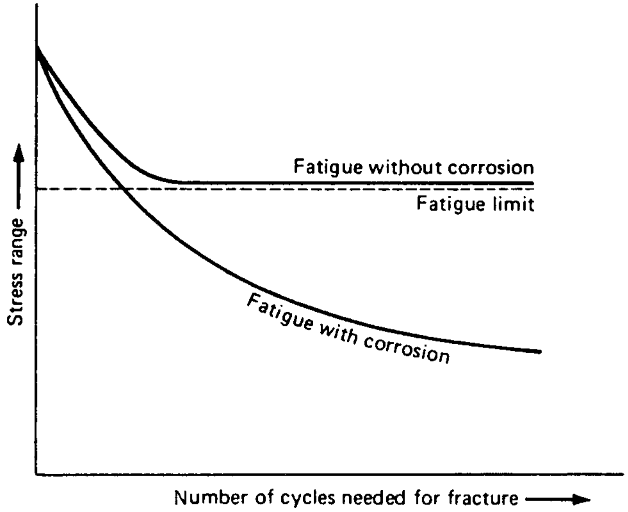


FIGURE A3.12 Effect of alternating stresses with and without corrosion for ferrous material that normally exhibits an endurance limit. (*Atlas of Fatigue Curves*, ASM.)

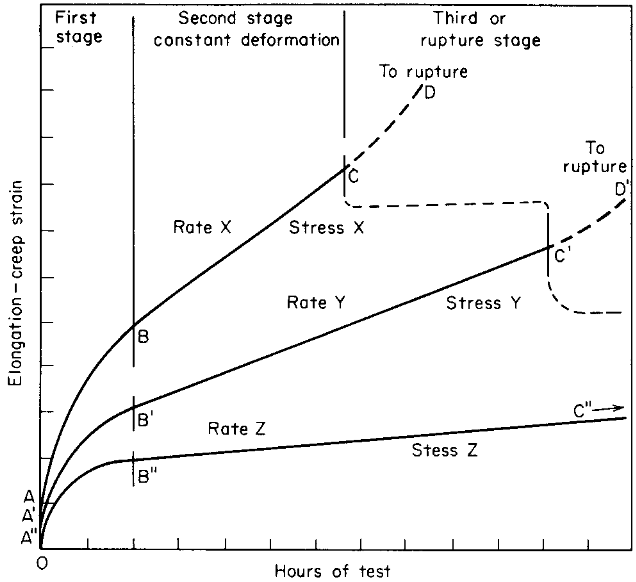


FIGURE A3.13 Creep time versus elongation curves at a given temperature.

properties at potential use temperatures above room temperature. A heating chamber is combined with a conventional tensile testing machine, and special strain measuring extensometers are used that are capable of withstanding the test temperatures. Generally, as temperature increases, yield and ultimate strengths decrease, and ductility increases.

Creep is defined as the time-dependent deformation of a material that occurs under load at elevated temperatures. The test is performed by holding a specimen, similar in configuration to a tensile specimen, at a uniform temperature and a constant load (usually using a dead weight) and allowing the specimen to gradually elongate to ultimate failure. The practice is defined in ASTM Specification E 139.

The simplest test method records only the applied stress (based on original test specimen cross section), time to failure, and total elongation at failure. This is called a *stress rupture test.* If periodic measurements of strain accumulation versus test duration are also taken, the test is referred to as a *creep-rupture test.*

A representation of typical creep strain-versus-time data is shown in Fig. A3.13. Three stages of creep behavior are exhibited. Upon initial loading, instantaneous straining occurs. Almost immediately, the rate of creep strain accumulation (creep rate) is high but continuously decreasing. The test then progresses into a phase where the strain rate slows and becomes fairly constant for a long period of time. Finally, with decreasing load-bearing cross section of the specimen due to specimen stretching and necking, applied stress begins to increase steadily, as does the creep rate, until failure occurs. These three regions are termed the primary, secondary, and tertiary stages of creep. The intent of safe design practice is to avoid the third stage, where strain accumulations are rapid and material behavior less predictable.

After accumulating a number of rupture data points (i.e., time to failure of a metal at various applied stresses), the data is generally represented as a stress rupture curve (Fig. A3.14). Each curve represents the time to failure at various applied stresses, at a given test temperature. Another useful property that can be measured in these tests is the creep rate during the second stage of creep, for a given applied stress and temperature. This, along with time to onset of the tertiary creep stage, are useful properties to the design engineer and are used in establishing allowable design tension stresses in design codes.

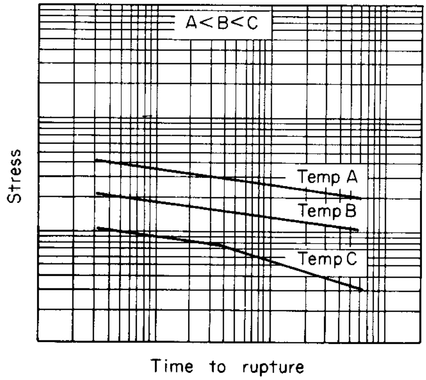


FIGURE A3.14 Typical stress-to-rupture curves.

Metals that experience creep will accumulate a progressively larger amount of microscopic damage to the structure of the material. Damage is first observed microscopically as small cavities, or voids, that begin appearing in the grain boundaries of the metal, particularly at triple points (i.e., where three grains come together). Further progression of damage entails formation of more voids along many of the adjacent grain boundaries, until ultimately they link together to form grain boundary microcracks. With more time, these form larger macrocracks that lead to ultimate failure of the metal component.

The determination of a metal's degree of creep damage, and its consequence on the continued safe operation of the component, has developed into a sophisticated science referred to as component condition assessment, or estimation of remaining life. This will be addressed in more detail later in the chapter.

A practice essentially identical to cyclic fraction life summation used in fatigue design can be employed in material creep analysis to estimate the percentage of creep life expended. Here the individual life fraction corresponds to the amount of time a component spends at a given stress and temperature, compared to the total time to failure given on the stress rupture curve for the same applied stress and temperature. All of these fractions for all the operating conditions are then added together, and compared to an appropriate design limit (1.0 or less).

Physical Properties of Metals

Physical properties are those, other than mechanical properties, that pertain to the physics of a material. Physical properties of importance to the materials and design engineer are material density, thermal conductivity, thermal expansion, and specific heat.[2]

Density. Density is the ratio of the mass of a material to its volume. In vessel and piping design, the density of a construction material versus its strength per unit area of cross section is often an important consideration.

Thermal Conductivity. This is the characteristic ability of a material to transmit energy in the form of heat from a high-temperature source to a point of lower temperature. The ability to transmit heat is usually expressed as a coefficient of

TABLE A3.2 Thermal Conductivity and Expansion of Piping Material

	Thermal conductivity		Linear thermal expansion average	
Material	$\text{Btu}\Big/\left(\text{hr °F}\,\frac{\text{ft}^2}{\text{ft}}\right)$	Temperature, °F	Microinch/(in °F)	Temperature range, °F
Pure iron	43	70	6.83	68–212
	28	752	8.97	932–1112
Gray cast iron	27	70	5.83	32–212
	23.7	752		
Malleable cast iron ferritic	. . .	. . .	6.6	70–750
Malleable cast iron pearlitic	. . .	. . .	6.6	70–750
Nodular iron	18 (Pearlitic)	212	6.46	68–212
	20 (Ferritic)	212	6.97	68–600
			7.49	68–1000
			7.69	68–1400
Wrought iron	34	212		
	26	752		
Wrought carbon steel: 0.06 C, 0.38 Mn	34	32	7.83	70–800
			7.95	70–900
			8.02	70–1000
			8.21	70–1100
			8.36	70–1200
0.23 C, 0.635 Mn	30	70		
	25	752	6.50	68–212
	17	2192		
0.435 C, 0.69 Mn	. . .	. . .	6.44	68–212
			8.39	68–1292
1.22 C, 0.35 Mn	26	70		
	22	752	5.89	122–212
	16	2192	9.33	932–1832
Carbon–½ Mo	25.8	212	7.70	68–800
			7.85	68–1000
			7.95	68–1100
			8.07	68–1200
1¼ Cr–½ Mo	17.9	212	7.32	70–800
			7.44	70–900
			7.56	70–1000
			7.63	70–1100
			7.74	70–1200
			7.82	70–1300
2¼ Cr–1 Mo	16.3	212	7.49	70–800
			7.65	70–900
			7.72	70–1000
			7.78	70–1100
			7.84	70–1200
			7.88	70–1300

1. Btu/(hr °F$\cdot$ft^2/ft) = 0.5780101 Watt/meter^2/°C/meter (W/m^2/°C/m).
2. °C = (°F − 32)/1.8.

TABLE A3.2 Thermal Conductivity and Expansion of Piping Material (*Continued*)

Material	Thermal conductivity		Linear thermal expansion average	
	$\text{Btu}\Big/\left(\text{hr °F}\,\frac{\text{ft}^2}{\text{ft}}\right)$	Temperature, °F	Microinch/(in °F)	Temperature range, °F
5 Cr–½ Mo	21.2	212	6.44	0–212
	20.8	392	6.91	70–800
	20.4	572	7.02	70–900
	19.8	752	7.10	70–1000
	19.5	932	7.19	70–1100
			7.31	70–1200
			7.35	70–1300
9 Cr–1 Mo	. . .	. . .	6.28	70–300
			6.60	70–800
			6.75	70–900
			6.81	70–1000
			6.95	70–1100
			7.07	70–1200
			7.13	70–1300
3½% Ni steel	21	212		
	14	1472		
Type 304 wrought	9.4	212	9.6	32–212
	10.3	392	9.9	32–600
	11.0	572	10.2	32–1000
	11.8	752	10.4	32–1200
	12.5	932	11.2	32–1800
CF-8 cast	9.2	212		
	12.1	1000		
Type 316 wrought	9.0	212	8.9	32–212
	12.1	932	9.0	32–600
			9.7	32–1000
			10.3	32–1200
			11.1	32–1500
CF-8M cast	9.4	212	8.9	68–212
	12.3	1000	9.7	68–1000
Type 321 wrought	9.3	212	9.3	32–212
	10.2	392	9.5	32–600
	11.1	752	10.3	32–1000
	11.9	932	10.7	32–1200
	12.8		11.2	32–1500
Type 347 wrought	9.3	212	9.3	32–212
	10.2	392	9.5	32–600
	11.1	572	10.3	32–1000
	11.9	752	10.6	32–1200
	12.8	932	11.1	32–1500
CF-8C cast	9.3	212	9.3	68–212
	12.8	1000	10.3	68–1000
405 wrought	. . .	. . .	6.0	32–212
			6.4	32–600
			6.7	32–1000
			7.5	32–1200

TABLE A3.2 Thermal Conductivity and Expansion of Piping Material (*Continued*)

Material	Thermal conductivity		Linear thermal expansion average	
	$\text{Btu}\Big/\left(\text{hr}\ {}^\circ\text{F}\ \frac{\text{ft}^2}{\text{ft}}\right)$	Temperature, °F	Microinch/(in °F)	Temperature range, °F
CA15 cast	14.5	212	5.5	68–212
	16.7	1000	6.4	68–1000
			6.7	68–1300
410 wrought	14.4	212	6.1	32–212
	16	752	7.2	32–1000
			7.6	32–1832
446 wrought	12.1	212	5.9	32–212
	14.1	932	6.3	32–1000
			7.6	32–1832
CC50 cast	12.6	212		
	17.9	1000	5.9	68–212
	20.3	1500	6.4	68–1000
	24.2	2000		
Aluminum 1100	128	70	12.2	−58 to +68
			13.1	68–212
			13.7	68–392
			14.2	68–572
Aluminum 6061	99 (0 temper)	70	12.1	−76 to +68
	90 (T4 temper)	70	13.0	68–212
	90 (T6 temper)	70	13.5	68–392
			14.1	68–572
Aluminum 43	82 (as cast)	70	12.2	68–212
	94 (annealed)	70	12.8	68–392
			13.3	68–572
Aluminum 356	97 sand cast T51	70	11.9	68–212
	88 sand cast T6	70	12.8	68–392
			13.0	68–572
Copper (DHP)	196	68	9.8	68–572
Red brass	92	68	10.4 cold rolled	68–572
Yellow brass	67	68	11.3	68–572
Admiralty brass	64	68	11.2	68–572
Manganese bronze	61	68	11.8	68–572
Cupronickel (70–30)	17	68	9.0	68–572
Aluminum bronze (3)	44	68	9.0	68–572
Beryllium copper	33–41 cold worked	68	9.3	68–212
			9.4	68–392
	48–68 precipitation hardened		9.9	68–572
Chemical lead	. . .	. . .	16.3	65–212
			14.7	−130 to +66
50/40 SnPb solder	27	129	13.0	60–230

TABLE A3.2 Thermal Conductivity and Expansion of Piping Material (*Continued*)

Material	Thermal conductivity		Linear thermal expansion average	
	$\text{Btu}\Big/\left(\text{hr}\,^\circ\text{F}\,\frac{\text{ft}^2}{\text{ft}}\right)$	Temperature, °F	Microinch/(in °F)	Temperature range, °F
Nickel (A) wrought...	35	32–212	7.4	77–212
Monel (70 Ni–30 Cu) (wrought)	15	32–212	7.8	32–212
Inconel........................	8.4	70–212	6.4 8.3	68–212 70–1000
Incoloy........................	6.8	32–212	8.0	32–212
Hastelloy B................	6	. . .	5.3 7.8	70–200 70–1600
Hastelloy C................	5	70	6.6 8.2	70–200 70–1600
Tin...............................	36	32	12.8	32–212
Titanium (99.0%).......	9.0–11.5 12.4	68 1500	4.8 5.6 5.7	68–200 68–1200 68–1600
Tantalum....................	31	68	3.6	

thermal conductivity (k) whose units are a quantity of heat transmitted through a unit thickness per unit time per unit area per unit difference in temperature.

For example:

$$k = \frac{\text{Btu}\cdot\text{ft}}{\text{h}\cdot\text{ft}^2\,^\circ\text{F}} \quad \text{or} \quad \frac{\text{cal}\cdot\text{cm}}{\text{sec}\cdot\text{cm}^2\,^\circ\text{C}} \tag{A3.2}$$

The lower the value of k, the more resistant the material is to the flow of thermal energy. Good insulators possess low coefficients of thermal conductivity.

Thermal conductivity is a function of the temperature of the material. For example, the coefficient of thermal conductivity of carbon steel decreases as its temperature increases, thereby decreasing its ability to transfer heat energy. Austenitic stainless steels, on the other hand, increase in k value with temperature. However, they remain lower than carbon steels in normal piping system temperature ranges.

Thermal Expansion. Expressed as the coefficient of linear expansion, thermal expansion is a ratio of the change in length per degree of temperature, to a length at a given standard temperature (such as room temperature, or the freezing point of water). The units of the coefficient are length of growth per unit length per degree of temperature. The value of the coefficient varies with temperature.

Specific Heat. This is a measure of the quantity of heat required to raise a unit weight of a material one degree in temperature.

Some values of physical properties of a number of materials of interest are given in Table A3.2 and Table A3.3.

TABLE A3.3 Some Physical Properties of Piping Materials

Material	Density, lb/in^3*	Specific heat, mean (temperature, °F)	Melting temperature,** °F
Pure iron	0.2845	0.112 (122–212) 0.170 (1562–1652)	2781–2799
Gray cast iron	0.251–0.265	...	2150–2360
Malleable cast iron ferritic	0.260–0.265	0.11 (at 70) 0.165 (at 800)	2750
Malleable cast iron pearlitic	0.264	0.11 (at 70) 0.165 (at 800)	2750
Nodular iron	0.257	...	2050–3150
Wrought iron	0.28	...	2750
0.06 C, 0.38 Mn	0.2844	0.115 (122–212) 0.264 (1292–1382)	2600
0.23 C, 0.35 Mn	0.2839	0.116 (122–212) 0.342 (1292–1382)	2600
0.43 C, 0.69 Mn	0.2834	0.116 (122–212) 0.227 (1292–1472)	2600
1.22 C, 0.35 Mn	0.2839	0.116 (122–212) 0.499 (1292–1382)	2600
Carbon–½ Mo	0.28	...	2600–2800
1¼ Cr–½ Mo	0.283	0.114 (122–212)	2600–2800
2¼ Cr–1 Mo	0.283	0.11	2600–2800
5 Cr–½ Mo	0.28	0.11	2700–2800
9 Cr–1 Mo	0.28	0.11	2700–2800
3½% Ni steel	0.28	0.115 (212)	...
Type 304 wrought	0.29	0.12 (32–212)	2550–2650
CF-8 cast	0.28	0.12	2600
Type 316 wrought	0.29	0.12 (32–212)	2500–2550
CF-8M cast	0.28	0.12	2550
Type 321 wrought	0.29	0.12 (32–212)	2550–2600
Type 347 wrought	0.29	0.12 (32–212)	2550–2660
CF-8C cast	0.28	0.12	2550–2600
405 wrought	0.28	0.11	2700–2790
CA15 cast	0.275	0.11	2750
410 wrought	0.28	0.11	2700–2790
446 wrought	0.273	0.144	2550–2750
CC50 cast	0.272	0.12	2725
Aluminum 1100	0.098	0.23 (212)	1190–1215
Aluminum 6061	0.098	0.23 (212)	1080–1200
Aluminum 4043	0.097	0.23 (212)	1065–1170
Aluminum 356	0.097	0.23 (212)	1035–1135
Copper (DHP)	0.323	0.092	1981
Red brass (wrought)	0.316	0.09	1810–1880
Yellow brass (wrought)	0.306	0.09	1660–1710
Admiralty brass (wrought)	0.308	0.09	1650–1720
Manganese bronze (wrought)	0.302	0.09	1590–1630
Cupronickel (70–30) (wrought)	0.323	0.09	2140–2260
Aluminum bronze (3) (wrought)	0.281	0.09	1910–1940
Beryllium copper (wrought)	0.297	0.10 (86–212)	1587–1750
Chemical lead	0.4097	0.0309	618

TABLE A3.3 Some Physical Properties of Piping Materials (*Continued*)

Material	Density, lb/in^3*	Specific heat, mean (temperature, °F)	Melting temperature,** °F
50/50 Sn Pb solder	0.321	0.046	361–421
Nickel (A) (wrought)	0.321	0.13	2615–2635
Monel (70 Ni–30 Cu) (wrought)	0.319	0.127	2370–2460
Inconel (wrought)	0.307	0.11	2540–2600
Incoloy (wrought)	0.290	0.12	2540–2600
Hastelloy B (wrought)	0.334	0.091	2410–2460
Hastelloy C (wrought)	0.323	0.092	2320–2380
Tin	0.26	0.0534	449.4
Titanium (99.0%)	0.163	0.125	3002–3038
Tantalum	0.600	0.034	5425

* lb/in^3 = 2.76798 × 10^{-2} kg/cm^3
** °C = (°F − 32)/1.8.
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Other Metallurgical Properties of Metals

In addition to the properties already described, other characteristics of metals can have an important effect on the design process. These may profoundly affect the uniformity, achievable level, or stability of mechanical strength and ductility over long periods of usage.

Grain Size. Upon solidification from the molten state, metals take crystalline form. Rather than a single, large crystal, the material consists of many small crystals that initiate independently and nearly simultaneously from separate nuclei sites. These individual crystals are called *grains*, and their outer surfaces are called *grain boundaries*. Grains form initially during the solidification process, but they may also reform, grow, or rearrange while in the solid state.

Some properties of many engineering metals are very dependent on grain size (Fig. A3.15). For example, austenitic stainless steels, such as Type 304 (18% Cr-8% Ni-Fe), possess excellent creep strength when the material has a coarse grain structure, but very poor strength with fine (small) grains.

If this same austenitic material is plastically cold-worked, these grains will become distorted and possess high levels of lattice strain and residual stress. Subsequent heat treatment can cause the crystal lattice to reform unstrained grains initiating at lattice defects which act as nuclei. The process, called *recrystallization*, results in an initially very small grain size as the nucleated stress-free grains begin to grow. If heavily strained material is placed into elevated temperature service at temperatures sufficient to cause recrystallization, it will initially exhibit good creep strength until the grains begin to reform,

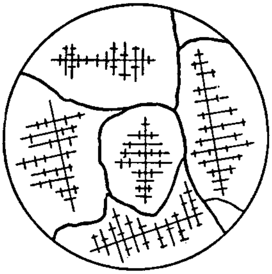

FIGURE A3.15 Sketch illustrating individual grain growth from nuclei and dendrites.

upon which the result is very poor creep rupture strength. The material will only return to its prestrained creep-strength level if additional heat treatment is performed, resulting in further grain growth.

Grain size is a material characteristic that is sometimes directly inspected in the base material testing and certification process. The test entails retrieving a piece of the material and then metallographically polishing and etching the specimen with a weak acid solution, which reveals the grain boundaries under magnification. The test is described in ASTM Specification E 112. Grain size can be measured and reported a number of ways. The most commonly used method involves reporting grain size as an ASTM grain size number (n), corresponding to the exponent of the following equation:

$$\text{Number of grains per square inch viewed} = 2^n \text{ at 100 magnifications}$$

ASTM has correlated this grain size number, which increases as grain diameter decreases, to a series of photographs representing the grain structure at 100 magnifications. The grain size number can then be estimated by visual comparison. Examples of this comparative standard are shown in Fig. A3.16.

Fine-grained carbon- and low-alloy steels tend to possess better notch toughness and ductility than coarse-grained steel. As noted earlier, as operating temperature increases into the creep regime, engineering material strength properties are usually enhanced with coarser grains. Although this is an oversimplified (and perhaps overstated) rule of thumb, it is important for the engineer to take grain size into account for critical structures.

Hardenability. This is a property of certain steels that allows them to be strengthened, or hardened, by *heat treating*. In carbon and alloy steels, for example, this hardening is accomplished by heating the material to a temperature above about 1550°F (843°C), where the material completely changes its crystal structure from BCC to FCC. When this is followed by rapid cooling or quenching, usually in water or oil, the result is a crystal structure akin to the original BCC, but distorted along one of the unit cell directions. In the case of steels the result is a martensitic structure possessing a lattice, termed a *body-centered tetragonal* (BCT), with a larger volume per unit cell than the starting BCC.

The maximum hardness achieved in a quenched structure is primarily a function of the steel's carbon content: the higher the carbon content, the greater the hardness. The depth into the material to which a high hardness is achieved for a given quenching operation is a function of the total alloy content within the steel. The substitutional alloying element nickel has perhaps the strongest effect on increasing the depth to which hardness extends.[3] Other elements creating similar if less potent effects are manganese and boron, substitutional and interstitial alloying elements, respectively.

Standard specimens and procedures have been adopted for testing the hardenability of steels. The test rates a combination of the highest hardness achievable and the depth to which significant elevation of hardness occurs. It is called the *Jominy End-Quench test* and is performed using a 1-in-diameter cylindrical specimen machined from the metal in question and heated to a temperature in its austenitic phase (FCC) region. The heated specimen is removed from the heating oven and quickly set in a water-quenching fixture, operating under prescribed conditions of water temperature and flow rate, quenching only the cylinder end face. Upon cooling, the cylinder is parted longitudinally (axially) down the center, and a series of Rockwell hardness readings are taken from the quenched edge. A hardness scan

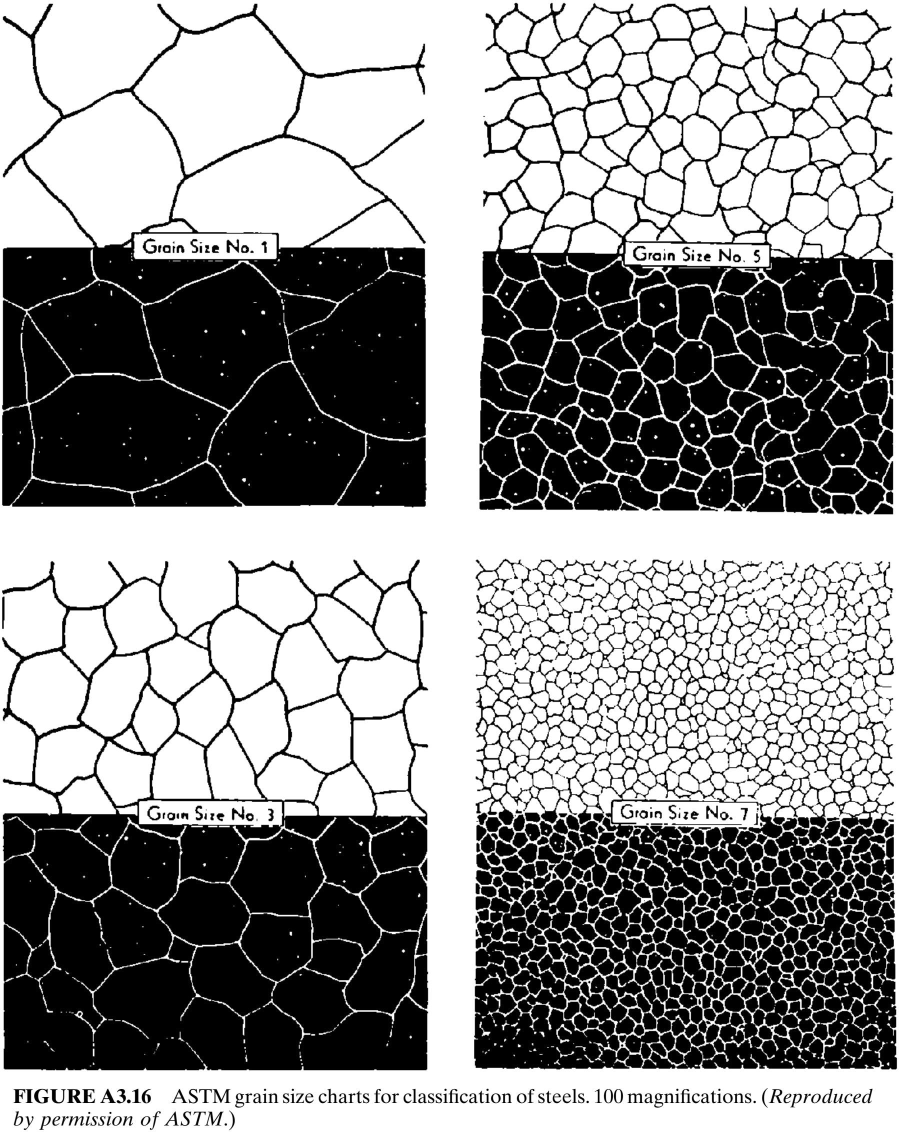

FIGURE A3.16 ASTM grain size charts for classification of steels. 100 magnifications. (*Reproduced by permission of ASTM.*)

for several alloy steels is shown in Fig. A3.17. The Jominy test procedure is defined in ASTM A 255.

Many other metal alloys harden or strengthen with special aging or tempering heat treatments. However, this trait is normally not referred to as hardenability. These will be discussed in more detail later in the chapter.

Property Stability. The mechanical properties of materials may degrade with service time. In particular, alloys that depend on heat treatment or cold working

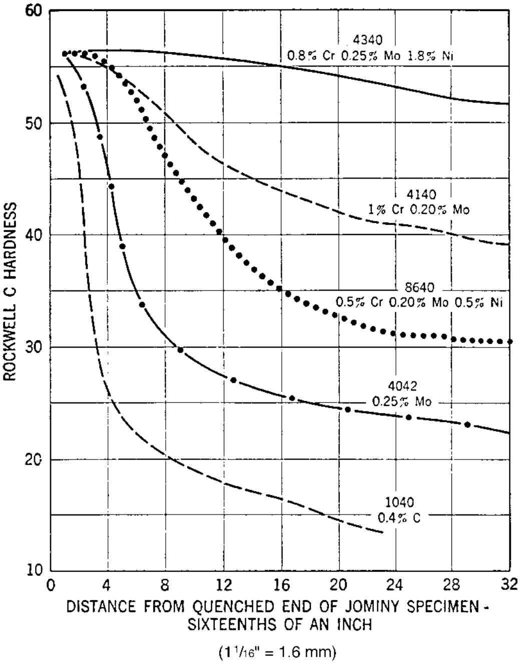

FIGURE A3.17 Jominy end-quench hardenability curves for various 0.40 percent carbon steels. (*Molybdenum Steels Iron Alloys*, Archer et al., Climax Molybdenum Company.)

to develop their strength may weaken if operated for long times at elevated temperatures. The actual exposure to service temperatures acts as a continuation of the heat-treating process, albeit at a significantly reduced rate of effect. In many engineering metals, this effect is actually a property degradation due to overtempering of the material.

A number of thermodynamic relationships exist that relate material strength and time and temperature of exposure for carbon and alloy steels. The most famous and widely used of these is the *Hollomon-Jaffe Parameter* (HJP). It is defined as the following:

$$\text{HJP} = (T + 273)(C + \log t) \times 10^{-3} \tag{A3.3}$$

where T is temperature in degrees Celsius, t is time in hours, and C is a constant, usually around 20 for carbon steels.[4] Using this equation and solving for HJP for a given set of time and temperature conditions, the engineer can determine the time at a different temperature of interest that can result in an equivalent metallurgical effect.

A limitation exists on the range of temperatures over which the predictive capability of the Holloman-Jaffe equation can be considered reliable. Phenominologically, the same metallurgical processes must be in effect over the range of temperatures under consideration. For example, if a phase change occurs, or if other important microstructural constituents, such as carbides, are not stable at the two temperatures being compared, the correlation is not valid.

Design codes using allowable design stresses based on creep properties of the metals, by the nature of the long-term rupture tests involved, take these degrading tendencies into account. However, it is not always appreciated that the time-dependent properties, such as ultimate tensile strength and yield strength, can be decreased significantly below the starting property level by the same long-term service. This fact would be important to an engineer concerned with designing a high-temperature structure that must tolerate shock loads, such as seismic effects, that can occur near the end-of-life of the component.

More on degradation of properties and the mechanisms involved is discussed later in this chapter.

METALLIC MATERIALS

Metals are divided into two types: ferrous, which includes iron and iron-base alloys; and nonferrous, covering other metals and alloys. Metallurgy deals with the extraction of metals from ores and also with the combining, treating, and processing of metals into useful engineering materials. This section presents the fundamental metallurgical concepts and practices associated with the most common engineering metals, and outlines metallurgical considerations appropriate in the selection process of metals for piping system construction.

Ferrous Metals

Metallic iron, one of the most common of metals, is very rarely found in nature in its pure form. It occurs in the form of mineral oxides (Fe_2O_3 or Fe_3O_4), and as such it comprises about 6 percent of the earth's crust. The first step in the production of iron and steel is the reduction of the ore with coke and limestone in the blast furnace. In this process, the oxygen is removed from the ore, leaving a mixture of iron and carbon and small amounts of other elements as impurities. Coke is the reducing element and source of heat. The limestone ($CaCO_3$) acts as a fluxing agent which combines with impurities of the ore in the molten state and floats them to the top of the molten metal pool, where they can be removed as slag. The product removed from the blast furnace is called *pig iron* and is an impure form of iron containing about 4 percent carbon by weight percent. Liquid pig iron cast from the blast furnace is sometimes used directly for metal castings. More often, however, the iron is remelted in a cupola, or furnace, to further refine it and adjust its composition.[5]

Cast Iron

Pig iron that has been remelted is known as *cast iron*, a term applicable to iron possessing carbon in excess of 2 weight percent. Compared with steel, cast iron is inferior in malleability, strength, toughness, and ductility. On the other hand, cast iron has better fluidity in the molten state and can be cast satisfactorily into complicated shapes. It is also less costly than steel. The most important types of cast iron are white and gray cast irons.

White cast iron is so known because of the silvery appearance of its fracture surface when broken. In this alloy, the carbon is present in the form of iron carbide (Fe_3C), also known as *cementite*. This carbide is chiefly responsible for the high hardness, brittleness, and poor machineability characteristic of white cast iron. Chilled iron, a form of white cast iron, is cast against metal chills that cause rapid cooling, promoting the formation of cementite. Consequently, a structure is obtained which possesses high wear- and abrasion-resistance, the principal attribute of the material, but retains white cast iron's characteristic brittleness.

Malleable cast iron is the name given to white cast iron that has been heat-treated to change its cementite into nodules of graphite. The iron becomes more malleable because, in this condition, the carbon as carbide no longer exists continuously through the metal matrix.

Gray iron is a widely used type of cast iron. In this alloy, the carbon predominantly exists in the form of graphite flakes. The typical appearance of a fracture of this iron is gray since the graphite flakes are exposed. The strength of gray iron depends on the size of the graphite particles and the amount of cementite formed together with the graphite. The strength of the iron increases as the graphite crystal size decreases and the amount of cementite increases. This material is easily machined. A wide range of tensile strengths can be achieved by alloying gray iron with elements, such as nickel, chromium, and molybdenum.

Another member of the cast-iron family is so-called *ductile* iron. It is a high-carbon magnesium-treated product containing graphite in the form of spheroids. Ductile iron is similar to gray cast iron in machineability, but it possesses superior mechanical properties. This alloy is especially suited for pressure castings. By special procedures (casting against the chill) it is possible to obtain a carbide-containing, abrasion-resistant surface with an interior possessing good ductility.[5]

Steel

Steel is defined as an alloy of iron with not more than 2.0 weight percent carbon. The most common method of producing steel is to refine pig iron by oxidation of impurities and excess carbon, which have a greater affinity for oxygen than iron.

The principal reduction methods used are the basic oxygen process (BOP) and the electric furnace process, each representing a type of furnace in which the refining takes place. The BOP primarily uses molten pig iron as the initial furnace charge; the electric furnace can use a charge of selected steel scrap. Another process, called the basic open-hearth process, is no longer in use in the United States. Although it constituted the major steel producing process for decades, it has succumbed to the more advanced and economical BOP and electric furnaces.[6]

The pig iron is reduced to the desired steel composition through use of acid and/or basic reactions with fluxing agents, heat, oxygen, and time. Excess carbon is oxidized and lost as gas; impurities float to the surface. Often desired alloying elements are added to the molten pool. The steel can be further refined by using one of various methods of vacuum degassing. As the name suggests, the molten steel is passed through a vacuum chamber with the purpose of removing entrained gases such as oxygen, hydrogen, and carbon dioxide. This operation is performed when extra steel purity is desired, and it results in improved and more uniform properties in the final product form.

The molten steel is then cast into molded ingots, which are then further reduced by hot working in rolling and drawing operations. Alternately, the molten steel may be directly cast into continuous smaller billet or hollow products. The latter process is called *continuous casting* and has become the preferred method of making steel since it avoids the costly ingot reduction operations.

Alloying additions are made, if required, to the molten steel either while in the reducing furnace as already noted, in the ladle into which the steel is put, or in the ingot into which steel is poured from the ladle.

While the steel is molten in the furnace, oxygen is forcibly injected into it to refine the charge. The oxygen combines with excess carbon and is released as a gas. Excess oxygen is, however, unavoidably left in the molten steel. This results in the formation of oxide inclusions in the steel, or porosity, which appear upon solidification. The process of removing the oxygen is known as *deoxidizing practice*. Deoxidation is achieved by adding silicon, aluminum, or other deoxidizing agents to the molten steel, the amount of which determines the degree of deoxidation and the type of steel seated. The common names given to these various steel types are *killed steel*, *semikilled steel*, and *rimmed steel*.

Steel of the killed type is deoxidized almost completely; that is, sufficient deoxidizing agent is added to the molten pool to combine with all the excess entrained oxygen. The result is a large number of tiny oxides in the melt. The lack of gas in the molten pool gives the effect of ‘‘killing’’ any visible bubbling activity of the steel, thus the name. Killed steel has a more uniform composition than any of the other types, and usually possesses the best formability at room temperature. A fine-grained structure results from this practice because the many oxides formed act as initiation sites of new grains upon solidification and subsequent recrystallization. This fine-grained character offers toughness superior to the other types of steel.

Rimmed steel employs no purposeful addition of deoxidizing agents, and is characterized by relatively violent bubbling and stirring action in the ingot mold. This type exhibits a marked variation in composition across and from top to bottom of the ingot. The outer rim or outer edge of the solidified ingot is relatively pure and ductile material. The amounts of carbon, phosphorous, sulfur, and nonmetallic inclusions in this rim are lower than the average composition of the whole ingot. The amount of these constituents in the inner portion or core is higher than the ingot average. This type of steel costs less to make than the other types and is widely used for structural applications, where good surface appearance of the final product is desired.

Semikilled steel is only partially deoxidized with silicon, aluminum, or both, taking advantage of the positive attributes of killed and rimmed steel.

After casting, or *teaming* into the ingot molds, the steel is normally further reduced in size and modified in shape by mechanical working. The majority of the reduction process is done hot. During hot working, sufficient heat is maintained to ameliorate the working effects and maintain a structure that is relatively soft and ductile throughout the reduction process.

The steel in the form of ingot, slab, bar, or billet is first brought to the proper temperature throughout and is then passed through rolls or dies. The flow of metal is continuous and preferentially in one (longitudinal) direction. The cross-sectional area is reduced, and the metal is shaped the desired form. The internal structure of the steel is also favorably affected. The working reduces the grain size of the material, and tends to homogenize the overall structure, compared with cast or unworked steel.

Processes used to manufacture pipe and tube are addressed in another chapter.

PHYSICAL METALLURGY OF STEEL

Like all other metals, iron and steel are crystalline in structure, composed of atoms in a fixed lattice. As noted earlier, iron may exist in one of two cubic forms, body-centered (BCC) or face-centered (FCC).

At room temperature, pure iron is composed of a body-centered cubic lattice. In this form it is known as *alpha* iron, also called *ferrite*, which is soft, ductile, and magnetic. When heated above about 1415°F (768°C), alpha iron loses its magnetism but retains its body-centered crystalline structure. This temperature is called the *Fermi temperature.* The crystal structure changes to face-centered cubic at about 1670°F (910°C), at which temperature alpha iron is transformed to *gamma* iron, the FCC form, and remains nonmagnetic. As temperature rises further, another phase change occurs at 2570°F (1410°C), when *delta* iron is formed. This phase is again body-centered like that of the low-temperature alpha iron. It is stable to the melting temperature. In cooling very slowly from the liquid state, the phases reappear in reverse order.

The solid-state transformations of atomic structure, which occur in pure iron during heating to and cooling from the melting point, are called *allotropic* changes. The temperatures at which these changes take place are known as *transformation* or *critical* temperatures.

When carbon is added to iron and steel is produced, the same changes in phase occur, but a more complex relationship with temperature occurs. The effects of varying amounts of carbon content in iron on phase stability as temperature varies is represented in Fig. A3.18. This diagram is called an *equilibrium phase diagram*, and in this case is the very familiar iron-carbon (Fe-C) phase diagram. With this diagram, one can determine which stable phase the steel will assume at a given composition and temperature. Likewise, the effect of increasing or decreasing the amount of carbon content in iron on these critical temperatures can be predicted.

Phase diagrams are plotted in weight or atomic percent (horizontal axis) versus temperature (vertical axis). A single-phase region usually represents an area of high concentration of a single element, or an intermetallic single phase stable over a range of composition and temperature. Between these single-phase regions are regions where multiple phases coexist, in relative amounts at any given temperature approximated by the proximity of the specific composition to the single-phase regions. On the Fe-C diagram, single-phase regions are represented by those marked as alpha, gamma, and delta, and Fe_3C or cementite, which is a stable intermetallic phase.

The critical transformation temperatures in steel are the A_1, corresponding to about 1335°F (724°C), and A_3 referred to as the lower and upper critical temperatures of steel. The A_3 constitutes the boundary with the gamma phase, and its temperature varies with carbon content. The lower critical temperature, on the other hand, stays constant over the entire range of steel compositions.

These critical temperatures, as well as the entire phase diagram, represent transformations that occur under controlled, very slow cooling and heating (i.e., equilibrium) conditions. More rapid heating and cooling rates, like those encountered in normal steel processing, change these critical temperatures upward and downward, respectively. Additions of other alloying elements also will shift the critical transformation points.

It is the effective use by the metallurgist of the knowledge contained on this and similar phase diagrams that allows for the manipulation of properties of engineering materials by varying their chemistry and heat treatment. For steel, the principal phases and their properties are briefly summarized in the following list:

Austenite: A single-phase solid solution of carbon in gamma iron (FCC). It exists in ordinary steels only at elevated temperatures, but it is also found at room temperatures, but it is also found at room temperature in certain stainless steels

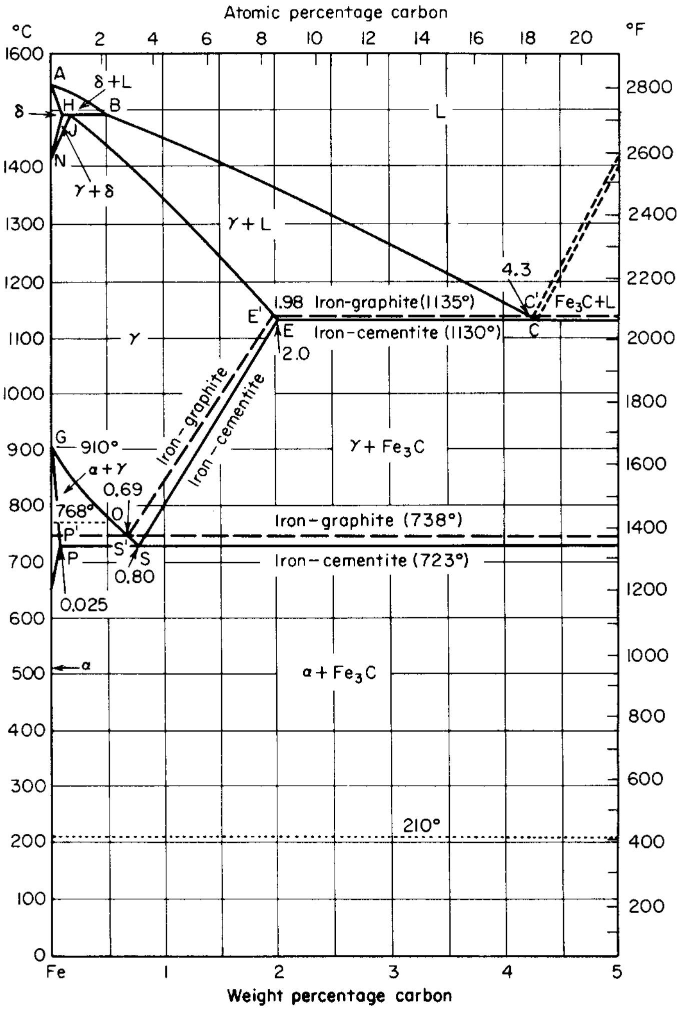

FIGURE A3.18 Iron-carbon equilibrium diagram.

(e.g., 18 Cr–8 Ni type) classified as *austenitic* stainless steels. This structure has high ductility and toughness.

Ferrite: Alpha iron (BCC), containing a small amount of carbon (0.04–0.05 percent) in solid solution. This phase is soft, ductile, and relatively weak.

Cementite: Iron carbide, Fe_3C, a compound containing 6.67 percent carbon, which is very hard and extremely brittle. Cementite appears as part of most steel structures, the form of which depends on the specifics of the heat treatment which the steel has received (see pearlite).

Pearlite: A mixture of alternating plates of iron carbide (cementite) and ferrite (lamellar structure), which form on slow cooling from within the gamma range.

This condition generally represents a good blend of strength, ductility, and fair machineability. It is the equilibrium structure in steel.

Bainite: A mixture of ferrite and cementite, which is harder and stronger than pearlite. It forms by the transformation of austenite in many steels during fairly rapid cooling, but not fast enought to cause martensite formation. The structure consists of ferrite and iron carbide, but unlike pearlite, the aggregate is nonlamellar.

Martensite: The hardest constituent achievable by heat-treating of steels, it is formed by the rapid cooling of austenite to a temperature below the *martensite start* or M_s temperature. Martensite consists of a distorted cubic unit cell (body-

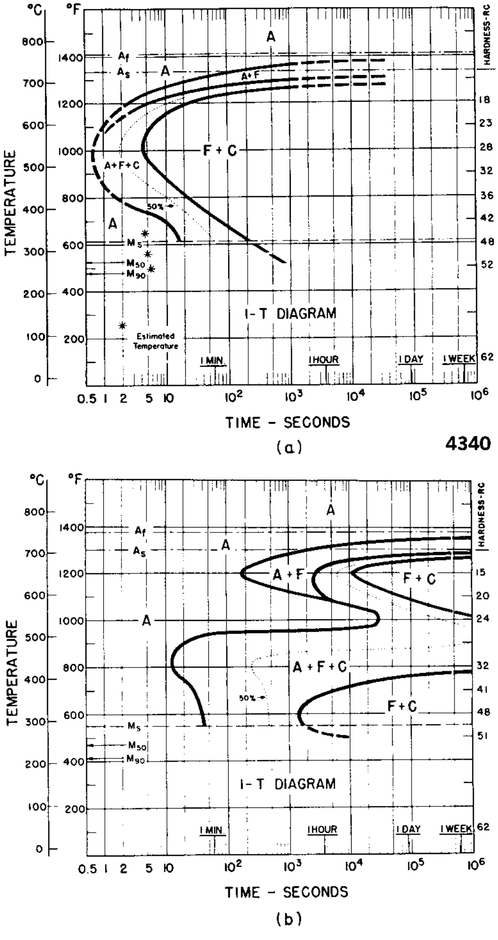

FIGURE A3.19 Isotherm transformation diagrams for AISI 1050 (*a*) and AISI 4340 (*b*). (From I-T Diagrams, *United States Steel*, ©1963.)

centered tetragonal) which contains substantial quantities of carbon in interstitial solution in the lattice. The M_s temperature varies with steel composition.

These latter two microstructural constituents, bainite and martensite, will not be found on the Fe-C phase diagram because they are the direct result of cooling steel at an accelerated rate, which prevents atomic diffusion required to maintain equilibrium conditions.

The effects of nonequilibrium cooling of a steel are represented on an *isothermal transformation* diagram, or a *time-temperature transformation* (T-T-T) diagram. An example of each is shown in Fig. A3.19. The horizontal axis of the diagram is time, usually log scale; the vertical axis is temperature. A single diagram represents a given steel alloy composition and depicts the various equilibrium and nonequilibrium phases that will be formed, and their mix, with a given cooling rate from a starting temperature in the austenitic phase region. The diagram is used by entering it at the alloys temperature at time = 0, represented as a point of the vertical axis. The cooling rate describes the time/temperature path taken by the material from the starting point, through the field of transformation phases, to the final point of sample cooling. The metallurgical phases or constituents in the final state can thus be predicted. The continuous path followed between the two points also has a bearing on final microstructure. The T-T-T diagram is similar to the equilibrium phase diagram in that single and multiple phase fields are depicted. However, it differs from the equilibrium diagram in that it is a dynamic representation of phase formation with time. Thus quickly cooling to a given temperature above the M_s will result, for example, in coexistence of austenite, ferrite and, cementite (A, F, and C on the figure). However, as time progresses at that temperature, the austenite continues to decompose into more ferrite and cementite, until complete transformation is achieved. Cooling to below the M_s temperature causes tranformation to martensite. If the path of cooling had intersected the ''nose'' of the T-T-T curve, some ferrite will form and be combined with the martensite in the final microstructure, since martensite can only be formed by quenching austenite. The ferrite that formed on cooling is stable and unaffected by further cooling.

ALLOYING OF STEEL

The alloying of carbon steel with other elements to obtain a wide range of desired properties is a mature science. The following summarizes the known effects of adding certain elements to steel[7]:

Carbon: In general, increasing the carbon content of steel alloys produces higher ultimate strength and hardness but may lower ductility and toughness. Carbon also increases air-hardening tendencies and weld hardness. In low-alloy steel for high-temperature applications, the carbon content is usually restricted to a maximum of about 0.15 percent in order to assure optimum ductility for welding, expanding, and bending operations. An increasing carbon content lessens the thermal and electrical conductivities of steel.

Phosphorus: High phosphorus content has an undesirable effect on the properties of carbon steel, notably on shock resistance and ductility (see the section on temper embrittlement). Phosphorus is effective, however, in improving machineability. In steels, it is normally controlled to less than 0.04 weight percent.

Silicon: Used as a deoxidizing agent, silicon increases the tensile strength of steel without increasing brittleness when limited to less than about 2 percent. Silicon increases resistance to oxidation, increases electrical resistivity, and decreases hysteresis losses. Thus it is used for electrical applications. Adding silicon may reduce creep rupture strength.

Manganese: Manganese is normally present in all commercial steels. The manganese combines with sulfur, thus improving hot-working characteristics. In alloy steels, manganese decreases the critical cooling rate to cause a hardened or martensitic structure and thus contributes to deep-hardening.

Nickel: As an alloying element in alloy steels, nickel is a ferrite strengthener and toughener and is soluble in all proportions. Nickel steels are easily hardened because nickel lowers the critical cooling rate necessary to produce hardening on quenching. In heat-treated steel, nickel increases the strength and toughness. In combination with chromium, nickel produces alloy steels possessing higher impact and fatigue resistance than can be obtained with straight carbon steels.

Chromium: As an alloying element in steel, chromium is miscible in iron as a solid solution, and forms a complex series of carbide compounds. Chromium is essentially a hardening element and is frequently used with a toughening element such as nickel to produce superior mechanical properties. At higher temperatures, chromium contributes increased strength and is ordinarily used in conjunction with molydenum. Additions of chromium significantly improve the elevated temperature oxidation resistance of steels.

Molybdenum: In steel, molybdenum can form a solid solution with the iron and, depending on the molybdenum and carbon content, can also form a carbide. A deeper hardening steel results. The molybdenum carbide is very stable and is responsible for matrix strengthening in long-term creep service.

Vanadium: This element is one of the strong carbide formers. It dissolves to some degree in ferrite, imparting strength and toughness. Vanadium steels show a much finer grain structure than steels of a similar composition without vanadium.

Boron: Boron is usually added to steel to improve hardenability; that is, to increase the depth of hardening during quenching.

Aluminum: Aluminum is widely used as a deoxidizer in molten steel and for controlling grain size. When added to steel in controlled amounts, it produces a fine grain size.

Sulfur: Present to some degree in all steel (less than 0.04 weight percent), sulfur forms a nonmetallic inpurity that, in large amounts, results in cracking during forming at high temperatures (hot shortness). Combining it with managanese forms a MnS compound that is relatively harmless.

Copper: Copper dissolves in steel and strengthens the iron as a substitutional element. The use of copper in certain alloys increases resistance to atmospheric corrosion and increases yield strength. However, excessive amounts of copper (usually above 0.3 percent are harmful to elevated temperature performance since the lower melting point element segregates to grain boundaries and locally melts (liquates), causing intergranular separation under applied stress.

In general, when used in combination, alloying elements may complement each other and give greater overall benefits than when used singly in much larger quantities.

CLASSIFICATION OF STEELS

There are literally hundreds of wrought grades of steel that range in composition with the variation of the many major and minor alloying elements. The simplest of these classes is known as plain carbon steel, with carbon varying between approximately 0.05 and 1.0 weight percent. Within this broad range fall three general groups according to carbon content; they are defined as follows:

1. Low carbon steels—0.05 to 0.25 percent carbon
2. Medium carbon steels—0.25 to 0.50 percent carbon
3. High carbon steels—0.50 percent and greater carbon content

Alloy steels are generally considered to be steels to which one or more alloying elements, other than carbon, have been added to give them special properties that are different than those of straight carbon steels. From the standpoint of composition, steel is considered to be an alloy steel when amounts of manganese, silicon, or copper exceed the maximum limits for the carbon steels, or when purposeful addition of minimum quantities of other alloying elements are added. These could be chromium, molybdenum, nickel, copper, cobalt, niobium, vanadium, or others.

The next higher class of alloyed steel useful to the piping industry is ferritic and martensitic stainless steels. These are steels alloyed with chromium contents above about 12 percent. Because of the chromium, these materials possess good corrosion resistance. They retain a ferritic (BCC) crystal structure, allowing the grades to be hardened by heat treatment.

When sufficient nickel is added to iron-chromium alloys, an austenitic (FCC) structure is retained at room temperature. Austenitic stainless steels possess an excellent combination of strength, ductility, and corrosion resistance. These steels cannot be hardened by quenching, since the austenite does not transform to martensite.

A stronger type of stainless steel has been developed which takes advantage of precipitation reactions within the metal matrix made possible by addition of elements such as aluminum, titanium, copper, and nitrogen. These materials are referred to as precipitation—hardenable stainless steels. Both martensitic and austenitic stainless steels can be enhanced in this manner.

As annealed, these materials are soft and readily formed. When fully hardened, through aging heat treatments, they attain their full strength potential.

STEEL HEAT-TREATING PRACTICES

Various heat treatments can be used to manipulate specific properties of steel, such as hardness and ductility, to improve machinability, to remove internal stresses, or to obtain high strength levels and impact properties. The heat treatments of steel commonly employed—annealing, normalizing, spheroidizing, hardening (quenching), and tempering—are briefly described in the following paragraphs.[8]

Annealing

Several types of annealing processes are used on carbon and low-alloy steel. These are generally referred to as *full annealing, process annealing*, and *spheroidizing annealing*.

In full annealing, the steel is heated to just above the upper critical (A_3) temperature, held for a sufficient length of time to fully austenitize the material structure, and then allowed to cool at a slow, controlled rate in the furnace. The microstructure of fully annealed low-carbon steel consists of ferrite and pearlite. A full anneal provides a relatively soft, ductile material, free of internal stresses.

Process annealing sometimes referred to as *stress-relieving*, is carried out at temperatures below the lower critical (A_1) temperature. This treatment is used to improve the ductility and decrease residual stresses in work-hardened steel.

The usual purpose of spheroidizing is to soften the steel and improve its machinability. Heating steel that possesses a pearlite microstructure for a long time at just below the lower critical temperature, followed by very slow cooling, will cause spheroidization. This is an agglomeration of the iron carbide, which eventually assumes a spheroidal shape. The properties of this product normally represent the softest condition that can be achieved in the grade of steel being heat-treated.

The austenitic stainless steels are annealed differently from carbon steels. First, since they posses a fully austenitic structure, the temperature used is not related to a critical transformation temperature. Rather, the intent of the annealing is to remove residual strain in the lattice, recrystallize the metal grains, and to dissolve any iron and chromium carbides that may exist in the matrix material. The temperature selected is usually at or above 1900°F (1038°C). Second, the cooling rate from the annealing temperature is normally as rapid as possible. This suppresses the reformation of carbides at the austenitic grain boundaries during cooling. Formation of grain boundary carbides results in local depletion of chromium in the matrix in the vicinity of the carbides, rendering this thin band of material susceptable to attack in a number of corrosive media. This susceptible condition is referred to as sensitization, and the resultant corrosion is termed intergranular attack.

The temperature range in which carbides are most apt to form in austenitic stainless steels is between about 850 and 1500°F (454 and 816°C). Slow cooling through or holding in this zone will sensitize the steel. The degree of sensitization that will occur can be greatly reduced by adding small amounts of elements that possess a stronger tendency to form carbides than the chromium. Two such elements, niobium and titanium, are added to form the so-called stabilized austenitic stainless steels. Alternately, the carbon content can be held as low as possible, thereby resulting in as few carbides as possible. These are termed the *L grade* stainless steels.

Ferritic and martensitic stainless steels will also be adversely affected by slow cooling from annealing temperatures. When slow cooled, or held in the temperature range of 750 to 950°F (400 to 510°C), these materials embrittle (see discussion on ‘‘474°C’’ embrittlement).

Normalizing

This carbon and low-alloy steel heat treatment is similar to the annealing process, except that the steel is allowed to cool in air from temperatures above the upper critical temperature. Normalizing relieves the internal stresses caused by previous working. While it produces sufficient softness and ductility for many purposes, it leaves the steel harder and with higher tensile strength than after annealing. Normalizing is often followed by tempering.

Hardening (Quenching)

When steels of the higher-carbon grades are heated to produce austenite and then cooled rapidly (quenched), the austenite transforms into martensite. Martensite is formed at temperatures usually below about 400°F (204°C), depending on the carbon content and the type and amount of alloying steel. It is the hardest form of heat-treated steel and has high strength and resistance to abrasion. Martensitic steels have poor impact strength and are difficult to machine.

Tempering

Tempering is a secondary heat treatment performed on some normalized and almost all hardened steel structures. The object of tempering is to remove some of the brittleness by allowing certain solid-state transformations to occur. It involves heating to a predetermined level, always below the lower critical temperature, followed by a controlled rate of cooling. In most cases tempering reduces the hardness of the steel, increases its toughness, and eliminates residual stresses. The higher the tempering temperature used for a given time, the more pronounced is the property change. Some steels may become embrittled on slowly cooling from certain tempering temperatures. Steels so affected are said to be *temper-brittle*. To overcome this difficulty, steels of that type are cooled rapidly from the tempering temperature. Temper embrittlement is covered elsewhere in this chapter.

DEGRADATION OF MATERIALS IN SERVICE

A number of metallurgically based processes can occur in steels which contribute to loss of engineering strength, and even premature failure. Several of these are addressed in the following paragraphs.

Aging of Properties

A number of steels that have accumulated considerable service time are known to have experienced changes in their properties, usually to their detriment. This phenomenon has been called *aging*, and occurs in materials that are heat-treated or cold-worked to achieve high strength levels and to be used at elevated temperatures. These materials are potentially more susceptible to failure after the condition has developed.

''Aging'' in this case should not be confused with the same term used to represent the purposeful heat treatment performed to some types of nonferrous alloys. In the context being addressed here, aging refers to that normally very slowly progressing metallurgical reaction that occurs in a number of alloys while at operating temperatures for extended periods of time. Some specific types of this behavior (i.e., temper embrittlement and ''885'' embrittlement) are addressed in the paragraphs that follow.

Components that experience considerable service time contain materials that have aged with time. The materials of special interest are those that regularly experience higher operating temperatures; for example, ferritic steels above 900°F (482°C) and austenitic stainless steels at or above 1000°F (538°C). A study sponsored by the ASME Boiler and Pressure Vessel Code attempted to identify and quantify these effects. The effort was the result of concerns for near end-of-life seismic loadings in elevated-temperature nuclear boilers.

Data gathered from a number of sources have shown that the room and elevated temperature yield strengths of both ferritic and austenitic steels may degrade after long exposure times. Ultimate tensile strength is affected, but to a lesser degree. The yield strength reductions can amount to as much as 40 percent in ferritic and 20 percent in austenitic steels.

Creep tests have also been run after long-term (e.g., 10,000 h) static exposure to elevated temperatures. No substantial negative effect on creep properties were noted in these tests.

In the case of ASME Boiler and Pressure Vessel Code and ASME B31.1 Power Piping Code design and construction, the degradation of yield strength does not generally violate or invalidate the conservatism built into their design rules, as manifest by the allowable design stresses. For example, in Section 1 of the ASME Boiler Code, addressing design and construction of power boilers, the material design allowable stresses for wrought materials are established by applying the following factors to base material properties. The lowest calculated value of all the following is assumed as the design allowable stress at a given temperature:

- ¼ specified minimum tensile strength at room temperature
- ⅔ specified minimum yield strength at room temperature
- ¼ tensile strength at the temperature of interest above room temperature
- ⅔ yield strength at the temperature of interest above room temperature
- 67 percent of the average stress to cause rupture in 100,000 h
- 80 percent of the minimum stress to cause rupture in 100,000 h
- 100 percent of the stress to produce 0.01 percent strain in 1000 h

In this manner, short-term properties, stress rupture strength, and creep rate are all taken into account. Typically, at the lower end of the temperature use range, the factored tensile and yield strength controls, and at higher temperatures, the creep properties set the allowable stresses.

Since most aging occurs at the higher temperatures, tensile and yield strength degradation does not normally cause concern. However, if large shock loads can occur late in component life (as is possible under seismic conditions), these short-term, time-independent properties can be critical to the components' continued safe operation.

As an illustration of the effect reduced yield strength has on fatigue, consider that with a lower yield strength, more plastic strain will result from a given high thermal, or mechanically induced stress. Since these stresses are usually due to operational transients, stress reversals can occur during continued operation (i.e., temperature stabilization at steady state, or ultimately, component shutdown). The greater the plastic strain cycle, the greater the damage, and the sooner the failure.

It is clear that as components experience increasing service time, they become less resilient to significant operational transients. That is, materials are less likely to withstand these transients than earlier in their life, not only because more cycles have continued to accumulate (toward an end-of-life limit), but also because material strength properties are degrading with time.

Temper Embrittlement

Temper embrittlement is a phenomenon that occurs in carbon and alloy steels when aged in the temperature range roughly between 660 and 1020°F (350 and 550°C). The property most significantly affected is toughness. The time in which this occurs is a function of the steel's chemical composition, heat treatment condition, fabrication history, and service temperature. The most severe degradation occurs in weld regions. Due to the extensive use of Cr–Mo steels in the petrochemical and power boiler industries, most of the studies have concentrated on this family of materials.

It has been recognized for some years that a steel's susceptibility to temper embrittlement is due to the existence and amount of the trace elements antimony (Sb), phosphorous (P), tin (Sn), and arsenic (As), with P and Sn having the greatest effect. Other elements that may contribute to reduced toughness are silicon, manganese, and copper. Beneficial effects can be gained by additions of molybdenum and aluminum. The obvious dependency of temper embrittlement severity and chemistry has led to the development of a number of embrittlement *factors*.[9]

Bruscato made the first attempt to combine the effects of various elements into a single factor, known as the *embrittlement factor X*, which is expressed as follows:

$$X = \frac{1}{100}(10\text{P} + 5\text{Sb} + 4\text{Sn} + \text{As}) \qquad \text{(A3.4)}$$

The concentration of elements is in parts per million (ppm).

Miyano and Adachi arrived at a J-factor defined as:

$$J = (\%\text{Si}) + (\%\text{Mn}) \times (\%\text{P}) + (\%\text{Sn}) \times 10^4 \qquad \text{(A3.5)}$$

Finally, Katsumata et al, asserted that the following embrittlement factor (E.F.) was appropriate for 2¼ Cr–1Mo and 3 Cr–1Mo steels.

$$\text{E.F.} = (\%\text{Si}) + (\%\text{Mn}) + (\%\text{Cu}) + (\%\text{Ni}) \cdot Y$$

$$Y = \frac{1}{100}(10\text{P} + 5\text{Sn} + \text{Sb} + \text{As}) \qquad \text{(in ppm)}$$

$$Y = \frac{1}{100}(10\text{P} + 5\text{Sn} + \text{Sb} + \text{As}) \qquad \text{(in ppm)}$$

All of these are useful in assessing the relative susceptibility of various steel compositions to temper embrittlement. In all cases, the larger the factor, the more susceptible the particular heat of steel is to embrittlement.

The type of heat treatment applied to the materials may also affect a material's susceptibility to temper embrittle. For example, a number of experimenters have confirmed that 2¼ Cr–1 Mo alloy steels' susceptibility increases as austenitizing temperature used during its heat treatment increases. Inversely, susceptibility is lowest after an intercritical hold, at a temperature between the lower and upper critical temperature (Ac_1 and Ac_3, respectively). This effect is believed to be associated with the grain size achieved during the hold time, a larger grain being more detrimental. Although intercritically treated materials are less susceptible to temper embrittlement, they are weaker in the as-heat-treated condition.

In a parallel fashion, the degree of embrittlement, as measured by loss of toughness or shift of nil ductility temperature, is decreased if the material is more substantially tempered prior to the embrittling treatment. In this context, "tempered" represents the planned heat treatment that typically follows a normalizing or austenitizing and rapid quenching operation. A longer or higher temperature temper results in a softer, less strong, and more ductile condition, usually accompanied by good fracture toughness.

Luckily, the temper embrittled condition is reversible. Heat treatment for short periods of time at temperatures well above the upper critical will result in reestablishing nearly virgin properties in these materials.

Hydrogen Attack

Hydrogen attack is one of the most important problems with materials used in ammonia synthesis, oil refining, and coal gasification equipment.[9]

The first major failure of an ammonia convertor attributable to hydrogen damage was in 1933. Since then more failures and untold damage to materials have accumulated, with the majority of damage occurring in the welds or weld heat-affected zones of these components.

When carbon and low-alloy steels are held in hydrogen at high temperature and pressure for an extended period of time, these materials can suffer degrading effects to their tensile and creep rupture properties. This is accompanied by the formation of intergranular fissures, blisters on the surface, and loss of carbon content (decarburization). The phenomenon is called *hydrogen attack* and is generally attributed to the formation of methane (CH_4) within the steel.

The microstructural damage occurs when methane bubbles form and grow around precipitates at the grain boundaries within the material. The continued growth of the bubbles causes grains to separate along their boundaries and the bubbles, or voids, to coalesce. The rate of growth of the bubbles is a function of the ease by which the steel carbides give up carbon atoms to the intruding hydrogen atoms to form the methane. The more stable the carbide, the slower this reaction will take place. Thus, it has been long recognized that additions of chromium and molybdenum, both strong carbide stablizers, improves hydrogen-attack resistance of steels. Addition of other carbide-stabilizing elements such as titanium and tungsten has also assisted in reducing susceptibility.

Weld regions are more susceptible to hydrogen damage because they possess less stable carbides. It is also readily apparent that carbon content of the base material is an important variable in determining the susceptibility of a steel to hydrogen damage. In general, steels used in this service are kept below 0.20 weight percent carbon content. Certain other elements, such as nickel and copper, are known to also have a detrimental effect.

Nelson curves have proven indispensable in the selection of materials in hydrogen service. These curves (see Fig. A3.20. for an example) were originally based on experience gathered over several decades, and have been revised as new experience has been gained. These curves identify a ‘‘safe’’ regime in which an alloy will perform acceptably at various temperatures and hydrogen partial pressures. Where these curves have proven unconservative have been associated with weld heat-affected zones that had been inadequately postweld heat-treated (PWHT). The high residual stresses and high hardness left in the weld region contribute to accelerated damage. For this reason, most specifications for hydrogen service equipment stipulate a maximum hardness in weld regions that will assure adequacy of the PWHT. The limit is usually placed at 210 Brinell hardness, corresponding approximately to a 100,000 psi (690 Ma) ultimate tensile strength.

Austenitic stainless steels are essentially immune to hydrogen damage. The numerous sites within the FCC lattice in which the hydrogen atoms can be safely accommodated, and the inherent ductility of the lattice, gives austenitic materials this freedom from hydrogen damage. However, when stainless overlay weld metal has been used over carbon or low-alloy vessel steels, hydrogen-induced cracking can occur at the weld fusion line just inside the ferritic material.

‘‘885°F’’ (474°C) Embrittlement

One of the limitations of ferritic stainless steels (those alloys of iron possessing greater than about 14 pecent chromium) has been the loss of toughness at room

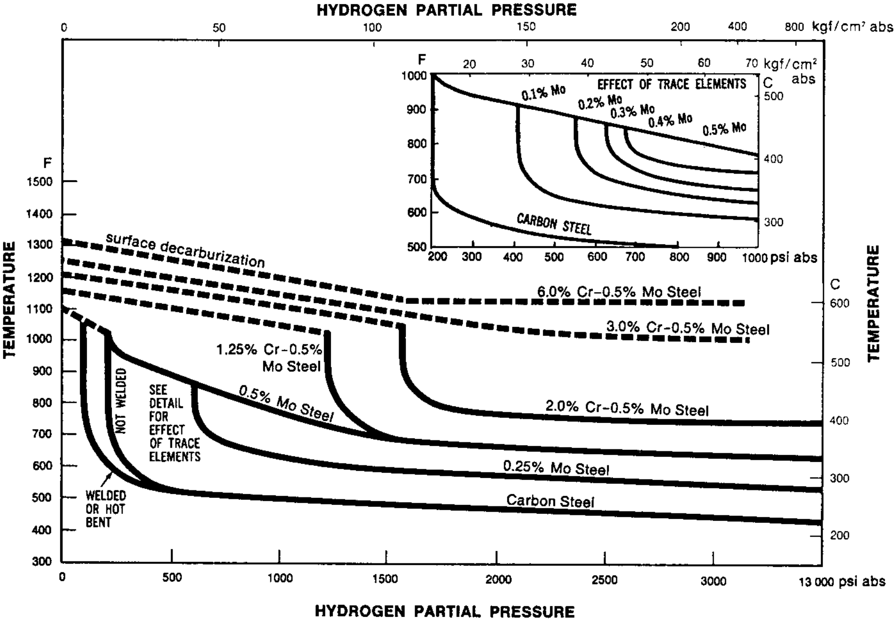

FIGURE A3.20 The classic Nelson diagram indicating the choice of steel warranted to avoid hydrogen attack as a function of operating temperature and partial pressure of hydrogen. Austenitic materials are satisfactory at all temperatures and pressure from hydrogen damage. (Dunn et al., *Molybdenum's Place in the Pressure-Vessel Field*, Climax Molybdenum Company.)

temperature that occurs after these materials are exposed for long times to temperatures in the range of 610 to 1000°F (320 to 538°C). This is commonly referred to as *885°F (474°C) embrittlement*, corresponding approximately to the temperature at which many of the alloys degrade the fastest.

The compositional effects in commercial alloys on 885°F (474°C) embrittlement have not been systematically investigated. However, it is clear that the degree of embrittlement increases as chromium content increases. The effects that other elements may have is not clear. Of these, most important is carbon, and it has been reported as having from no effect to a retarding effect on embrittlement.

This phenomenon results in increased hardness and strength, with a corresponding decrease in ductility, fracture toughness, and a decrease in corrosion resistance. Loss of toughness can be particularly severe, and in fact has tended to relegate the use of this class of alloy to temperature regimes below which significant embrittlement can occur.

Graphitization

Graphitization is a time- and temperature-dependent nucleation and growth process, in which iron carbide in the form of pearlite first spheroidizes, and later forms graphite nodules. There are two general types:

1. Formation of randomly, relatively uniformly distributed graphite nodules in the steel. This reduces the room temperature mechanical strength somewhat, but does not affect the creep-rupture strength at elevated temperature.
2. A concentrated formation of graphite most frequently along the edges of the heat-affected zone of weldments. This is referred to as chain graphite, since a plane of nodules exists paralleling the weld bead contours.

The formation of these nodules, when aligned through the wall of a pressure part, creates planes of weakness, subject to rupture. Fracture characteristically occurs without prior warning.

The first graphitization failure of a low-carbon steam piping material occurred in the early 1940s. The failure occurred after five and a half years of service in a steam line made of aluminum-killed carbon-molydenum steel. The fracture surface was located approximately 1⁄16 in (1.6 mm) from the fusion zone of a butt weld. The failure precipitated numerous and extensive research programs to understand the key variables of the mechanism and to determine the steels which would resist graphitization.

Research has helped in the understanding of the problem, and led to restrictions adopted by the various design codes on use of materials subject to graphitization. Carbon steel and carbon-molybdenum grades are the most susceptible to this degradation process, with the latter being more so. Relative susceptibility of these two grades is also dependent on the steel's aluminum content; the more aluminum, the greater the susceptibility. Additions of chromium in amounts as low as 0.5 weight percent make the steel essentially immune to graphitization.

The ASME Code permits the use of carbon and carbon-molybdenum steels in ASME Section 1 boiler applications up to 1000°F (538°C). A cautionary note is provided in the allowable stress tables of Section I indicating the carbon steels and carbon-molybdenum steels may be susceptible to graphitization at temperatures above about 800 and 875°F (427 to 468°C), respectively. ASME B31.1 has a similar precautionary note specifying limits of 775 and 850°F (413 and 454°C), respectively. Graphitization is a mechanism dependent on diffusion and is not associated with a precise temperature of initiation (it occurs sooner at higher temperatures). Thus, the differences between the design codes only reflect different levels of conservatism in dealing with the failure mode. Many manufacturers extend even more severe restrictions, some prohibiting the use of these steels in piping applications outside the boiler or pressure vessel where rupture creates a serious safety hazard. Substitution of chromium-containing steel grades, such as SA.335 P2(½Cr-½Mo), P11 (1¼Cr-½Mo), and P22 (2¼Cr-1Mo), is normally recommended for these applications. Grade P91 (9Cr-1Mo-V) is increasingly being used in high-temperature applications where use of P11 and P22 is not desirable due to their reduced mechanical strength.

Intergranular Attack

When an unstabilized austenitic stainless steel is held at a temperature within the range of 850 to 1500°F (454 to 816°C), chromium carbides will quickly and preferentially form at the austenitic grain boundaries. The formation of these carbides deletes the surrounding grain matrix of chromium atoms, rendering the thin zone adjacent to grain boundary susceptible to corrosive attack in aqueous environments. This condition is called *sensitization*, and the resulting corrosion is termed *intergranular attack* (IGA). When also in the presence of local high-tension stresses, the result can be *intergranular stress corrosion cracking* (IGSCC). Avoidance of these failure mechanisms is best achieved by minimizing sensitization (fast cool from anneal; stabilized or L-grade steels), and eliminating local stresses.

The area of piping components most often attacked is weld regions. Sensitization can readily occur in a narrow band of base material in the heat-affected zone, caused by the heat of the weld pool. Corrosion of this area has been called *knife line attack* due to the characteristic appearance of a thin crack along a weld edge.

Sigmatization

A hard, brittle, nonmagnetic phase will form in some Fe-Cr and Fe-Ni-Cr alloys upon prolonged exposure to temperatures between about 1100 and 1475°F (593 and 800°C). Those austentic stainless steels containing higher alloy content, such as type 310 (25% Cr–20% Ni) are susceptible, as well as any grades that possess residual ferrite in their microstructure, a constituent which will transform to sigma, preferentially at grain boundaries.

The most deterimental effect of sigma is reduction of toughness. Charpy V-notch impact toughness can degrade to less than 10 ft · lb (14 joules) at room temperature if as much as 10 percent of the volume of material transforms. Toughness is usually not significantly degraded at higher temperatures, above about 1000°F (538°C).

Chemically, sigma is not as resistant to oxidizing media as the austenite, such as acidic environments, thus, the materials will undergo intergranular attack.

At normal metal operating temperatures in power plants, sigmatization of pressure piping made of these high-alloy materials takes very long times to form. Once formed, the phase can be redissolved by subjecting the material to an annealing heat treatment.

Creep Damage and Estimation of Remaining Creep Life

The type of damage observed in components operating at high temperatures, and high stress, typically progresses in stages occurring over a considerable period of time. Elongation or swelling of the component may be observed. Material damage manifests itself in the microstructure in characteristic form at grain boundaries. Voids will form first, which then subsequently link up to form cracks. These cracks increase in size or severity as the end-of-life condition is approached. Severe-damage indications invariably signal the need for near-term corrective action. Such corrective action may entail repair or replacement of the component in question, depending upon the extent of the damage and the feasibility of repair. It is important to note that, except in the most severe cases, damage is not readily detectable by the naked eye, or even by conventional nondestructive techniques such as ultrasonic, magnetic particle, or liquid penetrant examination methods.

The degree of microstructural damage can be assessed by conventional metallographic procedures that may either take a destructive sampling approach or use nondestructive in-place (in-situ) methods. Since the determination of the structural damage allows for a ready estimation of expended creep-rupture life, these inspection methods have recently been adopted to piping and other structural components. The power piping industry, in particular, has seen a wholesale application of metallographic examination to components that have experienced extensive time in elevated temperature service. Several serious steam line ruptures have caused deaths, serious injury, and significant lost operating time at fossil energy power plants. The steam lines that have come under the greatest scrutiny are reheat superheater piping which, based on their relatively large diameters and thin walls, had been made from rolled and welded plate. The failures have been associated with the longitudinal weld regions, which are inherently more susceptible to problems due to danger of latent defects (lack of fusion, slag entrapment, solidification cracks), and the variability in mechanical properties across the welds heat-affected zone.

Destructive sampling of material surfaces of suspected creep-damaged components, to allow for metallographic examination, has evolved to the point where there can be minimal disturbance to surrounding material. Test samples are either trepanned through thickness or smaller silver (boat-shaped) samples are removed by sawing, electro discharge machining, or other methods. However, arc gouging or any other form of heat-producing mechanism must be avoided. It not only can significantly metallurgically alter surrounding material but also can damage the destructive sample, sometimes rendering it unusable for microscopic analysis. The small samples, once properly removed, are metallographically prepared in the standard fashion. These are then examined at high magnification in metallurgical microscopes for evidence of creep damage. The area from which this sample was removed must be weld repaired, employing the required preheat, postweld heat treatment, and weld inspections.

Alternately, an evaluation of microstructure can be performed in place on the component surface, in the area of interest using a procedure called *replication*, which provides, in a manner of speaking, a fingerprint image of the surface. The area to be examined is first carefully polished to a mirrorlike finish using ever-increasing fineness of sandpapers or grinding disks, and then polishing compounds. The surface is then etched with an appropriate acid. A thin, softened plastic film is then applied to the surface. Upon drying, the film hardens, retaining the microstructure in relief. When properly done by skilled technicians, the resolution of the metal structure at magnifications up to 500X or higher is almost equal to that achieved on an actual metal sample. The disadvantage of the replication method is that only the surface of the material can be examined, leaving any subsurface damage undetected. However, this method has proven useful when applied to weld regions, or other high-stressed areas where damage is suspected.

Remaining creep-life determination done in this fashion is not exact; the correlation between the type and degree of damage, and expended creep life is only approximate. In most cases, follow-up inspection several years hence is necessary to determine the rate of damage progression. Usually, when a network of microcracks has been generated, it is time to consider repair or replacement.

The science of estimating the expected growth rate of these cracks by creep evolved very rapidly in the 1980s. Armed with sufficient baseline creep data of a given alloy, formulas have been developed that can predict creep crack growth rates reasonably accurately. Analysis can also be made whether a pipeline would ‘‘leak before break’’; that is, weep fluid for a time prior to catastrophic rupture. All of these tools are available to the piping designer and to operating management, but will not be discussed in any greater detail in this chapter.

Oxide Thickness and Estimation of Remaining Creep Life

Another method for estimating remaining creep life of certain high-temperature tubing and piping components considers the amount of metal oxide scale that has formed on the metals surface. Understandably, this method only applies when the tubular items contain relatively benign substances under oxidizing conditions. It has found its use in steam-carrying piping and components. This method is based on the knowledge that a given thickness of oxide scale on the tube or pipe surface represents growth for a certain time at some temperature. Since oxide growth kinetics of many alloys are well characterized, the effective temperature at which the tube was operating for a known time (service life) can be estimated. The combination of effective temperature and time can then be compared to the typical creep life of the alloy at an applied stress or stresses that are known to have acted on the component during its service life.

As noted, the two principal tools needed by the metallurgist to estimate life using the oxide measurement technique are (1) steam oxidation data for the alloy in question, and (2) uniaxial creep-rupture data for that alloy across the temperature range of interest. This latter information can be found for many of the most widely

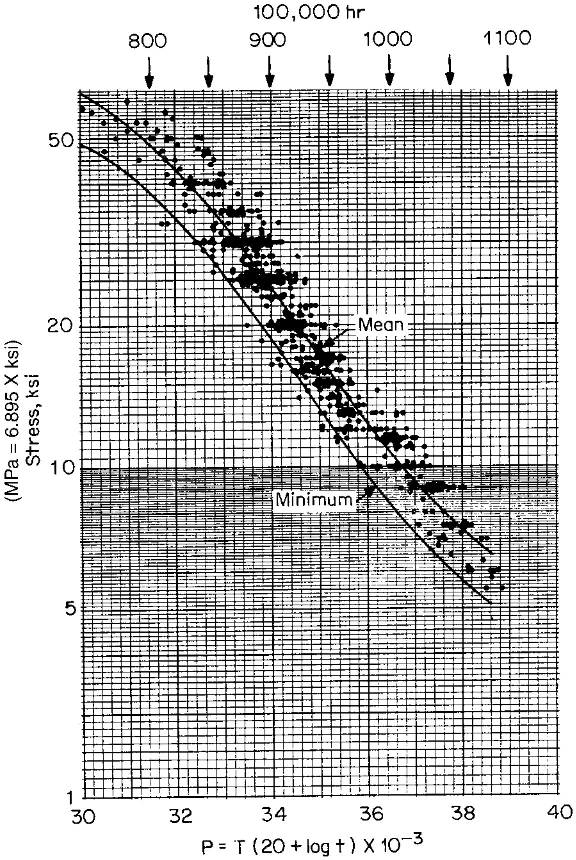

FIGURE A3.21 Variation of Larson-Miller rupture parameter with stress for wrought 1¼ Cr ½ Mo-Si steel. (*Evaluation of the Elevated Temperature Tensile and Creep-Rupture Properties of ½ Cr-½ Mo, 1 Cr-½ Mo, and 1¼ Cr-½ Mo-Si Steels,* ASTM Data Series Publication DS50.)

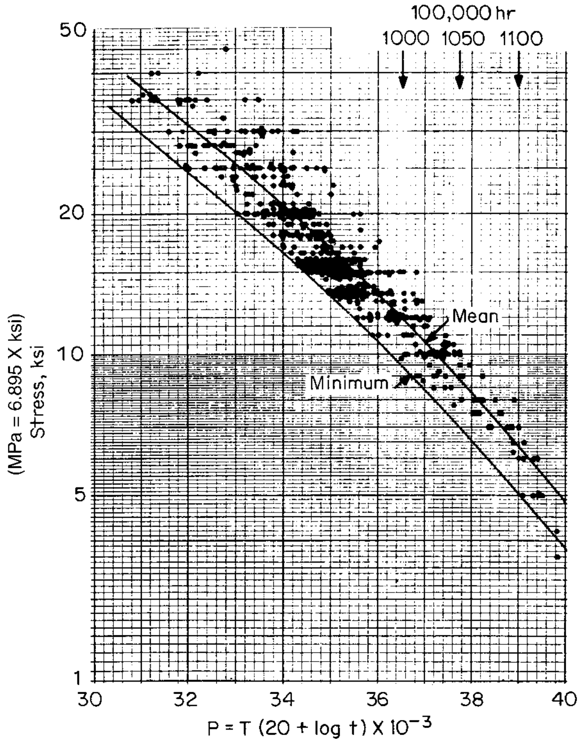

FIGURE A3.22 Variation of Larson-Miller parameter with stress for rupture of annealed 2¼ Cr-1 Mo steel. (*Supplemental Report on the Elevated-Temperature Properties of Chromium-Molybdenum Steels*, ASTM Data Series Publication DS 652.)

used ferrous alloy piping materials in ASTM references. The specific steps followed in this approach are as follows:

1. Oxide thickness is measured either metallographically on a sample or using specialized ultrasonic techniques. Operating time is known.
2. The effective operating temperature is determined from the oxidation data. The effective temperature is defined as the constant temperature that the particular tube metal would have had to have operated at for the known service time to have resulted in the measured oxide thickness. (This is an approximation, since the tube or pipe would have operated at various temperatures, perhaps even in upset conditions well above the design temperature limit.)
3. The hoop stress is calculated using an appropriate formula, knowing the tube or pipe size and operating pressure.
4. The Larsen-Miller Parameter (LMP) is calculated for the service time and effective temperature of the subject tube. The LMP is defined as:

$$\text{LMP} = T(20 + \log t) \times 10^{-3} \qquad \text{(A3.6)}$$

Where T is temperature in degrees Rankine and t is time in hours. This is a simple factor representing the actual condition of the operating component.

5. Uniaxial creep-rupture data is obtained for the alloy in question. Examples of data for 1¼Cr-½Mo-Si and 2¼Cr-1Mo, taken from creep data sources ASTM DS50 and DS652 are shown as Fig. A3.21 and Fig. A3.22. This rupture data is normally represented by curves of minimum and average behavior, and lists applied stress versus LMP.
6. The ASTM rupture curve is entered on the stress axis at the level of appropriate calculated operating stress (from step 3). In this manner, the LMP representing the expected minimum and average total creep life at that stress is determined.
7. The operating LMP calculated in step 4 is compared to the LMPs derived in step 6. The differential in time represented by these parameters can be easily calculated from the Larsen-Miller formula, and the percentage of expended life versus minimum and average expected life can be determined by taking a ratio of these values.

This method for estimating remaining creep life has found its greatest use in the fossil power boiler industry, particularly for ferritic alloy steam piping and superheater tubing. Since a great majority of the operating power boilers in the United States are approaching their originally intended lifetime, the method is critical for establishing when major repair or replacement is necessary to restore the unit to safer and more reliable operation.

MATERIAL SPECIFICATIONS

The American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE) have devised a standardized numbering system for the various classes of carbon and alloy steels that has gained widespread acceptance in North America.

This system employs a four-digit number for carbon and low-alloy steels, and a three-digit number for stainless steels. Regarding the former, the first two digits represents the major alloying elements of the grade. The final two digits represent the nominal carbon content of each alloy, in hundreds of weight percent. For example, 10XX represents simple carbon steels, and 41XX stands for steels with chromium-molybdenum as the major alloying elements. In both classes, a specific grade possessing a nominal carbon content of 0.20 percent would be, respectively, 1020 and 4120. In this fashion the many possible alloy steels can be systematically identified.

Table A3.4 lists the carbon and alloy steel grades categories recognized by AISI and SAE.

The stainless steels are assigned a three-digit code by AISI. Those austenitic stainless steels composed of chromium, nickel, and manganese are the 2XX series. Chromium-nickel austenitic stainless steels are 3XX; ferritic and martensitic stainless steels are 4XX. In the case of stainless steels, the last two digits represent a unique overall composition rather than the level of carbon.

Due to increasing international technical community involvement and cooperation, and with each country possessing its own alloy numbering system, a worldwide universal system of material identification was needed. The Unified Numbering System (UNS) was the result. In this system a letter is followed by a five-digit

TABLE A3.4 Carbon and Alloy Steel Grade Categories: AISI, SAE, UNS

Numerals and digits		
UNS	SAE/AISI	Types of identifying elements
		Carbon steels
G10*XX*0	10*XX*	Nonresulfurized, manganese 1.00% maximum
G11*XX*0	11*XX*	Resulfurized
G12*XX*0	12*XX*	Rephosphorized and resulfurized
		Alloy steels
G13*XX*0	13*XX*	Manganese steels
G23*XX*0	23*XX*	Nickel steels
G25*XX*0	25*XX*	Nickel steels
G31*XX*0	31*XX*	Nickel-chromium steels
G32*XX*0	32*XX*	Nickel-chromium steels
G33*XX*0	33*XX*	Nickel-chromium steels
G34*XX*0	34*XX*	Nickel-chromium steels
G40*XX*0	40*XX*	Molybdenum steels
G41*XX*0	41*XX*	Chromium-molybdenum steels
G43*XX*0	43*XX*	Nickel-chromium-molybdenum steels
G44*XX*0	44*XX*	Molybdenum steels
G46*XX*0	46*XX*	Nickel-molybdenum steels
G47*XX*0	47*XX*	Nickel-chromium-molybdenum steels
G48*XX*0	48*XX*	Nickel-molybdenum steels
G50*XX*0	50*XX*	Chromium steels
G51*XX*0	51*XX*	Chromium steels
G50*XX*6	50*XXX*	Chromium steels
G51*XX*6	51*XXX*	Chromium steels
G52*XX*6	52*XXX*	Chromium steels
G61*XX*0	61*XX*	Chromium-vanadium steels
G71*XX*0	71*XXX*	Tungsten-chromium steels
G72*XX*0	72*XX*	Tungsten-chromium steels
G81*XX*0	81*XX*	Nickel-chromium-molybdenum steels
G86*XX*0	86*XX*	Nickel-chromium-molybdenum steels
G87*XX*0	87*XX*	Nickel-chromium-molybdenum steels
G88*XX*0	88*XX*	Nickel-chromium-molybdenum steels
G92*XX*0	92*XX*	Silicon-manganese steels
G93*XX*0	93*XX*	Nickel-chromium-molybdenum steels
G94*XX*0	94*XX*	Nickel-chromium-molybdenum steels
G97*XX*0	97*XX*	Nickel-chromium-molybdenum steels
G98*XX*0	98*XX*	Nickel-chromium-molybdenum steels
		Carbon and alloy steels
G*XXXX*1	*XX*B*XX*	B denotes boron steels
G*XXXX*4	*XX*L*XX*	L denotes leaded steels
		Stainless steels
S2*XXXX*	302*XX*	Chromium-nickel steels
S3*XXXX*	303*XX*	Chromium-nickel steels
S4*XXXX*	514*XX*	Chromium steels
S5*XXXX*	515*XX*	Chromium steels
		Experimental steels
None	Ex…	SAE Experimental steels

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TABLE A3.5 Selected Piping System Materials—ASME Specifications

	ASME Specification		Other comments	
Metal or Alloy	Number	Grade	ksi*	MPa
	Pipe			
Carbon steel	SA-53	A	48,000 UTS/30,000YS	(330/205)
Carbon steel	SA-106	B	60,000 UTS/35,000YS	(415/240)
Carbon steel	SA-106	C	70,000 UTS/40,000YS	(485/275)
½ Cr–½ Moly	SA-335	P2	55,000 UTS/30,000YS	(380/205)
1 Cr–½ Moly	SA-335	P12	60,000 UTS/32,000YS	(415/220)
1¼ Cr–½ Mo-Si	SA-335	P11	60,000 UTS/30,000YS	(415/205)
2¼ Cr–1 Mo	SA-335	P22	60,000 UTS/30,000YS	(415/205)
5 Cr–1 Mo	SA-335	P5	60,000 UTS/30,000YS	(415/205)
9 Cr–1 Mo	SA-335	P9	60,000 UTS/30,000YS	(415/205)
9 Cr–1 Mo-V	SA-335	P9	85,000 UTS/60,000YS	(585/415)
304H	SA-376	TP304H	0.04% Min carbon	
304H	SA-430	FP304H	Forged and bored pipe	
316H	SA-376	TP316H	75,000 UTS/30,000YS	(515/205)
Forgings/fittings				
Carbon steel	SA-105	—	Rolled or forged bar	
Carbon steel	SA-181	C170	70,000 UTS/36,000YS	(485/250)
Carbon steel	SA-266	C12	70,000 UTS/30,000YS	(485/205)
Carbon-Moly	SA-182	F1	0.5% Mo	
½ Cr–½ Moly	SA-182	F2	—	
1 Cr–½ Moly	SA-182	F12	70,000 UTS/40,000YS	(485/275)
1¼ Cr–½ Mo-Si	SA-182	F11a	75,000 UTS/45,000YS	(515/310)
1¼ Cr–½ Mo-Si	SA-182	F11b	60,000 UTS/30,000YS	(415/205)
2¼ Cr–1 Mo	SA-234	WP12	Fittings	
5 Cr–1 Mo	SA-336	F5A	80,000 UTS/50,000YS	(550/345)
9 Cr–1 Mo-V	SA-234	WP9	Fittings	
304H	SA-336	F304H	1900°F Min anneal	
Tubing				
Carbon steel	SA-178	A	Electric resistance welded	
Carbon steel	SA-210	A1	60,000 UTS/37,000YS	(415/255)
Carbon-Moly	SA-209	T1a	Seamless	
½ Cr–½ Moly	SA-213	T2	60,000 UTS/30,000YS	(415/205)
2¼ Cr–1 Moly	SA-213	T22	60,000 UTS/30,000YS	(415/205)
9 Cr–1 Mo-V	SA-213	T91	Normalized and tempered	
304H	SA-213	TP304H	75,000 UTS/30,000YS	(515/205)

* UTS and YS in psi.

number which, taken together, uniquely defines each particular composition. Many of the conventions adopted in the AISI/SAE system were incorporated into the UNS numbers, as shown on Table A3.4.

The AISI and SAE specifications for alloys controls only material composition. Addition control over minimum properties, heat treatment, and other inspections was necessary to assure reproducibility and reliability of the materials for their

TABLE A3.6 Cross-Reference for ASME to UNS Selected Pipe and Tubing Specifications

ASME specification (and grade)	UNS number
SA-53 (E-A)(S-A)	K02504
SA-53 (E-B)(S-B)	K03005
SA-106 (A)	K02501
SA-106 (B)	K03006
SA-106 (C)	K03501
SA-178 (A)	K01200
SA-178 (C)	K03503
SA-209 (T1)	K11522
SA-209 (T1a)	K12023
SA-209 (T1b)	K11422
SA-210 (A1)	K02707
SA-210 (C)	K03501
SA-213 (T2)	K11547
SA-213 (T3b)	K21509
SA-213 (T5)	K41545
SA-213 (T7)	S50300
SA-213 (T9)	S50400
SA-213 (T11)	K11597
SA-213 (T12)	K11562
SA-213 (T21)	K31545
SA-213 (T22)	K21590
SA-213/SA-312 (304)	S30400
SA-213/SA-312 (304H)	S30409
SA-213/SA-312 (304L)	S30403
SA-213/SA-312 (304N)	S30451
SA-213/SA-312 (310)	S31000
SA-213/SA-312 (316)	S31600
SA-213/SA-312 (316H)	S31609
SA-213/SA-312 (316L)	S31603
SA-213/SA-312 (316N)	S31651
SA-213/SA-312 (321)	S32100
SA-213/SA-312 (321H)	S31209
SA-213/SA-312 (347)	S34700
SA-213/SA-312 (347H)	S34709
SA-213/SA-312 (348)	S34800
SA-213/SA-312 (348H)	S34809
SA-335 (P1)	K11522
SA-335 (P2)	K11547
SA-335 (P5)	K41545
SA-335 (P7)	S50300
SA-335 (P9)	S50400
SA-335 (P11)	K11597
SA-335 (P12)	K11562
SA-335 (P21)	K31545
SA-335 (P22)	K21590

TABLE A3.7 Nominal Compositions of Wrought Copper Materials

Alloy	Composition
Coppers	
Electrolytic tough pitch (ETP)	99.90 Cu–0.04 O
Phosphorized, high residual phosphorus (DHP)	99.90 Cu–0.02 P
Phosphorized, low residual phosphorus (DLP)	99.90 Cu–0.005 P
Lake	Cu–8 oz/ton Ag
Silver bearing (10–15)	Cu–10 to 15 oz/ton Ag
Silver bearing (25–30)	Cu–25 to 30 oz/ton Ag
Oxygenfree (OF) (no residual deoxidants)	99.92 Cu (min)
Free cutting	99 Cu–1 Pb
Free cutting	99.5 Cu–0.5 Te
Free cutting	99.4 Cu–0.6 Se
Chromium copper (heat treatable) (b)	Cu + Cr and Ag or Zn
Cadmium copper (b)	99 Cu–1 Cd
Tellurium nickel copper (heat treatable) (b)	98.4 Cu–1.1 Ni–0.5 Te
Beryllium copper (heat treatable)	Cu–2 Be–0.25 Co or 0.35 Ni
Plain brasses	
Gilding, 95%	95 Cu–5 Zn
Commercial bronze, 90%	90 Cu–10 Zn
Red brass, 85%	85 Cu–15 Zn
Low brass, 80%	80 Cu–20 Zn
Cartridge brass, 70%	70 Cu–30 Zn
Yellow brass, 65%	65 Cu–35 Zn
Muntz metal	60 Cu–40 Zn
Free-cutting brasses	
Leaded commercial bronze (rod)	89 Cu–9.25 Zn–1.75 Pb
Leaded brass strip (B121-3)	65 Cu–34 Zn–1 Pb
Leaded brass strip (B121-5)	65 Cu–33 Zn–2 Pb
Leaded brass tube (B135-3)	66 Cu–33.5 Zn–0.5 Pb
Leaded brass tube (B135-4)	66 Cu–32.4 Zn–1.6 Pb
Medium-leaded brass rod	64.5 Cu–34.5 Zn–1 Pb
High-leaded brass rod	62.5 Cu–35.75 Zn–1.75 Pb
Free-cutting brass rod (B16)	61.5 Cu–35.5 Zn–3 Pb
Forging brass	60 Cu–38 Zn–2 Pb
Architectural bronze	57 Cu–40 Zn–3 Pb
Miscellaneous brasses	
Admiralty (inhibited)	71 Cu–28 Zn–1 Sn
Naval brass	60 Cu–39.25 Zn–0.75 Sn
Leaded naval brass	60 Cu–37.5 Zn–1.75 Pb–0.75 Sn
Aluminum brass (inhibited)	76 Cu–22 Zn–2 Al
Manganese brass	70 Cu–28.7 Zn–1.3 Mn
Manganese bronze rod A (B138)	58.5 Cu–39 Zn–1.4 Fe–1 Sn–0.1 Mn
Manganese bronze rod B (B138)	65.5 Cu–23.3 Zn–4.5 Al–3.7 Mn–3 Fe

intended purpose. The American Society for Testing and Materials (ASTM), the American Society of Mechanical Engineers (ASME), and the American Petroleum Institute (API) have generated a series of comprehensive material specifications that extend this control. Table A3.5 lists the more common ASME specification and grade numbers for the common piping system materials of construction. Table A3.6 gives equivalencies between selected piping material grades in ASME with the Unified Numbering System (UNS).

Copper and Copper Alloys

The use of copper and copper alloys is limited to temperatures below the lower recrystallization temperature for the particular alloy. This is the temperature at which cold-worked specimens begin to soften. This recrystallization is usually accompanied by a marked reduction in tensile strength. Typical classes of wrought copper-based materials are given in Table A3.7.

Brasses containing 70 percent or more of copper may be used successfully at temperatures up to 400°F (200°C), while those containing only 60 percent of copper should not be used at temperatures above 300°F (150°C).

TABLE A3.8 Copper and Copper-Based Pipe and Tubing Alloy Specifications

ASME specification	UNS grade number	Characteristics
SB-42/SB-68	C10200	99.95 Cu
SB-42/SB-68	C12000	99.90 plus low Phos
SB-42/SB-68	C12200	99.9 plus high Phos
SB-43	C23000	Red Brass
SB-75/SB-111	C10200	Oxygen Free
SB-75/SB-111	C12000	—
SB-75/SB-111	C12200	—
SB-75/SB-111	C14200	Phosphorized, Arsenical
SB-111	C23000	Red Brass
SB-111	C28000	Muntz Metal
SB-111	C44300	Admiralty Metal
SB-111	C44400	Cu-Zn
SB-111	C44500	Cu-Zn
SB-111	C60800	Aluminum Bronze
SB-111	C68700	Aluminum Brass
SB-111	C70400	95-5 Cu-Ni
SB-111	C70600	90-10 Cu-Ni
SB-111	C71000	80-20 Cu-Ni
SB-111	C71500	70-30 Cu-Ni
SB-315	C65500	High-Si Bronze
SB-466	C70600	90-10 Cu-Ni
SB-466	C71500	70-30 Cu-Ni
SB-467	C70600	Welded 90-10
SB-467	C71500	Welded 70-30

TABLE A3.9 Nickel and Nickel-Based Pipe and Tubing Alloy Specifications

ASME specifications	UNS grade number	Characteristics
SB-161	N02200	Nickel 200; 99% Ni
SB-161	N02201	Low Carbon
SB-163/SB-407	N08800	Alloy 800 Tubing (Ni-Fe-Cr)
SB-163/SB-165	N04400	70-30 Ni-Cu Monel
SB-163/SB-167	N06600	Alloy 600 (Ni-Cr-Fe)
SB-163/SB-167	N06690	Alloy 690 (60-30-10)
SB-163/SB-423	N08825	Alloy 825

The ASME Boiler and Pressure Vessel Code limits the use of brass and copper pipe and tubing (except for heater tubes) to temperatures not to exceed 406°F (208°C). The ASME B31 Code for Pressure Piping also limits brass and copper pipe and tubing to this temperature for steam, gas, and air piping.

Table A3.8 lists a number of ASME specifications for copper and copper alloy piping and tubing.

Nickel and Nickel Alloys

Nickel is a tough, malleable metal that offers good resistance to oxidation and corrosion. When nickel is combined with copper as the secondary element, the well-known series of Monel alloys are created. Nickel, Monel, and various modifications of these materials are used in piping systems, turbine blading, valves, and miscellaneous power plant accessories handling steam.

The presence of even a small amount of sulfur in a reducing environment will result in embrittlement as temperatures of 700–1200°F (370–650°C).

TABLE A3.10 Designation System for Wrought Aluminum and Aluminum Alloy

Composition	Alloy no.
Aluminum, 99.0% min and greater	1*XXX*
Aluminum alloys grouped by major alloying element	
Copper	2*XXX*
Manganese	3*XXX*
Silicon	4*XXX*
Magnesium	5*XXX*
Magnesium and silicon	6*XXX*
Zinc	7*XXX*
Other elements	8*XXX*
Unused series	9*XXX*

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TABLE A3.11 Chemical Composition Limits for Wrought Aluminum Alloys Where No Range Is Given (Single Number Indicates Maximum Permissible Percentage)

Alloy number	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Others	
										Each	Total
EC	(Al 99.45 min)										
1100	1.0 Si + Fe		0.20	0.05	—	—	—	0.10	—	0.05(a)	0.15
1060	0.25	0.35	0.05	0.03	0.03	—	—	0.05	0.03	0.03(a)	—
1085	0.10	0.12	0.03	0.02	0.02	—	—	0.03	0.02	0.01(b)	—
1099	(Al 99.99 min)										
2011	0.04	0.7	5.0–6..0	—	—	—	—	0.30	—	0.05(c)	0.15
2014	0.50–1.2	1.0	3.9–5.0	0.40–1.2	0.20–0.8	0.10	—	0.25	0.15	0.05(a)	0.15
2017	0.8	1.0	3.5–4.5	9.40–1.0	0.20–0.8	0.10	—	0.25	—	0.05	0.15
2117	0.8	1.0	2.2–3.0	0.20	0.20–0.50	0.10	—	0.25	—	0.05	0.15
2618	0.25	0.9–1.3	1.9–2.7	—	1.3–1.8	—	0.9–1.2	—	0.04–0.10	0.05	0.15
2219	0.20	0.30	5.8–6.8	0.20–0.40	0.02	—	—	0.10	0.02–0.10	0.05(d)	0.15
X2020	0.40	0.04	4.0–5.0	0.30–0.8	0.03	—	—	0.25	0.10	0.05(c)	0.15
2024	0.50	0.50	3.8–4.9	0.30–0.9	1.2–1.8	0.10	—	0.25	—	0.05	0.15
3003	0.6	0.7	0.20	1.0–1.5	—	—	—	0.10	—	0.05(a)	0.15
3004	0.30	0.7	0.25	1.0–1.5	0.8–1.3	—	—	0.25	—	0.05(a)	0.15
4032	11.0–13.5	1.0	0.50–1.3	—	0.8–1.3	0.10	0.50–1.3	0.25	—	0.05	0.15
4043	4.5–6.0	0.8	0.30	0.05	0.05	—	—	0.10	0.20	0.05(a)	0.15
5005	0.40	0.7	0.20	0.20	0.50–1.1	0.10	—	0.25	—	0.05	0.15
5050	0.40	0.7	0.20	0.10	1.0–1.8	0.10	—	0.25	—	0.05(a)	0.15
5052	0.45 Si + Fe		0.10	0.10	2.2–2.8	0.15–0.35	—	0.10	—	0.05(a)	0.15
5154	0.45 Si + Fe		0.10	0.10	3.1–3.9	0.15–0.35	—	0.20	0.20	0.05(a)	0.15
5155	0.30	0.70	0.25	0.20–0.60	3.5–5.0	0.05–0.25	—	0.15	0.15	0.05	0.15

TABLE A3.11 Chemical Composition Limits for Wrought Aluminum Alloys Where No Range Is Given (Single Number Indicates Maximum Permissible Percentage) (*Continued*)

Alloy number	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Others	
										Each	Total
5454	0.40 Si + Fe		0.10	0.50–1.0	2.4–3.0	0.05–0.20	—	0.25	0.20	0.05	0.15
5056	0.30	0.40	0.10	0.05–0.20	4.5–5.6	0.05–0.02	—	0.10	—	0.05(a)	0.15
5456	0.40 Si + Fe		0.10	0.50–1.0	4.7–5.5	0.05–0.20	—	0.25	0.20	0.05	0.15
5357	0.12	0.17	0.07	0.15–0.45	0.8–1.2	—	—	—	—	0.05	0.15
5457	0.08	0.10	0.20	0.15–0.45	0.8–1.2	—	—	—	—	0.03	0.10
5557	0.10	0.12	0.15	0.10–0.40	0.40–0.8	—	—	—	—	0.03	0.10
5083	0.40	0.40	0.10	0.30–1.0	4.0–4.9	0.05–0.25	—	0.25	0.15	0.05	0.15
5086	0.40	0.50	0.10	0.20–0.7	3.5–4.5	0.05–0.25	—	0.25	0.15	0.05	0.15
6151	0.6–1.2	1.0	0.35	0.20	0.45–0.8	0.15–0.35	—	0.25	0.15	0.05	0.15
6351	0.7–1.3	0.6	0.10	0.40–0.8	0.40–0.8	—	—	—	0.20	0.05	0.15
6053	(f)	0.35	0.1	—	1.1–1.4	0.15–0.35	—	0.10	—	0.05	0.15
6061	0.40–0.8	0.7	0.15–0.40	0.15	0.8–1.2	0.15–0.35	—	0.25	0.15	0.05	0.15
6062	0.40–0.8	0.7	0.15–0.40	0.15	0.8–1.2	0.04–0.14	—	0.25	0.15	0.05	0.15
6063	0.20–0.6	0.35	0.10	0.10	0.45–0.9	0.10	—	0.10	0.10	0.05	0.15
6066	0.9–1.8	0.50	0.7–1.2	0.6–1.1	0.8–1.4	0.40	—	0.25	0.20	0.05	0.15
7072(g)	0.7 Si + Fe		0.10	0.10	0.10	—	—	0.8–1.3	—	0.05	0.15
7075	0.50	0.7	1.2–2.0	0.30	2.1–2.9	0.18–0.40	—	5.1–6.1	0.20	0.05	0.15
7277	0.50	0.7	0.8–1.7	—	1.7–2.3	0.18–0.35	—	3.7–4.3	0.10	0.05	0.15
7178	0.50	0.7	1.6–2.4	0.30	2.4–3.1	0.18–0.40	—	6.3–7.3	0.20	0.05	0.15
7079	0.30	0.40	0.40–0.8	0.10–0.30	2.9–3.7	0.10–0.25	—	3.8–4.8	0.10	0.05	0.15
X8001	0.17	0.45–0.7	0.15	—	—	—	0.9–1.3	—	—	0.05(h)	0.15

Source: *American Society for Metals, Metals Handbook,* Vol. 1, 8th Ed., p 917.

By addition of Cr, Co, Mo, Ti, Al, or Nb, the high temperature strength and creep resistance of the nickel-base materials can be substantially increased. However, these alloys possess low ductility values and require special care in forming of these materials, even at elevated temperatures.

Table A3.9 lists a number of ASME specifications for nickel-based alloy piping and tubing.

Aluminum and Aluminum Alloys

Aluminum and many of its alloys are highly resistant to atmospheric corrosion and to attack by many chemical agents, with the exception of strong alkalis. However, they are subject to galvanic attack if coupled with more noble materials.

Additions of alloying elements increases strengh, but to the detriment of thermal and electrical conductivity, and lowers the material's melting point. Alloying with Cu, Mg, and Si creates heat-treatable alloys that are age-hardenable. Maximum strength can usually be achieved by heating to about 300 to 500°F (150 to 260°C). Effects of working or precipitation hardening can be removed by annealing at temperatures of 600 to 800°F (315 to 425°C).

A system has been devised to designate alloys of aluminum based on the major alloying constituent. See Table A3.10.

Typical classes of wrought aluminum-based materials are given in Table A3.11. The UNS number for each alloy is easily determined by taking the alloy number given in Table A3.11 and preceding it with A9. Thus, for example, the UNS numbers for alloy 6061 is A96061.

Appendix A5 provides a list of material specifications which are acceptable for design and construction of piping systems within the jurisdiction of the ASME Boiler and Pressure Vessel Code and the ASME B31, Code for Pressure Piping. Appendix A6 lists some international material specifications for piping.

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