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PERFORMANCE OF ENGINEERING MATERIALS

CHAPTER 32

SOLID MATERIALS

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This chapter summarizes the structure of solids, including atomic bonding forces, atomic structures, crystal imperfections, slip, and mechanical strength. The section on mechanical properties and tests discusses all the hardness tests and includes a detailed explanation of the tensile test and tensile properties. The section on strength, stress, and strain relations includes many new relationships that have been developed during the past two decades and are not found in other handbooks. The mechanical property data presented in this section are in a new format that is well suited for use in computer-aided-engineering (CAE) applications.

32.1 STRUCTURE OF SOLIDS

A study of the mechanical properties of materials must begin with an understanding of the structure of solid materials. In this context, *structure* refers to the atomistic and crystalline patterns of which the solid material is composed. The definitions of the mechanical properties given in the following sections are on the basis of the crystalline structure of material. For example, *strength* (and *hardness*) is defined as the ability of the material to resist slip along its crystallographic planes. Thus, in order to increase the strength of a material, something must be done to it which will make

slip more difficult to initiate. The following sections will explain the manner in which the various thermal and mechanical processes affect the structure of a material, which in turn determines the mechanical properties. The next section presents a brief review of atomic structure.

32.2 ATOMIC BONDING FORCES

The smallest particles that must be considered in the preceding context are atoms. The manner in which atoms are arranged in a solid material determines the material's crystal structure. The crystal structure and the type of interatomic bonding forces determine the strength and ductility of the material.

The simple model of an atom is a dense *nucleus*, consisting of *protons* and *neutrons*, surrounded by discrete numbers of planetary *electrons* orbiting in shells at specific distances from the nucleus. Each proton has a positive electric charge of unity (1+). The number of protons in the nucleus determines the nuclear charge of the atom and is called the *atomic number*. The neutrons have no charge, but they do have mass. The *atomic weight* of an atom is the sum of the number of protons and neutrons. The electrons have negligible mass and a negative charge of unity (1−). The number of electrons in a given type of atom is also equal to the atomic number of that element. The maximum number of electrons in any shell is $2n^2$, where n is the *quantum number* of the shell. Thus the maximum number of electrons that can be present in the first (innermost) shell is 2, and 8 is the maximum in the second shell. However, no more than 8 electrons are ever present in the outermost shell of an atom. The *valence* of an element is either the number of electrons in its outermost shell or the number of electrons necessary to fill that shell, whichever number is lower.

The interatomic bonding forces are determined by the valence, or outer-shell, electrons. There are four types of atomic bonding forces that hold the atoms of a solid material in their relatively fixed positions. The three strongest (*ionic*, *covalent*, and *metallic*) types of bond are referred to as *primary*; the fourth (*molecular*) is referred to as a *secondary* type of bond.

32.2.1 Ionic Bonds

From the preceding brief description of atomic structure, it is evident that the uncombined atom is electrically neutral—the number of protons (+ charges) in the nucleus exactly equals the number of electrons (− charges). When atoms combine, only the valence electrons are involved and not the nuclei. When a metal combines with a nonmetal, each metal atom “loses” its valence electrons and thus acquires a positive charge that is equal to the number of electrons so lost. Likewise each non-metallic atom “gains” a number of electrons equal to its valence and acquires an equal negative charge. While in this state, the positively charged metallic atom and the negatively charged nonmetallic atom are called *ions*.

Like-charged particles repel each other and oppositely charged particles attract each other with an electric force called the *Coulomb force*. When a material is maintained in the solid state by the mutual attraction of positively and negatively charged ions, the interatomic bonding force is called *ionic*.

The Coulomb forces attracting oppositely charged ions are very large. Therefore, ionic-bonded solids exhibit very high strength and relatively low melting tempera-

tures. However, they exhibit very low ductility under normal conditions because the interatomic bonds must be broken in order for the atoms to slide past each other. This is one of the most important distinctions between ionic (or covalent) bonding and metallic bonding and is discussed later.

32.2.2 Covalent Bonds

Covalent bonds are those in which the atoms reach a stable configuration (filled outer shell) by *sharing* valence electrons. Unlike ionic bonds, which are nondirectional, covalent bonds act between specific pairs of atoms and thus form molecules. Covalent bonds are most prevalent in gas molecules. Covalent bonding also results in the formation of very large molecules which are present as solids rather than as liquids and gases. Diamond, silicon, and silicon carbide are examples of such covalent-bonded solids. They are characterized by high strength and melting temperature and low ductility. The atoms in the diamond structure are arranged on two interpenetrating face-centered cubic lattices. The entire crystal is composed of only one molecule, and in order to fracture the crystal, the strong covalent interatomic bonds must be broken.

32.2.3 Metallic Bonds

Of the three primary bonding forces, the metallic bond is by far the most important for an understanding of the mechanical properties of the materials with which the practicing engineer is concerned. The *metallic bond* is a special type of covalent bond wherein the positively charged nuclei of the metal atoms are attracted by electrostatic forces to the valence electrons that surround them. Unlike the common covalent bond, which is directional, i.e., between a pair of atoms, the metallic bond is nondirectional, and each nucleus attracts as many valence electrons as possible. This leads to a dense packing of the atoms, and thus the most common crystal structures of the metals are the close-packed ones: face- and body-centered cubic and hexagonal close-packed structures.

The reason that metal atoms have their own unique type of bonding force is the looseness with which their valence electrons are held in the outer shell. This is evident from the fact that the ionization potential of metal atoms is one-half to two-thirds that of nonmetal atoms. The mean radius of the valence electrons in a free (isolated) metal atom is larger than the interatomic distance of that metal in the solid crystalline state. This means that the valence electrons are closer to a nucleus in the solid metal than they are in a free atom, and thus their potential energy is lower in the solid.

Since the valence electrons are not localized between a pair of positive ions, they are free to move through the solid. Thus the structure of the solid metal is a close-packed arrangement of positive ion “cores” (the nucleus plus the nonvalence electrons) that is permeated by an electron “gas” or “cloud.” This ability of the valence electrons to move freely through the solid explains the high thermal and electrical conductivities of metals. Also, the fact that the valence electrons are nondirectional (not shared by only two atoms) explains the relatively low strength and high ductility of elemental metals, since the positive ions can move relative to one another without breaking any primary bonds. This mechanism is referred to as *slip* and is discussed in more detail in a following section on crystal structures.

32.2.4 Molecular or van der Waals Bonds

In addition to the three strong primary bonds discussed above, there are also several much weaker (and therefore called *secondary*) bonds which provide the interatomic attractive forces that hold some types of atoms together in a solid material. These forces are referred to as either *secondary* bonds, *molecular* bonds, or *van der Waals* bonds. These bonds are due to residual electrostatic fields between neutral molecules whose charge distribution is not uniform.

Covalently bonded atoms frequently form molecules that behave as electric or magnetic *dipoles*. Although the molecule itself is electrically neutral, there is an electrical imbalance within the molecule. That is, the center of the positive charge and the center of the negative charge do not coincide, and it is this dipole that creates molecular bonding.

32.3 ATOMIC STRUCTURES

Whereas the electrical properties of a material depend on the internal structure of the atoms, the mechanical properties depend on the types of structures that groups of atoms form. In this context, *atomic structures* refer to the structures that are built by particular arrangements of atoms, not to the internal structure of individual atoms. All solid materials can be classified on the basis of atomic structure into three groups: amorphous, molecular, or crystalline (in order of increasing importance to mechanical properties). Knowledge of the atomic structure of solids makes it possible to understand why a given material has its unique properties and thus to be able to specify the type of material and the condition it should be in to achieve optimum mechanical properties.

32.3.1 Amorphous Solids

Amorphous materials are those whose structure has no repetitive arrangement of the atoms of which it is comprised. In a sense, they have no “structure.” Although gases and liquids are amorphous materials, the only important amorphous solids are the glasses, and they are frequently considered simply as supercooled liquids.

Glass behaves as a typical liquid at high temperatures. The atoms are very mobile and do not vibrate in a fixed location in space. A given mass of hot glass, like any liquid, takes the shape of the container in which it is placed.

As a hot glass cools, its atoms vibrate at lower amplitudes and come closer together, resulting in an overall thermal contraction or decrease in specific volume. This decrease in specific volume of a liquid as temperature decreases is approximately linear and occurs with all liquids, including liquid metals. This is illustrated in Fig. 32.1.

When any unalloyed liquid metal (a pure metallic element) or chemical compound is cooled to its freezing (or melting) temperature T_m , the atoms come much closer together and become relatively immobile with respect to one another. They form a crystalline structure with very efficient packing, and thus there is a very marked decrease in specific volume at this temperature, as shown in Fig. 32.1. When an alloyed liquid metal freezes to form a solid solution, the transition from liquid to solid takes place in the range of temperatures between the liquidus and the solidus. Further cooling of both solid metals results in a further decrease in specific volume, also linear but of lower slope than in the liquid state.

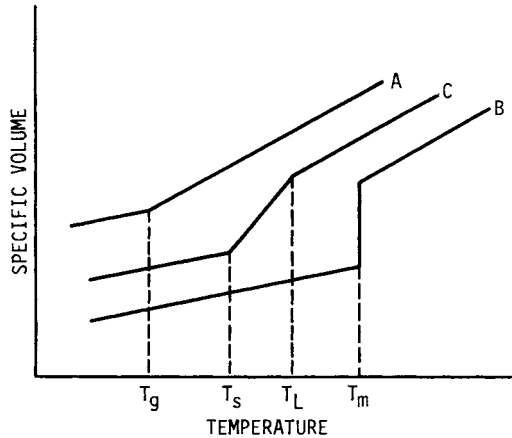


FIGURE 32.1 Specific volume versus temperature. (A) Glass with a transition temperature T_g ; (B) a crystal that melts at a fixed temperature T_m , such as a pure element or a compound; (C) a crystal that melts over a range of temperature, such as a solid-solution alloy with T_L the liquidus temperature and T_s the solidus temperature.

When hot liquid glass is cooled to some temperature T_g , called the *glass transition temperature*, there is an abrupt change in the slope of the specific volume versus temperature curve. Unlike crystalline solids, the glass shows no marked decrease in specific volume at this temperature. Below T_g , glass behaves as a typical solid.

32.3.2 Molecular Solids

A *molecule* is a group of atoms that are held together by strong ionic or covalent bonds. A *molecular solid* is a structure made up of molecules that are attracted to each other by weak van der Waals forces. The two most common types of molecular solids are silicates and polymers. The silicates have ionic intramolecular bonds, and the polymers have covalent ones. Since it is the latter materials that are more important in terms of mechanical properties, they will be discussed in more detail.

Polymers are organic compounds of carbon, hydrogen, and oxygen to which other elements such as chlorine or fluorine may be added. They cover a wide range of structural arrangements, with resulting variations in properties. Large molecules are constructed from a repeating pattern of small structural units. The hydrocarbons have repeating structural units of carbon and hydrogen atoms.

Figure 32.2 shows some of the more common monomers or unsaturated molecules that are used in the building of macromolecules. The simplest monomer is ethylene (C_2H_4); it is shown in Fig. 32.2a. It is the base of the group of hydrocarbons called *olefins*. The olefins have the chemical formula C_nH_{2n} . The benzene molecule, shown in Fig. 32.2d, is another important building unit. Because of the shape of the molecule, it is described as a ring molecule or compound. The benzene group is also called the *aromatic* hydrocarbons.

Figure 32.3 illustrates the addition polymerization of the ethylene monomer. The double bonds of ethylene are broken in the presence of a catalyst such as boron tri-

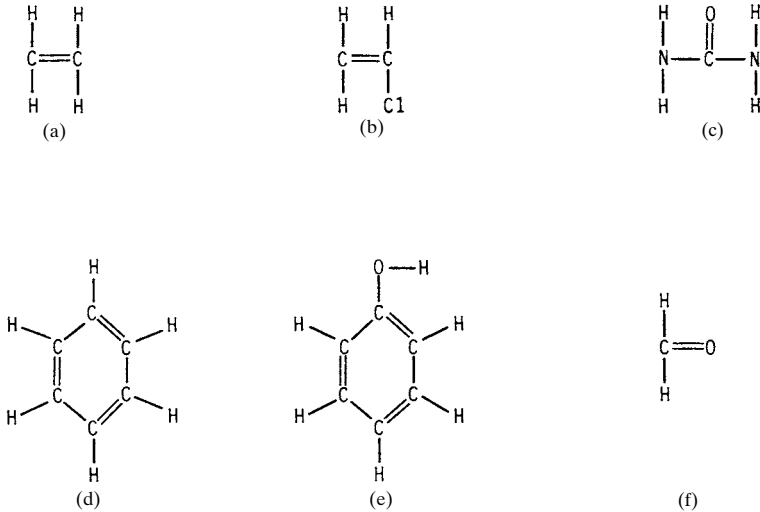


FIGURE 32.2 Monomers: Small unsaturated (double-bonded) molecules that are building units for large polymer molecules. (a) Ethylene; (b) vinyl chloride; (c) urea; (d) benzene; (e) phenol; (f) formaldehyde.

fluoride. The vinyl chloride monomer, as shown in Fig. 32.2*b*, is similar to ethylene except that one of the hydrogen atoms is replaced with a chlorine atom. The polymerization of this monomer results in polyvinyl chloride. These macromolecules resemble, more or less, smooth strings or chains, as can be seen from their structural arrangement.

Some macromolecules resemble rough chains—that is, chains with many short side arms branching from them. Polystyrene, which is a very important industrial polymer, is of this type. The styrene monomer is made from the benzene ring (C_6H_6) with one of the hydrogen atoms replaced with a $CH=CH_2$ molecule, as shown in Fig. 32.4*a*. Polymerization then occurs by breaking the double bond in the $CH=CH_2$ group with the help of a peroxide catalyst and joining two of them together, as shown in Fig. 32.4*b*.

The polymers just described are *thermoplastic*; they melt or soften when they are heated. This is due to the fact that the individual macromolecules are stable and the linkages to other macromolecules are loose (since they are attracted to each

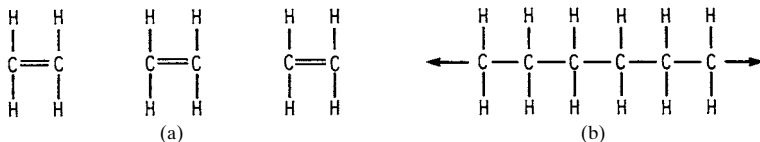


FIGURE 32.3 Addition polymerization. (a) Three individual monomers of ethylene; (b) a portion of a polyethylene molecule formed when each double bond of the monomers is broken by a catalyst to form two single bonds and join the individual molecules together.

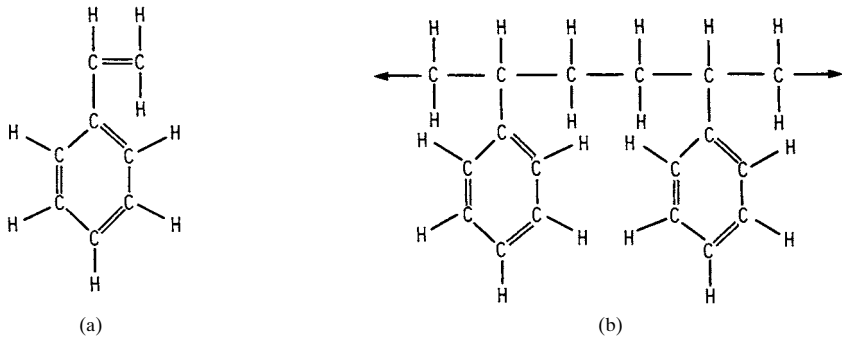


FIGURE 32.4 (a) Styrene structure; (b) polystyrene structure. The polymerization takes place in the presence of a peroxide catalyst.

other by weak van der Waals forces). Some polymers are *thermosetting*; they do not soften when they are heated, but retain their “set” or shape until charred. This is due to the fact that the individual macromolecules unite with each other and form many cross-linkages. Bakelite (phenol formaldehyde) is such a polymer. Figure 32.5 shows how each formaldehyde monomer joins two phenol monomers together, under suitable heat and pressure, to form a macromolecule. This is a condensation type of polymerization because one water molecule is formed from the oxygen atom of each formaldehyde molecule and a hydrogen atom from each of the two phenol molecules.

32.3.3 Mechanical Properties of Molecular Structures

The mechanical properties of polymers are determined by the types of forces acting between the molecules. The polymers are amorphous with random chain orientations while in the liquid state. This structure can be retained when the polymer is cooled rapidly to the solid state. In this condition, the polymer is quite *isotropic*. However, with slow cooling or plastic deformation, such as stretching or extruding, the molecules can become aligned. That is, the long axes of the chains of all the molecules tend to be parallel. A material in this condition is said to be “oriented” or “crystalline,” the degree of orientation being a measure of the crystallinity. When the molecular chains of a polymer have this type of directionality, the mechanical properties are also directional and the polymer is *anisotropic*. The strength of an aligned polymeric material is stronger along the axis of the chains and much lower in the perpendicular directions. This is due to the fact that only weak van der Waals forces hold the individual, aligned macromolecules together, whereas the atoms along the axes of the chains are held together by strong and covalent bonds. The intermolecular strength of linear polymers can be increased by the addition of polar (dipole) groups along the length of the chain. The most frequently used polar groups are chlorine, fluorine, hydroxyl, and carboxyl.

The thermosetting (cross-linked) types of polymers have all the macromolecules connected together in three directions with strong covalent bonds. Consequently, these polymers are stronger than thermoplastic ones, and they are also more isotropic.

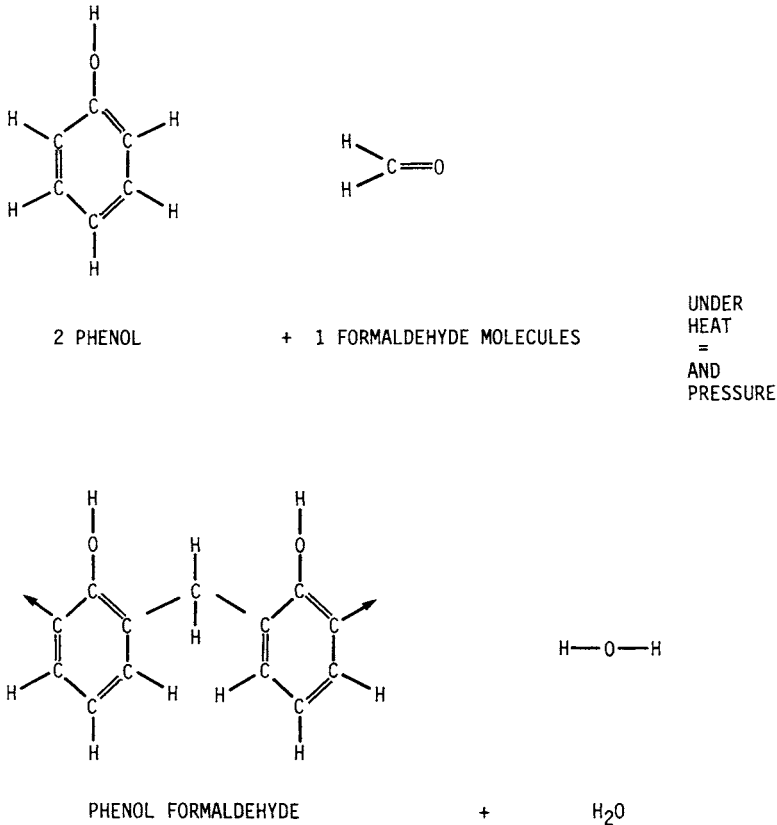


FIGURE 32.5 Condensation polymerization of phenol and formaldehyde into bakelite.

32.3.4 Crystalline Solids

Crystalline solids are by far the most frequently used ones on the basis of mechanical properties or load-carrying capacity. Moreover, of all the crystalline solids, metals are the most important. A *crystal* (or crystalline solid) is an orderly array of atoms having a repeating linear pattern in three dimensions. The atoms are represented as spheres of radius r . A *space lattice* is the three-dimensional network of straight lines that connects the centers of the atoms along three axes. The intersections of the lines are *lattice points*, and they designate the locations of the atoms. Although the atoms vibrate about their centers, they occupy the fixed positions of the lattice points. Figure 32.6 is a sketch of a space lattice, with the circles representing the centers of the atoms. A space lattice has two important characteristics: (1) The space-lattice network divides space into equal-sized prisms whose faces contact one another in such a way that no void spaces are present, and (2) every lattice point of a space lattice has identical surroundings.

The individual prisms that make up a space lattice are called *unit cells*. Thus a unit cell is the smallest group of atoms which, when repeated in all three directions, make up the space lattice, as illustrated by the dark-lined parallelepiped in Fig. 32.6.

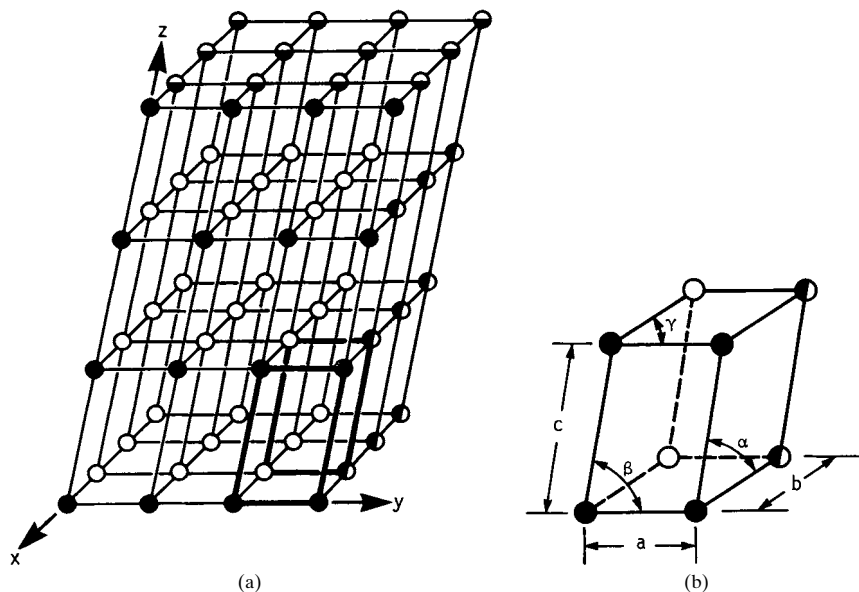


FIGURE 32.6 A space lattice. (a) A unit cell is marked by the heavy lines. Black circles are on the front face; horizontal shading on the top face; vertical shading on the right side face; hidden circles are white. (b) An isolated unit cell showing dimensions a , b , and c and angles α , β , and γ .

Only 14 different space lattices and 7 different systems of axes are possible. Most of the metals belong to three of the space-lattice types: face-centered cubic, body-centered cubic, and hexagonal close-packed. They are listed in Table 32.1, along with four metals that have a rhombohedral and two that have orthorhombic structures.

TABLE 32.1 Lattice Structure of Metal Crystals

Face-centered cubic	Body-centered cubic	Hexagonal close-packed	Rhombohedral	Orthorhombic
Ag	Cb	Be	As	Ga
Al	α -Cr	Cd	Bi	U
Au	Cs	α -Co	Hg	
Ce	α -Fe	β -Cr	Sb	
β -Co	δ -Fe	Hf		
Cu	K	Mg		
γ -Fe	Li	Os		
Ir	Mo	Ru		
Ni	Na	Se		
Pb	Ta	Te		
Pd	V	Ti		
Pt	W	Tl		
Rh		Y		
Sc		Zn		
Th		Zr		
β -Ti				

The crystalline structure is not restricted to metallic bonding; ionic and covalent bonding are also common. Metallic-bonded crystals are very ductile because their valence electrons are not associated with specific pairs of ions.

32.3.5 Face-Centered Cubic

Most of the common metals (see Table 32.1) have face-centered cubic structures. Figure 32.7 shows the arrangement of the atoms, represented by spheres, in the face-centered cubic (FCC) structure as well as that fraction or portion of each atom associated with an individual unit cell. Each atom in the FCC structure has 12 contacting atoms. The number of contacting atoms (or nearest neighbors) is called the *coordination number*.

The FCC structure is referred to as a dense or closely packed structure. A quantitative measure of how efficiently the atoms are packed in a structure is the *atomic packing factor (APF)*, which is the ratio of the volume of the atoms in a cell to the total volume of the unit cell. The APF for the FCC structure is 0.74. This means that 26 percent of the FCC unit cell is “void” space.

32.3.6 Body-Centered Cubic

Many of the stronger metals (Cr, Fe, Mo, W) have body-centered cubic (BCC) lattice structures, whereas the softer, more ductile metals (Ag, Al, Au, Cu, Ni) have the FCC structure (see Table 32.1). Figure 32.8 shows the arrangement of atoms in the BCC structure. There are two atoms per unit cell: one in the center (body center) and $\frac{1}{8}$ in each of the eight corners. As can be seen in Fig. 32.8, each atom is contacted by eight other atoms, and so its coordination number is 8. The atomic packing factor for the BCC structure is 0.68, which is a little lower than that for the FCC structure.

The *Miller indices* are used to designate specific crystallographic planes with respect to the axes of the unit cell. They do not fix the position in terms of distance from the origin; thus, parallel planes have the same designation. The Miller indices are determined from the three intercepts that the plane makes with the three axes of the crystal. Actually it is the reciprocal of the distances between the intercepts with

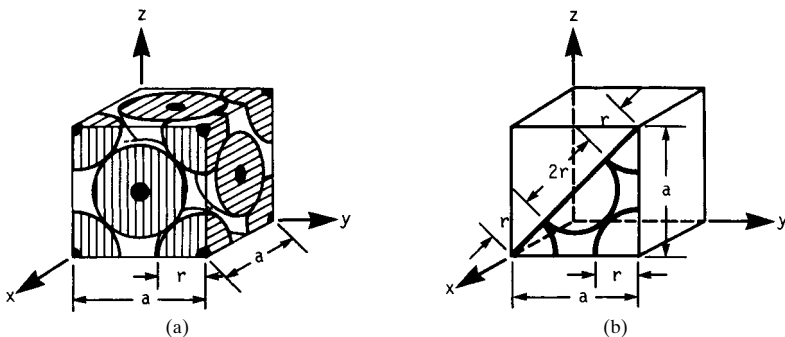


FIGURE 32.7 Unit cell of face-centered cubic structure. (a) The unit cell has 8 corners with $\frac{1}{8}$ atom at each plus 6 faces with $\frac{1}{2}$ atom, for a total of 4 atoms per unit cell; (b) one half of the front face showing the relationship between the lattice parameter a and the atomic radius r .

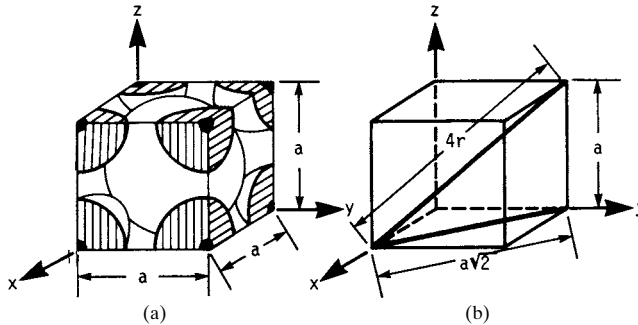


FIGURE 32.8 Unit cell of body-centered cubic structure. (a) The unit cell has $\frac{1}{8}$ atom at each of 8 corners and 1 atom at the geometric center of the cell, for a total of 2 atoms; (b) the relationship of the lattice parameter a and atomic radius r .

the axis and the origin measured in terms of multiples or fractions of the unit cell lengths a , b , and c used in the determination. The final steps in specifying the Miller indices are to reduce the three reciprocals to the lowest integers having the same ratio and then to enclose them in parentheses. As is true with direction indices, the sequence of integers relates to the distances along the x , y , and z axes, respectively. The following examples should make this procedure clear.

Figure 32.9a identifies the front face of the crystal with the Miller indices (100). This notation is arrived at as follows: The front face intercepts the x axis at one a distance, and it does not intercept the y and z axes (or it intercepts at zero b and zero c units). If the side lengths are dropped, the intercepts are 1, 0, and 0. The reciprocals of these are also 1, 0, and 0. Since these are already the smallest integers, the Miller indices are specified by enclosing them in parentheses: (100). The commas are not included because they are simply part of the sentence structure.

Figure 32.9b shows the (110) plane that is parallel to the z axis and is a face diagonal on the top and bottom faces of the unit cell. This plane intercepts the x axis at one a distance, the y axis at one b distance, and the z axis at zero c distance. The intercepts are 1, 1, and 0, and so are the reciprocals. Since these are the smallest integers, the Miller indices are specified as (110).

Figure 32.9d shows the crystallographic plane that intercepts the x axis at $\frac{1}{2}a$, the y axis at one b , and the z axis at one c . The reciprocals are therefore 2, 1, and 1, and so this plane is identified as the (211) plane.

Parentheses are used, as in the preceding examples, to specify a single plane or a family of parallel planes. Thus (100) represents all the planes that are parallel to the yz axes and intercept the lattice structure at one a , two a , three a , etc. distances. Wavy brackets, or braces, are used to designate all planes in a crystal that are equivalent. For example, the six face planes of a unit cell such as that in Fig. 32.9a are (100), (010), (001), ($\bar{1}00$), ($0\bar{1}0$), and ($00\bar{1}$). The notation {100} includes all these six planes.

32.4 CRYSTAL IMPERFECTIONS

The previous discussions on crystal structure assumed a perfect lattice; that is, an atom occupied each and every lattice point, and the distances between equivalent

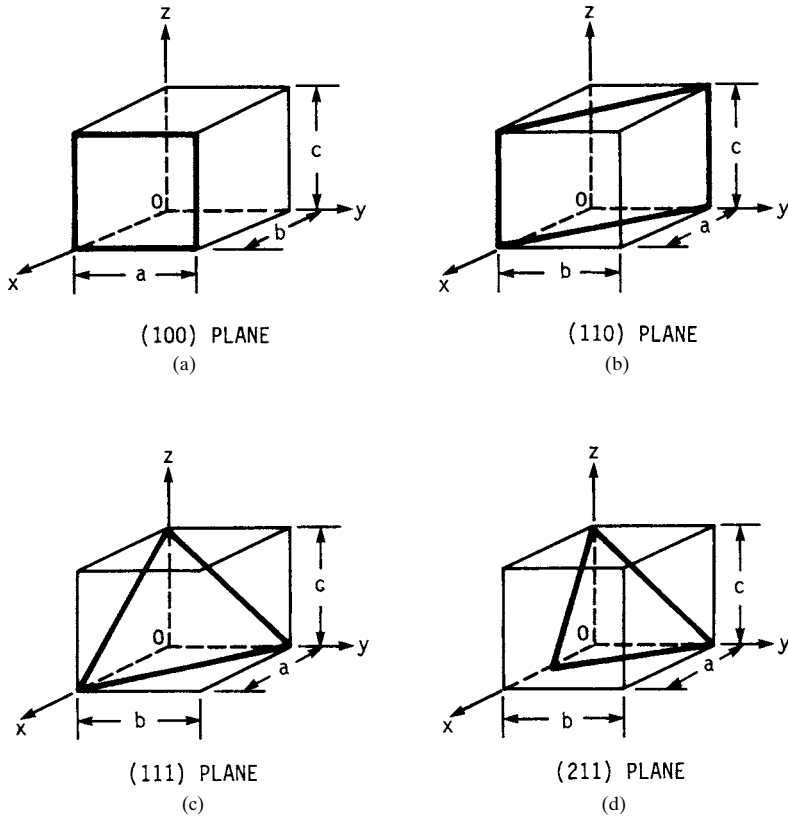


FIGURE 32.9 Miller indices for some crystallographic planes.

lattice points were all exactly the same. In the early 1900s it was found that real crystals did not have perfect properties. Notable among these properties was a mechanical strength much lower than crystals should have. As early as 1928 Prandtl suggested that slip (plastic deformation) in a crystal and the strength of a crystal are related to the presence of linear imperfections within the crystal. This type of imperfection is now called a *dislocation*. At the present time, the terms *imperfection* and *defect* refer to a deviation from a perfectly ordered lattice structure.

Lattice imperfections are classified into three types: *point defects*, where the imperfection is localized about a single lattice point and involves only a few atoms; *line defects*, where the imperfection lies along a line of finite length involving a row (line) or many atoms; and *planar defects* or *boundaries*, where the imperfections involve entire planes or atoms such as the interface between adjacent crystals.

32.4.1 Point Defects

Point defects are caused by (1) the absence of an atom from a lattice point, (2) the presence of an extra atom (usually a small foreign one) in the “void” spaces of the lattice,

(3) the presence of a foreign atom at one of the lattice sites, or (4) atoms that are displaced from their normal positions in the array. Figure 32.10 illustrates these defects.

The first type of point defect, the absence of an atom from a lattice point, is called a *vacancy*. Figure 32.10a shows a vacancy on the (100) planes of an FCC lattice. The sketch was not made to be a true representation in order to make the defect more apparent. In reality, the atoms that are near neighbors to the vacant site would be displaced from their normal positions in the array toward centers closer to the vacancy. Thus the lattice lines joining the centers of the atoms are not straight in the vicinity of the vacancy. In three dimensions this means that the crystallographic planes are warped inward near a vacancy. Individual vacancies can cluster together to form larger voids. Vacancies have no effect on the metallurgical control of the mechanical properties discussed in later sections. However, they do affect properties such as conductivity and diffusivity.

The second type of point defect, the presence of an extra atom at the interstices of the lattice, is known as an *interstitial defect*. This type of defect in the lattice structure is the basis for the strengthening mechanism known as *interstitial alloying*, where the solute atom fits in the interstices of the solvent lattice, and it accounts for the high strength in fully hardened (heat-treated) steel. Commercially pure iron (ferrite with a BCC structure) has a yield strength of 70 to 140 MPa. However, with 0.8 percent carbon dissolved interstitially in the iron and stress relieved after heat treating, it has a yield strength of 2400 to 2800 MPa. No other metal has such high room-temperature strength, and no other strengthening mechanism has a greater effect than the interstitial alloying of carbon in iron. The details of these strengthening mechanisms are discussed later.

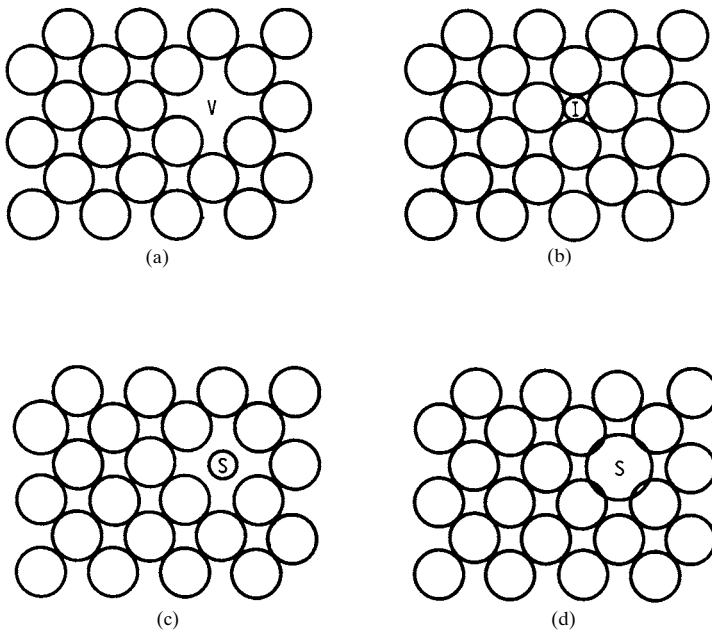


FIGURE 32.10 Some common point defects. (a) Vacancy; (b) interstitial atom I; (c) substitution of a smaller atom S; (d) substitution of a larger atom S.

Figure 32.10*b* shows an interstitial atom I in the solvent matrix. However, it does not lie in the plane of the solvent lattice but lies either above or below the sketched plane. Also, the foreign atom is always larger than the “void” space it occupies, and so it necessarily forces the surrounding solvent atoms out of their normal array. Therefore, the crystallographic planes are warped outward in the vicinity of an interstitial defect.

The third type of point defect, the presence of a foreign atom at one of the lattice points, is referred to as a *substitutional defect*. When an alloy is made by adding solute atoms that replace (substitute for) solvent atoms in the lattice structure, it is called a *substitutional alloy*. This type is the most common one in the metal system. Figure 32.10*c* and *d* shows the substitution of a smaller and a larger atom S at one of the lattice points. Unlike the interstitial atom, the substitutional one is in the plane of the solvent matrix. The crystallographic planes are also warped in the vicinity of the substitutional defect, inward for the smaller atom and outward for the larger atom. The distortion of the crystallographic planes is very important to an understanding of control of the strength of materials, which is presented later.

The fourth type of point defect, atoms that are displaced from their normal position, occurs in several forms. The atoms in the “contacting” planes of two adjoining crystals are not in their normal positions as a result of the crystals having solidified from the liquid without being in perfect registry with each other. This is considered to be a *grain boundary defect*, which has a significant effect on the strength of all polycrystalline materials.

Two additional types of atom displacement defects occur in ionic crystals that are not present in metallic-bonded crystals. A vacancy in an ionic crystal that is associated with a displaced pair, one cation and one anion, is called a *Schottky defect*. A *Frenkel defect* occurs when a small cation moves from a lattice point, leaving a vacancy, and occupies an interstitial site.

32.4.2 Line Defects or Dislocations

Examinations of crystals under the electron microscope have shown interruptions in the periodicity of the lattice structure in certain directions. In a two-dimensional representation these interruptions appear as lines; hence the name *line defects*. It is believed that a perfect crystal of a metal such as pure iron should have a strength of 1 or 2 million pounds force per square inch, whereas in reality such perfect crystals have a yield strength of only a few thousand. The reason given for the three orders of magnitude difference between the postulated and actual strength of metal crystals is the presence of these line defects.

The two most common line defects are edge dislocation and screw dislocation. An *edge dislocation* is the line defect that results from the presence of an extra plane of atoms in one portion of a crystal compared to the adjacent part. Actually, it is the edge of this extra plane of atoms and runs from one end of the crystal to the other. When looking at the crystalline plane that is perpendicular to the dislocation line, the imperfection appears as an extra row of atoms in a part of the crystal.

An edge dislocation is customarily represented by a symbol in which the vertical leg designates the extra plane of atoms. When the vertical leg is above the horizontal leg, the dislocation is considered positive. When the extra plane of atoms is in the bottom portion of the crystal, the vertical leg is placed below the horizontal one and the dislocation is said to be negative. The part of the crystal containing the extra plane of atoms is in compression, whereas that portion on the other side of the dislocation line is in tension. Since one dislocation line runs completely across a crystal, it deforms the lattice structure to a greater extent than does one point defect.

A *screw dislocation* is a crystal defect in which the lattice points lie on a spiral or helical surface that revolves around a center line that is called the *dislocation line*. A screw dislocation terminates at a crystal surface. Shear stresses are set up in the lattice surrounding a screw dislocation as a result of the distortion in atomic array that the defect causes.

The *Burgers vector* is the distance, measured in multiples of the lattice parameter, that is needed to close a straight-sided loop around a dislocation when going the same number of lattice distances in all four directions. It is the term used to define the size of a dislocation and is designated by the letter *b*. A characteristic of an edge dislocation is that it lies perpendicular to its Burgers vector, whereas a screw dislocation lies parallel to its Burgers vector.

32.4.3 Planar Defects

There are several types of planar (or surface) defects that occur from a change in the orientation of crystallographic planes across a surface boundary. The most important planar defect is the *grain boundary*, which is the imperfect plane surface that separates two crystals of different orientation in a polycrystalline solid. Grain boundaries originate when the last few remaining atoms of a liquid freeze onto the meeting faces of two adjacent crystals that have grown from the melt or, similarly, when two adjacent crystals that grow by recrystallization meet each other.

The material in the grain boundary is at a higher energy level than the material near the center of the grain because of the increased elastic strain energy of the atoms that are forced from their normal (lowest-energy) sites in a perfect lattice. This higher energy level and lattice distortion cause the grain boundary material to be stronger, have a higher diffusion rate, and serve as a more favorable site for the nucleation of second phases than the interior materials.

Another important planar defect is the *twin boundary*, which is the plane that separates two portions of a single crystal having slightly different orientations. The two twins are mirror images of each other. The distortion of the twinned lattice is low in comparison to that at a grain boundary. Twins which form in most FCC metal crystals, especially the copper- and nickel-base alloys, during freezing from the melt or recrystallization are called *annealing twins*. Twins which form in some metals during cold work (plastic deformation) are called *mechanical twins*.

A third planar defect is the *low-angle grain boundary* or *low-angle tilt boundary*, where the angular misalignment of the two grains is very small, on the order of a few degrees. In a sense it is a very undistorted grain boundary. The angular mismatch of the crystal planes is due to a row of dislocations piled above each other.

A *stacking fault* is a planar defect that occurs when one crystalline plane is stacked out of its normal sequence in the lattice array. The lattice on both sides of the defect is normal. For example, the normal FCC stacking of planes may be interrupted by one layer of a hexagonal close-packed (HCP) plane, since both are close-packed structures with atomic packing factors of 0.74. Such stacking faults can occur during the formation of a crystal or by plastic deformation.

32.5 SLIP IN CRYSTALLINE SOLIDS

Slip can be defined as the massive sliding movement of one large body of atoms with respect to the remaining body of atoms of the crystal along crystallographic planes. Slip can also be considered as an avalanche of dislocations along one plane that pile

up at grain boundaries or inclusions. The planes along which slip occurs are called *slip planes*. Slip occurs only with relatively high stresses, greater than the yield strength, and it causes plastic deformation.

When a crystalline solid or a single crystal is subjected to low loads, the atoms move slightly from their normal lattice sites and return to their proper positions when the load is removed. The displacements of the individual atoms are very small during elastic deformation. They are submicroscopic, a fraction of an atomic distance. Although there are some dislocation movements, they are few in number, involve very short distances, and are reversible.

Slip, however, is microscopic in size and causes plastic (permanent) deformation that is macroscopic. Figure 32.11 contains several two-dimensional lattice arrays which, in a simplified manner, illustrate the mechanism by means of which slip takes place. A typical perfect cubic lattice is shown in Fig. 32.11*a*, which is a small part of a single crystal. If sufficiently large shear stresses τ are placed on the crystal, all the atoms above the labeled slip plane move to the right simultaneously with respect to the atoms below the slip plane, as shown in Fig. 32.11*b*. The lattice is still a perfect cubic structure; only the outline or exterior shape of the single crystal has changed. It is believed, on the basis of the theories of elasticity, that the shear stress must be equal to the value of $G/2\pi$, where G is the shear modulus of elasticity. Young's modulus of elasticity E , Poisson's ratio ν , and G are related to one another by the equation

$$G = \frac{E}{2(1 + \nu)} \quad (32.1)$$

For iron, $E = 30$ Mpsi and $\nu = 0.30$, and so $G = 11.5$ Mpsi. Therefore, the so-called theoretical shear strength for slip to occur in iron is

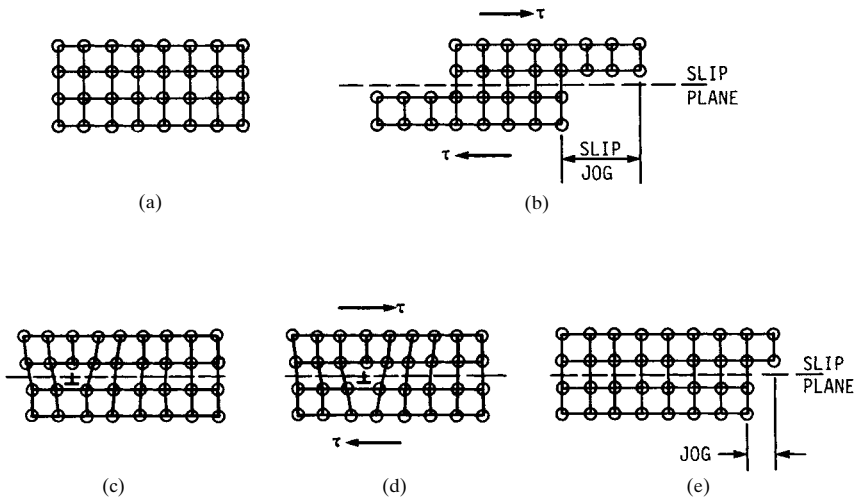


FIGURE 32.11 Two-dimensional sketch of the slip mechanism. (a) A perfect crystal; (b) idealized slip in a perfect crystal; (c) part of a crystal with one edge dislocation; (d) movement of dislocation subject to shear stress; (e) jog produced in the crystal face by dislocation motion.

$$\tau = \frac{G}{2\pi} = \frac{11.5}{2\pi} = 1.83 \text{ Mpsi}$$

However, slip occurs in iron crystals with shear stresses of only 4 to 5 kpsi, which is more than two orders of magnitude smaller. The “theoretical” shear strength of the other pure metals is also 400 to 500 times larger than the actual shear strength. The commonly accepted explanation of why the actual shear stress is so much lower than the theoretical value is that slip does not occur by the simultaneous movement of all the atoms along the slip plane; rather, it occurs by the movement of individual rows (the dislocation row or plane) of atoms. Thus it is the movement of dislocations along the slip plane to the grain boundary that causes the actual shear stress for plastic deformation to be so low. Figure 32.11c, d, and e illustrates the movement of a dislocation that results in slip.

In real crystals of metals, slip terminates at the grain boundaries or the free-surface faces and causes substantial jogs or steps, much larger than shown in Fig. 32.11. Experimental study of the spacings of the slip planes and the sizes of the jog have been made on some of the common metals. The spacing of the parallel planes along which slip occurs varies randomly, with an average distance between slip planes of about 2000 atom diameters. The length of the step or jog at the surface of the grain is approximately 200 to 700 atom diameters.

The atomic displacements associated with slip, unlike those of the initial movements of dislocations, are irreversible in that the slip jog remains when the shear stresses are removed. That is, slip causes a permanent change in shape, or *plastic deformation*, as it is called.

The evidence of slip is seen on metallurgically prepared samples as slip lines when examined under a microscope. The slip lines are the intersection of the crystallographic planes along which slip occurred with the etched surface of the specimen. Slip results in a narrow band on either side of the slip plane within which the lattice structure is severely distorted. These slip lines do not appear on the face of a specimen that is metallurgically polished after slip occurs; they appear only after etching with a suitable chemical reagent that dissolves the metal being studied. The slip lines become visible for the same reason that grain boundaries are visible after etching: The internal energy of the material within the distorted area is considerably higher than that of the material within the rest of the crystal. The metal in the higher energy level dissolves into the reagent much more rapidly than the rest of the crystal, leaving a narrow groove where the severely distorted band intersects the surface. Slip lines can also be seen on specimens that are polished prior to being plastically deformed and that have not been etched.

32.6 MECHANICAL STRENGTH

Although the specific mechanical properties of real materials are discussed in detail in the material that follows, it is very appropriate at this time to relate the concepts of the strengthening mechanisms to the previously described crystalline structures. Mechanical properties can best be studied on the basis of three precepts which encompass all the strengthening mechanisms. These three principles are stated here because they involve the distortion of the lattice structure that has just been discussed.

32.6.1 Principles of Mechanical Strength

Strength can be defined as a material's ability to resist slip. Thus it follows that the first principle of mechanical strength is this: *A material is strengthened when slip is made more difficult to initiate.* Therefore, to make a material stronger, it must be given a treatment that retards the avalanche of dislocations or, in other words, “pegs” the slip planes.

The second principle of mechanical strength is this: *Slip is retarded by inducing mechanical strains, or distortions, in the lattice structure of the material.* These distortions were discussed previously as lattice imperfections or defects. Thus it is a paradox that the source of strength in real polycrystalline materials is “crystal imperfections” or “crystal defects.”

The third principle of mechanical strength is this: *There are four methods to induce mechanical strains or lattice distortions in a material, namely, decreasing the grain size, low-temperature plastic deformation (cold work), single-phase alloying, and multiple-phase alloying.*

32.6.2 Grain Size

Local distortion of the lattice structure at the grain boundaries induces substantial strain energy in those regions. This distortion impedes slip, or causes the dislocations to pile up, and consequently, the grain-boundary material is stronger than the material at the central portions of the crystal. This is true for most metals at room temperature. However, as additional energy is added to a polycrystalline material by raising the temperature, the grain-boundary material softens (and also melts) sooner or at a lower temperature than the bulk of the grain. At some temperature, called the *equicohesive temperature*, the strengths at these two regions are equal. Above the equicohesive temperature, the grain-boundary material is the weaker of the two. This explains why materials that are used at elevated temperatures have higher creep strengths when their grains are coarse rather than fine.

The surface-area-to-volume ratio of a sphere is inversely proportional to its diameter. Therefore, as the diameter of a sphere decreases, its ratio of surface area to volume increases. This means that for a given weight or volume of a polycrystalline solid, the total grain-boundary surface increases as the grain size decreases. Since the grain-boundary material is stronger than the interior material, the strength also varies inversely with the grain size. Also, since the surface area of a sphere is proportional to the square of its diameter, it can be assumed as a first approximation that the yield strength is proportional to the reciprocal of the square of the grain diameter.

Figure 32.12a shows how the 0.2 percent offset yield strength of 70Cu-30Zn brass varies with grain size. In this case, the yield strength increases by a factor of 4 with a grain diameter ratio of 24. The strengths of some materials, such as aluminum or steel, are not so greatly affected by grain size alone.

32.6.3 Cold Work

Cold work is a more significant strengthening mechanism than decreasing the grain size for most metals. When a crystalline material is plastically deformed, there is an avalanche of dislocations (called *slip*) that terminates at the grain boundaries. It is a mass movement of a body of atoms along a crystallographic plane. This movement in a polycrystalline material distorts both the grain boundaries and the crystalline planes in the grain so that slip occurs in the adjacent grains as well. Actually, a por-

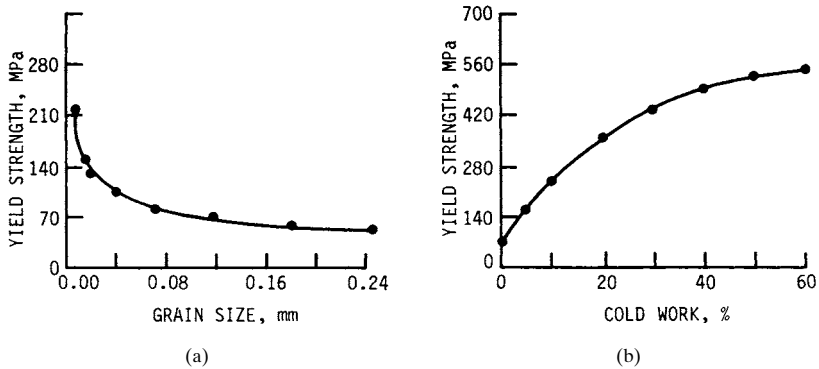


FIGURE 32.12 Yield strength versus grain size (a) and percent cold work (b) for 70Cu-30Zn brass.

tion of one grain intrudes into the space that was previously occupied by another grain, with a resulting distortion of the lattice in both grains.

Figure 32.12b illustrates the effect of cold work on the yield strength of 70Cu-30Zn brass. With only 10 percent cold work, the yield strength is raised by a factor of 3.5, and 60 percent cold work increases the strength nearly 8 times. In general, 10 percent cold work more than doubles the yield strength of most metals.

32.6.4 Single-Phase Alloying

Alloying (single- and multiple-phase) is the most important of the methods available to control or manipulate the mechanical properties of materials. The greatest increase in strength known today occurs when iron having a yield strength of 10 to 20 kpsi (70 to 140 MPa) is alloyed with less than 1.0 percent carbon to form a single phase (martensite) that has a yield strength of nearly 435 kpsi (3000 MPa).

The lattice is distorted and dislocation movement is impeded when foreign (solute) atoms are added to the lattice structure of a pure material. Figure 32.10b through *d* illustrates this condition, which was discussed previously under the heading “Point Defects.” Vacancy defects, as shown in Fig. 32.10a, are not a practical strengthening method. The reason single-phase alloying has such a great effect on strength is that the entire lattice network is distorted, and uniformly, whereas in the other mechanism, there are regions in each crystal that are severely distorted and other regions that are hardly distorted at all.

Figure 32.13a shows the effect on the strength of the material of adding a foreign element B or C to the lattice structure of element A. From this figure it is clear that not all elements have the same strengthening effect. In general, the further the ratio of diameters of solute to solvent atoms is from unity, the greater will be the strengthening effect. However, the further this ratio is from unity, as previously explained, the less soluble the two atoms are in each other’s lattice.

32.6.5 Multiple-Phase Alloying

This mechanism is sometimes referred to as *fine-particle strengthening*. In a sense, multiple-phase alloying is a combination of single-phase alloying and grain-boundary

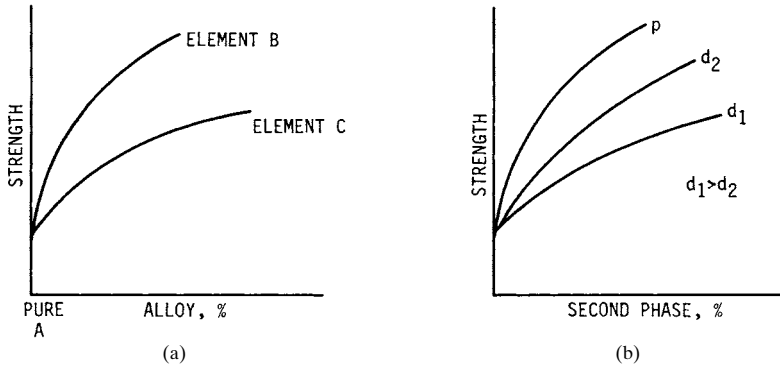


FIGURE 32.13 The effect of alloying on strength. (a) Single-phase alloying; atomic diameter ratio $B/A > C/A$; (b) multiple-phase alloying; p is a nonspherical-shaped particle, and d is the spherical particle diameter.

strengthening. That is, some of the added element goes into solution in the solvent lattice and thus has a strengthening effect; the remainder of the added element forms a second phase (either another solid solution or a compound) that is present as small grains or crystals.

Multiple-phase alloys can be made in three different ways. One method is by *annealing*. In this case, the alloy is heated to a one-phase region where the second element is completely soluble in the first. On slow cooling, the second phase precipitates as a massive network in the grain-boundary regions of the solvent matrix. This is the least beneficial form of alloying. The second method is similar except that the alloy is rapidly cooled from the high one-phase region so that a supersaturated solid phase occurs at room temperature. This material is then reheated to a relatively low temperature so that the second phase precipitates throughout the entire crystal as extremely fine particles rather than concentrating at the grain boundaries. This is the common *precipitation-hardening procedure*. The third method is to add a compound, in the form of small particles, that is insoluble in the parent material. Thus the two phases must be mixed in powder form and then sintered. This method is called *dispersion hardening*. At the present time there are only about a half dozen dispersion-hardenable alloys in commercial use. The most notable ones are Al_2O_3 particles in aluminum (called SAP, for sintered aluminum powder) and ThO in nickel.

32.7 MECHANICAL PROPERTIES AND TESTS

Most mechanical properties are structure-sensitive; that is, they are affected by changes in either the lattice structure or the microstructure. However, modulus of elasticity is one property that is structure-insensitive. For example, ductility and toughness of any material (regardless of whether it is a pure element such as copper, a simple alloy such as AISI 1080 steel, or a complex alloy such as a cobalt-base superalloy) vary with grain size, amount of cold work if any, or the microstructure if heat-treated. The modulus of elasticity of any material is the same regardless of grain size, amount of cold work, or microstructure.

Mechanical properties are discussed individually in the sections that follow. Several new quantitative relationships for the properties are presented here which make it possible to understand the mechanical properties to a depth that is not possible by means of the conventional tabular listings, where the properties of each material are listed separately.

32.8 HARDNESS

Hardness is used more frequently than any other of the mechanical properties by the design engineer to specify the final condition of a structural part. This is due in part to the fact that hardness tests are the least expensive in time and money to conduct. The test can be performed on a finished part without the need to machine a special test specimen. In other words, a hardness test may be a nondestructive test in that it can be performed on the actual part without affecting its service function.

Hardness is frequently defined as a measure of the ability of a material to resist plastic deformation or penetration by an indenter having a spherical or conical end. At the present time, hardness is more a technological property of a material than it is a scientific or engineering property. In a sense, hardness tests are practical shop tests rather than basic scientific tests. All the hardness scales in use today give relative values rather than absolute ones. Even though some hardness scales, such as the Brinell, have units of stress (kg/mm^2) associated with them, they are not absolute scales because a given piece of material (such as a 2-in cube of brass) will have significantly different Brinell hardness numbers depending on whether a 500-kg or a 3000-kg load is applied to the indenter.

32.8.1 Rockwell Hardness

The *Rockwell hardnesses* are hardness numbers obtained by an indentation type of test based on the depth of the indentation due to an increment of load. The Rockwell scales are by far the most frequently used hardness scales in industry even though they are completely relative. The reasons for their large acceptance are the simplicity of the testing apparatus, the short time necessary to obtain a reading, and the ease with which reproducible readings can be obtained, the last of these being due in part to the fact that the testing machine has a “direct-reading” dial; that is, a needle points directly to the actual hardness value without the need for referring to a conversion table or chart, as is true with the Brinell, Vickers, or Knoop hardnesses. Table 32.2 lists the most common Rockwell hardness scales.

TABLE 32.2 Rockwell Hardness Scales

	Scale								
	A	B	C	D	E	F	G	H	K
Indenter Load, kg	1 60	2 100	1 150	1 100	3 100	2 60	2 150	3 60	3 150

Indenter 1 is a diamond cone having an included angle of 120° and a spherical end radius of 0.008 in. Indenters 2 and 3 are $\frac{1}{16}$ -in-diameter and $\frac{1}{8}$ -in-diameter balls, respectively. In addition to the preceding scales, there are several others for testing very soft bearing materials, such as babbitt, that use $\frac{1}{4}$ -in-diameter and $\frac{1}{2}$ -in-diameter balls. Also, there are several “superficial” scales that use a special diamond cone with loads less than 50 kg to test the hardness of surface-hardened layers.

The particular materials that each scale is used on are as follows: the A scale on the extremely hard materials, such as carbides or thin case-hardened layers on steel; the B scale on soft steels, copper and aluminum alloys, and soft-case irons; the C scale on medium and hard steels, hard-case irons, and all hard nonferrous alloys; the E and F scales on soft copper and aluminum alloys. The remaining scales are used on even softer alloys.

Several precautions must be observed in the proper use of the Rockwell scales. The ball indenter should not be used on any material having a hardness greater than $50 R_C$; otherwise the steel ball will be plastically deformed or flattened and thus give erroneous readings. Readings taken on the sides of cylinders or spheres should be corrected for the curvature of the surface. Readings on the C scale of less than 20 should not be recorded or specified because they are unreliable and subject to much variation.

The hardness numbers for all the Rockwell scales are an inverse measure of the depth of the indentation. Each division on the dial gauge of the Rockwell machine corresponds to an 80×10^6 in depth of penetration. The penetration with the C scale varies between 0.0005 in for hard steel and 0.0015 in for very soft steel when only the minor load is applied. The total depth of penetration with both the major and minor loads applied varies from 0.003 in for the hardest steel to 0.008 in for soft steel ($20 R_C$). Since these indentations are relatively shallow, the Rockwell C hardness test is considered a nondestructive test and it can be used on fairly thin parts.

Although negative hardness readings can be obtained on the Rockwell scales (akin to negative Fahrenheit temperature readings), they are usually not recorded as such, but rather a different scale is used that gives readings greater than zero. The only exception to this is when one wants to show a continuous trend in the change in hardness of a material due to some treatment. A good example of this is the case of the effect of cold work on the hardness of a fully annealed brass. Here the annealed hardness may be $-20 R_B$ and increase to $95 R_B$ with severe cold work.

32.8.2 Brinell Hardness

The *Brinell hardness* H_B is the hardness number obtained by dividing the load that is applied to a spherical indenter by the surface area of the spherical indentation produced; it has units of kilograms per square millimeter. Most readings are taken with a 10-mm ball of either hardened steel or tungsten carbide. The loads that are applied vary from 500 kg for soft materials to 3000 kg for hard materials. The steel ball should not be used on materials having a hardness greater than about $525 H_B$ ($52 R_C$) because of the possibility of putting a flat spot on the ball and making it inaccurate for further use.

The Brinell hardness machine is as simple as, though more massive than, the Rockwell hardness machine, but the standard model is not direct-reading and takes a longer time to obtain a reading than the Rockwell machine. In addition, the indentation is much larger than that produced by the Rockwell machine, and the machine cannot be used on hard steel. The method of operation, however, is simple. The prescribed load is applied to the 10-mm-diameter ball for approximately 10 s. The part

is then withdrawn from the machine and the operator measures the diameter of the indentation by means of a millimeter scale etched on the eyepiece of a special Brinell microscope. The Brinell hardness number is then obtained from the equation

$$H_B = \frac{L}{(\pi D/2)[D - (D^2 - d^2)^{1/2}]} \quad (32.2)$$

where L = load, kg

D = diameter of indenter, mm

d = diameter of indentation, mm

The denominator in this equation is the spherical area of the indentation.

The Brinell hardness test has proved to be very successful, partly due to the fact that for some materials it can be directly correlated to the tensile strength. For example, the tensile strengths of all the steels, if stress-relieved, are very close to being 0.5 times the Brinell hardness number when expressed in kilopounds per square inch (kpsi). This is true for both annealed and heat-treated steel. Even though the Brinell hardness test is a technological one, it can be used with considerable success in engineering research on the mechanical properties of materials and is a much better test for this purpose than the Rockwell test.

The Brinell hardness number of a given material increases as the applied load is increased, the increase being somewhat proportional to the strain-hardening rate of the material. This is due to the fact that the material beneath the indentation is plastically deformed, and the greater the penetration, the greater is the amount of cold work, with a resulting high hardness. For example, the cobalt base alloy HS-25 has a hardness of 150 H_B with a 500-kg load and a hardness of 201 H_B with an applied load of 3000 kg.

32.8.3 Meyer Hardness

The *Meyer hardness* H_M is the hardness number obtained by dividing the load applied to a spherical indenter by the projected area of the indentation. The Meyer hardness test itself is identical to the Brinell test and is usually performed on a Brinell hardness-testing machine. The difference between these two hardness scales is simply the area that is divided into the applied load—the projected area being used for the Meyer hardness and the spherical surface area for the Brinell hardness. Both are based on the diameter of the indentation. The units of the Meyer hardness are also kilograms per square millimeter, and hardness is calculated from the equation

$$H_M = \frac{4L}{\pi d^2} \quad (32.3)$$

Because the Meyer hardness is determined from the projected area rather than the contact area, it is a more valid concept of stress and therefore is considered a more basic or scientific hardness scale. Although this is true, it has been used very little since it was first proposed in 1908, and then only in research studies. Its lack of acceptance is probably due to the fact that it does not directly relate to the tensile strength the way the Brinell hardness does.

Meyer is much better known for the original strain-hardening equation that bears his name than he is for the hardness scale that bears his name. The strain-hardening equation for a given diameter of ball is

$$L = Ad^p \quad (32.4)$$

where L = load on spherical indenter

d = diameter of indentation

p = Meyer strain-hardening exponent

The values of the strain-hardening exponent for a variety of materials are available in many handbooks. They vary from a minimum value of 2.0 for low-work-hardening materials, such as the PH stainless steels and all cold-rolled metals, to a maximum of about 2.6 for dead soft brass. The value of p is about 2.25 for both annealed pure aluminum and annealed 1020 steel.

Experimental data for some metals show that the exponent p in Eq. (32.4) is related to the strain-strengthening exponent m in the tensile stress-strain equation $\sigma = \sigma_0 \epsilon^m$, which is to be presented later. The relation is

$$p - 2 = m \quad (32.5)$$

In the case of 70-30 brass, which had an experimentally determined value of $p = 2.53$, a separately run tensile test gave a value of $m = 0.53$. However, such good agreement does not always occur, partly because of the difficulty of accurately measuring the diameter d . Nevertheless, this approximate relationship between the strain-hardening and the strain-strengthening exponents can be very useful in the practical evaluation of the mechanical properties of a material.

32.8.4 Vickers or Diamond-Pyramid Hardness

The *diamond-pyramid hardness* H_p , or the *Vickers hardness* H_V , as it is frequently called, is the hardness number obtained by dividing the load applied to a square-based pyramid indenter by the surface area of the indentation. It is similar to the Brinell hardness test except for the indenter used. The indenter is made of industrial diamond, and the area of the two pairs of opposite faces is accurately ground to an included angle of 136° . The load applied varies from as low as 100 g for microhardness readings to as high as 120 kg for the standard macrohardness readings. The indentation at the surface of the workpiece is square-shaped. The diamond pyramid hardness number is determined by measuring the length of the two diagonals of the indentation and using the average value in the equation

$$H_p = \frac{2L \sin(\alpha/2)}{d^2} = \frac{1.8544L}{d^2} \quad (32.6)$$

where L = applied load, kg

d = diagonal of the indentation, mm

α = face angle of the pyramid, 136°

The main advantage of a cone or pyramid indenter is that it produces indentations that are geometrically similar regardless of depth. In order to be geometrically similar, the angle subtended by the indentation must be constant regardless of the depth of the indentation. This is not true of a ball indenter. It is believed that if geometrically similar deformations are produced, the material being tested is stressed to the same amount regardless of the depth of the penetration. On this basis, it would be expected that conical or pyramidal indenters would give the same hardness num-

ber regardless of the load applied. Experimental data show that the pyramid hardness number is independent of the load if loads greater than 3 kg are applied. However, for loads less than 3 kg, the hardness is affected by the load, depending on the strain-hardening exponent of the material being tested.

32.8.5 Knoop Hardness

The *Knoop hardness* H_K is the hardness number obtained by dividing the load applied to a special rhombic-based pyramid indenter by the projected area of the indentation. The indenter is made of industrial diamond, and the four pyramid faces are ground so that one of the angles between the intersections of the four faces is 172.5° and the other angle is 130° . A pyramid of this shape makes an indentation that has the projected shape of a parallelogram having a long diagonal that is 7 times as large as the short diagonal and 30 times as large as the maximum depth of the indentation.

The greatest application of Knoop hardness is in the microhardness area. As such, the indenter is mounted on an axis parallel to the barrel of a microscope having magnifications of $100\times$ to $500\times$. A metallurgically polished flat specimen is used. The place at which the hardness is to be determined is located and positioned under the hairlines of the microscope eyepiece. The specimen is then positioned under the indenter and the load is applied for 10 to 20 s. The specimen is then located under the microscope again and the length of the long diagonal is measured. The Knoop hardness number is then determined by means of the equation

$$H_K = \frac{L}{0.07028d^2} \quad (32.7)$$

where L = applied load, kg
 d = length of long diagonal, mm

The indenter constant 0.07028 corresponds to the standard angles mentioned above.

32.8.6 Scleroscope Hardness

The *scleroscope hardness* is the hardness number obtained from the height to which a special indenter bounces. The indenter has a rounded end and falls freely a distance of 10 in in a glass tube. The rebound height is measured by visually observing the maximum height the indenter reaches. The measuring scale is divided into 140 equal divisions and numbered beginning with zero. The scale was selected so that the rebound height from a fully hardened high-carbon steel gives a maximum reading of 100.

All the previously described hardness scales are called *static hardnesses* because the load is slowly applied and maintained for several seconds. The scleroscope hardness, however, is a *dynamic hardness*. As such, it is greatly influenced by the elastic modulus of the material being tested.

32.9 THE TENSILE TEST

The tensile test is conducted on a machine that can apply uniaxial tensile or compressive loads to the test specimen, and the machine also has provisions for accu-

rately registering the value of the load and the amount of deformation that occurs to the specimen. The tensile specimen may be a round cylinder or a flat strip with a reduced cross section, called the *gauge section*, at its midlength to ensure that the fracture does not occur at the holding grips. The minimum length of the reduced section for a standard specimen is four times its diameter. The most commonly used specimen has a 0.505-in-diameter gauge section (0.2-in² cross-sectional area) that is 2¼ in long to accommodate a 2-in-long gauge section. The overall length of the specimen is 5½ in, with a 1-in length of size ¼-10NC screw threads on each end. The ASTM specifications list several other standard sizes, including flat specimens.

In addition to the tensile properties of strength, rigidity, and ductility, the tensile test also gives information regarding the stress-strain behavior of the material. It is very important to distinguish between *strength* and *stress* as they relate to material properties and mechanical design, but it is also somewhat awkward, since they have the same units and many books use the same symbol for both.

Strength is a property of a material—it is a measure of the ability of a material to withstand stress or it is the load-carrying capacity of a material. The numerical value of strength is determined by dividing the appropriate load (yield, maximum, fracture, shear, cyclic, creep, etc.) by the original cross-sectional area of the specimen and is designated as S . Thus

$$S = \frac{L}{A_0} \quad (32.8)$$

The subscripts y , u , f , and s are appended to S to denote yield, ultimate, fracture, and shear strength, respectively. Although the strength values obtained from a tensile test have the units of stress [psi (Pa) or equivalent], they are not really values of stress.

Stress is a condition of a material due to an applied load. If there are no loads on a part, then there are no stresses in it. (Residual stresses may be considered as being caused by unseen loads.) The numerical value of the stress is determined by dividing the actual load or force on the part by the actual cross section that is supporting the load. Normal stresses are almost universally designated by the symbol σ , and the stresses due to tensile loads are determined from the expression

$$\sigma = \frac{L}{A_i} \quad (32.9)$$

where A_i = instantaneous cross-sectional area corresponding to that particular load. The units of stress are pounds per square inch (pascals) or an equivalent.

During a tensile test, the stress varies from zero at the very beginning to a maximum value that is equal to the true fracture stress, with an infinite number of stresses in between. However, the tensile test gives only three values of strength: yield, ultimate, and fracture. An appreciation of the real differences between strength and stress will be achieved after reading the material that follows on the use of tensile-test data.

32.9.1 Engineering Stress-Strain

Traditionally, the tensile test has been used to determine the so-called engineering stress-strain data that are needed to plot the engineering stress-strain curve for a given material. However, since engineering stress is not really a stress but is a mea-

sure of the strength of a material, it is more appropriate to call such data either *strength–nominal strain* or *nominal stress–strain data*. Table 32.3 illustrates the data that are normally collected during a tensile test, and Fig. 32.14 shows the condition of a standard tensile specimen at the time the specific data in the table are recorded. The load-versus-gauge-length data, or an elastic stress-strain curve drawn by the machine, are needed to determine Young's modulus of elasticity of the material as well as the proportional limit. They are also needed to determine the yield strength if the offset method is used. All the definitions associated with engineering stress-strain, or, more appropriately, with the strength–nominal strain properties, are presented in the section which follows and are discussed in conjunction with the experimental data for commercially pure titanium listed in Table 32.3 and Fig. 32.14.

The elastic and elastic-plastic data listed in Table 32.3 are plotted in Fig. 32.15 with an expanded strain axis, which is necessary for the determination of the yield strength. The nominal (approximate) stress or the strength S which is calculated by means of Eq. (32.8) is plotted as the ordinate.

The abscissa of the engineering stress-strain plot is the *nominal strain*, which is defined as the unit elongation obtained when the change in length is divided by the original length and has the units of inch per inch and is designated as n . Thus, for tension,

$$n = \frac{\Delta \ell}{\ell} = \frac{\ell_f - \ell_0}{\ell_0} \quad (32.10)$$

where ℓ = gauge length and the subscripts 0 and f designate the original and final state, respectively. This equation is valid for deformation strains that do not exceed the strain at the maximum load of a tensile specimen.

It is customary to plot the data obtained from a tensile test as a stress-strain curve such as that illustrated in Fig. 32.16, but without including the word *nominal*. The reader then considers such a curve as an actual stress-strain curve, which it obviously is not. The curve plotted in Fig. 32.16 is in reality a load-deformation curve. If the ordinate axis were labeled load (lb) rather than stress (psi), the distinction between

TABLE 32.3 Tensile Test Data.

Material: A40 titanium; condition: annealed; specimen size: 0.505-in diameter by 2-in gauge length; $A_0 = 0.200 \text{ in}^2$

Yield load 9 040 lb		Yield strength 45.2 kpsi	
Maximum load 14 950 lb		Tensile strength 74.75 kpsi	
Fracture load 11 500 lb		Fracture strength 57.5 kpsi	
Final length 2.480 in		Elongation 24%	
Final diameter 0.352 in		Reduction of area 51.15%	
Load, lb	Gauge length, in	Load, lb	Gauge length, in
1 000	2.0006	6 000	2.0044
2 000	2.0012	7 000	2.0057
3 000	2.0018	8 000	2.0070
4 000	2.0024	9 000	2.0094
5 000	2.0035	10 000	2.0140

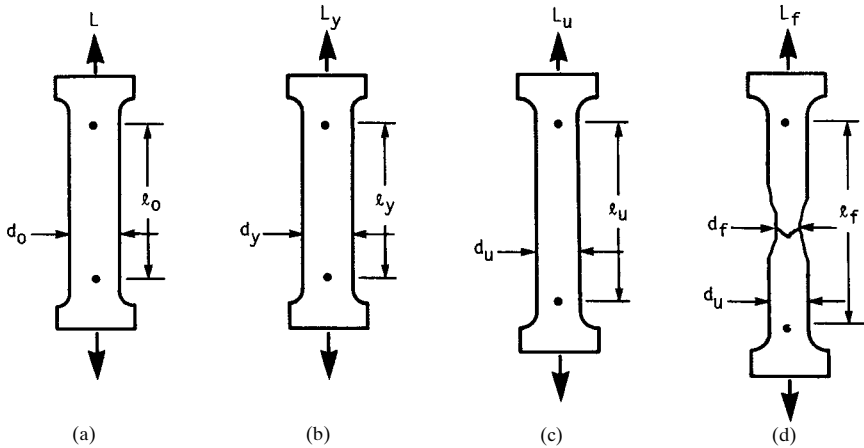


FIGURE 32.14 A standard tensile specimen of A40 titanium at various stages of loading. (a) Unloaded, $L = 0$ lb, $d_0 = 0.505$ in, $l_0 = 2.000$ in, $A_0 = 0.200$ in²; (b) yield load $L_y = 9040$ lb, $d_y = 0.504$ in, $l_y = 2.009$ in, $A_y = 0.1995$ in²; (c) maximum load $L_u = 14\,950$ lb, $d_u = 0.470$ in, $l_u = 2.310$ in, $A_u = 0.173$ in²; (d) fracture load $L_f = 11\,500$ lb, $d_f = 0.352$ in, $l_f = 2.480$ in, $A_f = 0.097$ in², $d_u = 0.470$ in.

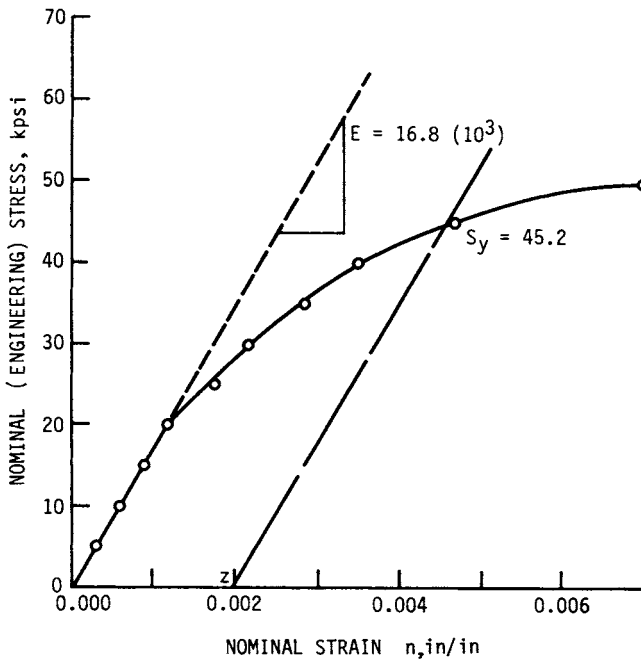


FIGURE 32.15 The elastic-plastic portion of the engineering stress-strain curve for annealed A40 titanium.

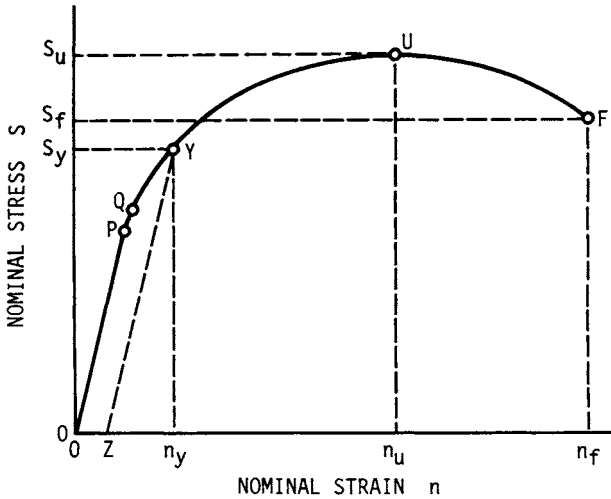


FIGURE 32.16 The engineering stress-strain curve. P = proportional limit, Q = elastic limit, Y = yield load, U = ultimate (maximum) load, and F = fracture load.

strength and stress would be easier to make. Although the fracture load is lower than the ultimate load, the stress in the material just prior to fracture is much greater than the stress at the time the ultimate load is on the specimen.

32.9.2 True Stress-Strain

The tensile test is also used to obtain true stress-strain or true stress–natural strain data to define the plastic stress-strain characteristics of a material. In this case it is necessary to record simultaneously the cross-sectional area of the specimen and the load on it. For round sections it is sufficient to measure the diameter for each load recorded. The load-deformation data in the plastic region of the tensile test of an annealed titanium are listed in Table 32.4. These data are a continuation of the tensile test in which the elastic data are given in Table 32.3.

The load-diameter data in Table 32.4 are recorded during the test and the remainder of the table is completed afterwards. The values of stress are calculated by means of Eq. (32.9). The strain in this case is the *natural strain* or *logarithmic strain*, which is the sum of all the infinitesimal nominal strains, that is,

$$\begin{aligned}\epsilon &= \frac{\Delta \ell_1}{\ell_0} + \frac{\Delta \ell_2}{\ell_0 + \Delta \ell_1} + \frac{\Delta \ell_3}{\ell_0 + \Delta \ell_1 + \Delta \ell_2} + \dots \\ &= \ln \frac{\ell_f}{\ell_0}\end{aligned}\quad (32.11)$$

The volume of material remains constant during plastic deformation. That is,

$$V_0 = V_f \quad \text{or} \quad A_0 \ell_0 = A_f \ell_f$$

TABLE 32.4 Tensile Test Data†

Load, lb	Diameter, in	Area, in ²	Area ratio	Stress, kpsi	Strain, in/in
12 000	0.501	0.197	1.015	60.9	0.0149
14 000	0.493	0.191	1.048	73.5	0.0473
14 500	0.486	0.186	1.075	78.0	0.0724
14 950	0.470	0.173	1.155	86.5	0.144
14 500	0.442	0.153	1.308	94.8	0.268
14 000	0.425	0.142	1.410	99.4	0.344
11 500	0.352	0.097	2.06	119.0	0.729

†This table is a continuation of Table 32.3.

Thus, for tensile deformation, Eq. (32.11) can be expressed as

$$\epsilon = \ln \frac{A_0}{A_f} \quad (32.12)$$

Quite frequently, in calculating the strength or the ductility of a cold-worked material, it is necessary to determine the value of the strain ϵ that is equivalent to the amount of the cold work. The *amount of cold work* is defined as the percent reduction of cross-sectional area (or simply the percent reduction of area) that is given the material by a plastic-deformation process. It is designated by the symbol W and is determined from the expression

$$W = \frac{A_0 - A_f}{A_0} (100) \quad (32.13)$$

where the subscripts 0 and f refer to the original and the final area, respectively. By solving for the A_0/A_f ratio and substituting into Eq. (32.12), the appropriate relationship between strain and cold work is found to be

$$\epsilon_w = \ln \frac{100}{100 - W} \quad (32.14)$$

The stress-strain data of Table 32.4 are plotted in Fig. 32.17 on cartesian coordinates. The most significant difference between the shape of this stress-strain curve and that of the load-deformation curve in Fig. 32.16 is the fact that the stress continues to rise until fracture occurs and does not reach a maximum value as the load-deformation curve does. As can be seen in Table 32.4 and Fig. 32.17, the stress at the time of the maximum load is 86 kpsi, and it increases to 119 kpsi at the instant that fracture occurs. A smooth curve can be drawn through the experimental data, but it is not a straight line, and consequently many experimental points are necessary to accurately determine the shape and position of the curve.

The stress-strain data obtained from the tensile test of the annealed A40 titanium listed in Tables 32.3 and 32.4 are plotted on logarithmic coordinates in Fig. 32.18. The elastic portion of the stress-strain curve is also a straight line on logarithmic coordinates as it is on cartesian coordinates. When plotted on cartesian coordinates, the slope of the elastic modulus is different for the different materials. However, when

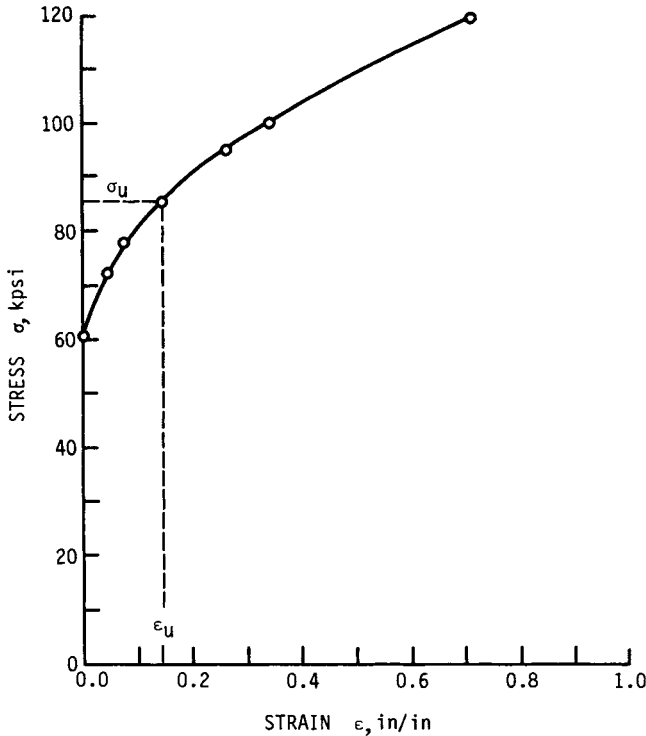


FIGURE 32.17 Stress-strain curve for annealed A40 titanium. The strain is the natural or logarithmic strain and the data of Tables 32.3 and 32.4 are plotted on cartesian coordinates.

plotted on logarithmic coordinates, the slope of the elastic modulus is 1 (unity) for all materials—it is only the height, or position, of the line that is different for different materials. In other words, the elastic moduli for all the materials are parallel lines making an angle of 45° with the ordinate axis.

The experimental points in Fig. 32.18 for strains greater than 0.01 (1 percent plastic deformation) also fall on a straight line having a slope of 0.14. The slope of the stress-strain curve in logarithmic coordinates is called the *strain-strengthening exponent* because it indicates the increase in strength that results from plastic strain. It is sometimes referred to as the *strain-hardening exponent*, which is somewhat misleading because the real strain-hardening exponent is the Meyer exponent p , discussed previously under the subject of strain hardening. The strain-strengthening exponent is represented by the symbol m .

The equation for the plastic stress-strain line is

$$\sigma = \sigma_0 \epsilon^m \quad (32.15)$$

and is known as the *strain-strengthening equation* because it is directly related to the yield strength. The proportionality constant σ_0 is called the *strength coefficient*. The strength coefficient σ_0 is related to the plastic behavior of a material in exactly

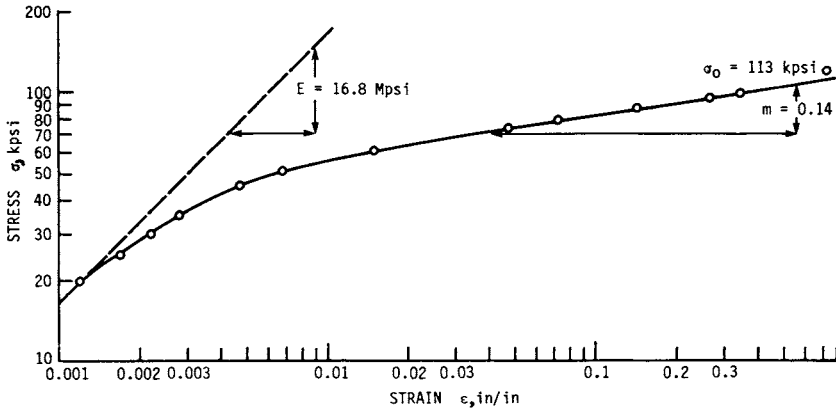


FIGURE 32.18 Stress-strain curve for annealed A40 titanium plotted on logarithmic coordinates. The data are the same as in Fig. 32.17.

the same manner in which Young's modulus E is related to elastic behavior. Young's modulus E is the value of stress associated with an elastic strain of unity; the strength coefficient σ_0 is the value of stress associated with a plastic strain of unity. The amount of cold work necessary to give a strain of unity is determined from Eq. (32.14) to be 63.3 percent.

For most materials there is an elastic-plastic region between the two straight lines of the fully elastic and fully plastic portions of the stress-strain curve. A material that has no elastic-plastic region may be considered an "ideal" material because the study and analysis of its tensile properties are simpler. Such a material has a complete stress-strain relationship that can be characterized by two intersecting straight lines, one for the elastic region and one for the plastic region. Such a material would have a stress-strain curve similar to the one labeled *I* in Fig. 32.19. A few real materials have a stress-strain curve that approximates the "ideal" curve. However, most engineering materials have a stress-strain curve that resembles curve *O* in Fig. 32.19. These materials appear to "overyield"; that is, they have a higher yield strength than the "ideal" value, followed by a region of low or no strain strengthening before the fully plastic region begins. Among the materials that have this type of curve are steel, stainless steel, copper, brass alloys, nickel alloys, and cobalt alloys.

Only a few materials have a stress-strain curve similar to that labeled *U* in Fig. 32.19. The characteristic feature of this type of material is that it appears to "underyield"; that is, it has a yield strength that is lower than the "ideal" value. Some of the fully annealed aluminum alloys have this type of curve.

32.10 TENSILE PROPERTIES

Tensile properties are those mechanical properties obtained from the tension test; they are used as the basis of mechanical design of structural components more frequently than any other of the mechanical properties. More tensile data are available for materials than any other type of material property data. Frequently the design engineer must base his or her calculations on the tensile properties even under

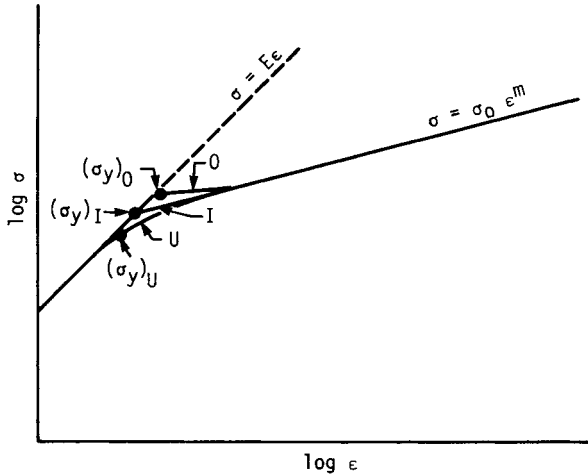


FIGURE 32.19 Schematic representation of three types of stress-strain curves. *I* is an “ideal” curve, and *O* and *U* are two types of real curve.

cyclic, shear, or impact loading simply because the more appropriate mechanical property data are not available for the material he or she may be considering for a specific part. All the tensile properties are defined in this section and are briefly discussed on the basis of the tensile test described in the preceding section.

32.10.1 Modulus of Elasticity

The *modulus of elasticity*, or *Young’s modulus*, is the ratio of stress to the corresponding strain during elastic deformation. It is the slope of the straight-line (elastic) portion of the stress-strain curve when drawn on cartesian coordinates. It is also known, as indicated previously, as Young’s modulus, or the proportionality constant in Hooke’s law, and is commonly designated as *E* with units of pounds per square inch (pascals) or the equivalent. The modulus of elasticity of the titanium alloy whose tensile data are reported in Table 32.3 is shown in Fig. 32.15, where the first four experimental data points fall on a straight line having a slope of 16.8 Mpsi.

32.10.2 Proportional Limit

The *proportional limit* is the greatest stress which a material is capable of developing without any deviation from a linear proportionality of stress to strain. It is the point where a straight line drawn through the experimental data points in the elastic region first departs from the actual stress-strain curve. Point *P* in Fig. 32.16 is the proportional limit (20 kpsi) for this titanium alloy. The proportional limit is very seldom used in engineering specifications because it depends so much on the sensitivity and accuracy of the testing equipment and the person plotting the data.

32.10.3 Elastic Limit

The *elastic limit* is the greatest stress which a material is capable of withstanding without any permanent deformation after removal of the load. It is designated as point Q in Fig. 32.16. The elastic limit is also very seldom used in engineering specifications because of the complex testing procedure of many successive loadings and unloadings that is necessary for its determination.

32.10.4 Yield Strength

The *yield strength* is the nominal stress at which a material undergoes a specified permanent deformation. There are several methods to determine the yield strength, but the most reliable and consistent method is called the *offset method*. This approach requires that the nominal stress-strain diagram be first drawn on cartesian coordinates. A point z is placed along the strain axis at a specified distance from the origin, as shown in Figs. 32.15 and 32.16. A line parallel to the elastic modulus is drawn from Z until it intersects the nominal stress-strain curve. The value of stress corresponding to this intersection is called the *yield strength* by the offset method. The distance OZ is called the *offset* and is expressed as percent. The most common offset is 0.2 percent, which corresponds to a nominal strain of 0.002 in/in. This is the value of offset used in Fig. 32.15 to determine the yield strength of the A40 titanium. An offset of 0.01 percent is sometimes used, and the corresponding nominal stress is called the *proof strength*, which is a value very close to the proportional limit. For some nonferrous materials an offset of 0.5 percent is used to determine the yield strength.

Inasmuch as all methods of determining the yield strength give somewhat different values for the same material, it is important to specify what method, or what offset, was used in conducting the test.

32.10.5 Tensile Strength

The *tensile strength* is the value of nominal stress obtained when the maximum (or ultimate) load that the tensile specimen supports is divided by the original cross-sectional area of the specimen. It is shown as S_u in Fig. 32.16 and is sometimes called the *ultimate strength*. The tensile strength is a commonly used property in engineering calculations even though the yield strength is a measure of when plastic deformation begins for a given material. The real significance of the tensile strength as a material property is that it indicates what maximum load a given part can carry in uniaxial tension without breaking. It determines the absolute maximum limit of load that a part can support.

32.10.6 Fracture Strength

The *fracture strength*, or *breaking strength*, is the value of nominal stress obtained when the load carried by a tensile specimen at the time of fracture is divided by its original cross-sectional area. The breaking strength is not used as a material property in mechanical design.

32.10.7 Reduction of Area

The *reduction of area* is the maximum change in area of a tensile specimen divided by the original area and is usually expressed as a percent. It is designated as A_r and is calculated as follows:

$$A_r = \frac{A_0 - A_f}{A_0} (100) \quad (32.16)$$

where the subscripts 0 and f refer to the original area and area after fracture, respectively. The percent reduction of area and the strain at ultimate load ϵ_u are the best measure of the ductility of a material.

32.10.8 Fracture Strain

The *fracture strain* is the true strain at fracture of the tensile specimen. It is represented by the symbol ϵ_f and is calculated from the definition of strain as given in Eq. (32.12). If the percent reduction of area A_r is known for a material, the fracture strain can be calculated from the expression

$$\epsilon_f = \ln \frac{100}{100 - A_r} \quad (32.17)$$

32.10.9 Percentage Elongation

The *percentage elongation* is a crude measure of the ductility of a material and is obtained when the change in gauge length of a fractured tensile specimen is divided by the original gauge length and expressed as percent. Because of the ductility relationship, we express it here as

$$D_e = \frac{\ell_f - \ell_0}{\ell_0} (100) \quad (32.18)$$

Since most materials exhibit nonuniform deformation before fracture occurs on a tensile test, the percentage elongation is some kind of an average value and as such cannot be used in meaningful engineering calculations.

The percentage elongation is not really a material property, but rather it is a combination of a material property and a test condition. A true material property is not significantly affected by the size of the specimen. Thus a ¼-in-diameter and a ½-in-diameter tensile specimen of the same material give the same values for yield strength, tensile strength, reduction of area or fracture strain, modulus of elasticity, strain-strengthening exponent, and strength coefficient, but a 1-in gauge-length specimen and a 2-in gauge-length specimen of the same material do not give the same percentage elongation. In fact, the percentage elongation for a 1-in gauge-length specimen may actually be 100 percent greater than that for the 2-in gauge-length specimen even when they are of the same diameter.

32.11 STRENGTH, STRESS, AND STRAIN RELATIONS

The following relationships between strength, stress, and strain are very helpful to a complete understanding of tensile properties and also to an understanding of their use in specifying the optimum material for a structural part. These relationships also help in solving manufacturing problems where difficulty is encountered in the fabrication of a given part because they enable one to have a better concept of what can be expected of a material during a manufacturing process. A further advantage of these relations is that they enable an engineer to more readily determine the mechanical properties of a fabricated part on the basis of the original properties of the material and the mechanisms involved with the particular process used.

32.11.1 Natural and Nominal Strain

The relationship between these two strains is determined from their definitions. The expression for the natural strain is $\epsilon = \ln (\ell_f/\ell_0)$. The expression for the nominal strain can be rewritten as $\ell_f/\ell_0 = n + 1$. When the latter is substituted into the former, the relationship between the two strains can be expressed in the two forms

$$\epsilon = \ln (n + 1) \quad \exp (\epsilon) = n + 1 \quad (32.19)$$

32.11.2 True and Nominal Stress

The definition of true stress is $\sigma = L/A_i$. From constancy of volume it is found that $A_i = A_0(\ell_0/\ell_i)$, so that

$$\sigma = \frac{L}{A_0} \left(\frac{\ell_i}{\ell_0} \right)$$

which is the same as

$$\sigma = \begin{cases} S(n + 1) \\ S \exp (\epsilon) \end{cases} \quad (32.20)$$

32.11.3 Strain-Strengthening Exponent and Maximum-Load Strain

One of the more useful of the strength-stress-strain relationships is the one between the strain-strengthening exponent and the strain at maximum load. It is also the simplest, since the two are numerically equal; that is, $m = \epsilon_u$. This relation is derived on the basis of the load-deformation curve shown in Fig. 32.20. The load at any point along this curve is equal to the product of the true stress on the specimen and the corresponding area. Thus

$$L = \sigma A$$

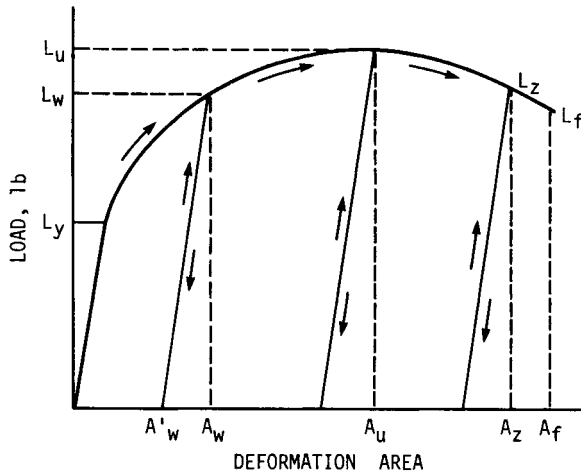


FIGURE 32.20 A typical load-deformation curve showing unloading and reloading cycles.

Now, since

$$\sigma = \sigma_0 \epsilon^m$$

and

$$\epsilon = \ln \frac{A_0}{A} \quad \text{or} \quad A = \frac{A_0}{\exp(\epsilon)}$$

the load-strain relationship can be written as

$$L = \sigma_0 A_0 \epsilon^m \exp(-\epsilon)$$

The load-deformation curve shown in Fig. 32.20 has a maximum, or zero-slope, point on it. Differentiating the last equation and equating the result to zero gives the simple expression $\epsilon = m$. Since this is the strain at the ultimate load, the expression can be written as

$$\epsilon_u = m \quad (32.21)$$

32.11.4 Yield Strength and Percent Cold Work

The stress-strain characteristics of a material obtained from a tensile test are shown in Fig. 32.18. In the region of plastic deformation, the relationship between stress and strain for most materials can be approximated by the equation $\sigma = \sigma_0 \epsilon^m$. When a load is applied to a tensile specimen that causes a given amount of cold work W (which is a plastic strain of ϵ_w), the stress on the specimen at the time is σ_w and is defined as

$$\sigma_w = \sigma_0(\epsilon_w)^m \quad (32.22)$$

Of course, σ_w is also equal to the applied load L_w divided by the actual cross-sectional area of the specimen A_w .

If the preceding tensile specimen were immediately unloaded after reading L_w , the cross-sectional area would increase to A'_w from A_w because of the elastic recovery or springback that occurs when the load is removed. This elastic recovery is insignificant for engineering calculations with regard to the strength or stresses on a part.

If the tensile specimen that has been stretched to a cross-sectional area of A'_w is now reloaded, it will deform elastically until the load L_w is approached. As the load is increased above L_w , the specimen will again deform plastically. This unloading-reloading cycle is shown graphically in Fig. 32.20. The yield load for this previously cold-worked specimen before the reloading is A'_w . Therefore, the yield strength of the previously cold-worked (stretched) specimen is approximately

$$(S_y)_w = \frac{L_w}{A'_w}$$

But since $A'_w = A_w$, then

$$(S_y)_w = \frac{L_w}{A_w}$$

By comparing the preceding equations, it is apparent that

$$(S_y)_w \cong \sigma_w$$

And by substituting this last relationship into Eq. (32.22), we get

$$(S_y)_w = \sigma_0(\epsilon_w)^m \quad (32.23)$$

Thus it is apparent that *the plastic portion of the $\sigma - \epsilon$ curve is approximately the locus of yield strengths for a material as a function of the amount of cold work*. This relationship is valid only for the axial tensile yield strength after tensile deformation or for the axial compressive yield strength after axial deformation.

32.11.5 Tensile Strength and Cold Work

It is believed by materials and mechanical-design engineers that the only relationships between the tensile strength of a cold-worked material and the amount of cold work given it are the experimentally determined tables and graphs that are provided by the material manufacturers and that the results are different for each family of materials. However, on the basis of the concepts of the tensile test presented here, two relations are derived in Ref. [32.1] between tensile strength and percent cold work that are valid when the prior cold work is tensile. These relations are derived on the basis of the load-deformation characteristics of a material as represented in Fig. 32.20. This model is valid for all metals that do not strain age.

Here we designate the tensile strength of a cold-worked material as $(S_u)_w$, and we are interested in obtaining the relationship to the percent cold work W . For any

specimen that is given a tensile deformation such that A_W is equal to or less than A_u , we have, by definition, that

$$(S_u)_W = \frac{L_u}{A'_W}$$

And also, by definition,

$$L_u = A_0(S_u)_0$$

where $(S_u)_0$ = tensile strength of the original non-cold-worked specimen and A_0 = its original area.

The percent cold work associated with the deformation of the specimen from A_0 to A'_W is

$$W = \frac{A_0 - A'_W}{A_0} (100) \quad \text{or} \quad w = \frac{A_0 - A'_W}{A_0}$$

where $w = W/100$. Thus

$$A'_W = A_0(1 - w)$$

By substitution into the first equation,

$$(S_u)_W = \frac{A_0(S_u)_0}{A_0(1 - w)} = \frac{(S_u)_0}{1 - w} \quad (32.24)$$

Of course, this expression can also be expressed in the form

$$(S_u)_W = (S_u)_0 \exp(\epsilon) \quad (32.25)$$

Thus *the tensile strength of a material that is prestrained in tension to a strain less than its ultimate load strain is equal to its original tensile strength divided by 1 minus the fraction of cold work*. This relationship is valid for deformations less than the deformation associated with the ultimate load, that is, for

$$A_W \leq A_u \quad \text{or} \quad \epsilon_W \leq \epsilon_u$$

Another relationship can be derived for the tensile strength of a material that has been previously cold-worked in tension by an amount greater than the deformation associated with the ultimate load. This analysis is again made on the basis of Fig. 32.20. Consider another standard tensile specimen of 1020 steel that is loaded beyond L_u (12 000 lb) to some load L_z , say, 10 000 lb. If dead weights were placed on the end of the specimen, it would break catastrophically when the 12 000-lb load was applied. But if the load had been applied by means of a mechanical screw or a hydraulic pump, then the load would drop off slowly as the specimen is stretched. For this particular example the load is considered to be removed instantly when it drops to L_z or 10 000 lb. The unloaded specimen is not broken, although it may have a “necked” region, and it has a minimum cross-sectional area $A_z = 0.100 \text{ in}^2$ and a diameter of 0.358 in. Now when this same specimen is again loaded in tension, it

deforms elastically until the load reaches L_z (10 000 lb) and then it deforms plastically. But L_z is also the maximum value of load that this specimen reaches on reloading. It never again will support a load of $L_u = 12\,000$ lb. On this basis, the yield strength of this specimen is

$$(S_y)_w = \frac{L_z}{A'_z} = \frac{10\,000}{0.101} = 99\,200 \text{ psi}$$

And the tensile strength of this previously deformed specimen is

$$(S_u)_w = \frac{L_z}{A_z} = \frac{10\,000}{0.101} = 99\,200 \text{ psi}$$

32.11.6 Ratio of Tensile Strength to Brinell Hardness

It is commonly known by mechanical-design engineers that the tensile strength of a steel can be estimated by multiplying its Brinell hardness number by 500. As stated earlier, this fact led to the wide acceptance of the Brinell hardness scale. However, this ratio is not 500 for all materials—it varies from as low as 450 to as high as 1000 for the commonly used metals. The ratio of the tensile strength of a material to its Brinell hardness number is identified by the symbol K_B , and it is a function of both the load used to determine the hardness and the strain-strengthening exponent of the material.

Since the Brinell hardness number of a given material is not a constant but varies in proportion to the applied load, it then follows that the proportionality coefficient K_B is not a constant for a given material, but it too varies in proportion to the load used in determining the hardness. For example, a 50 percent cobalt alloy (L605 or HS25) has a Brinell hardness number of 201 when tested with a 3000-kg load and a hardness of only 150 when tested with a 500-kg load. Since the tensile strength is about 145 000 psi for this annealed alloy, the value for K_B is about 970 for the low load and about 730 for the high load.

Since the material is subjected to considerable plastic deformation when both the tensile strength and the Brinell hardness are measured, these two values are influenced by the strain-strengthening exponent m for the material. Therefore, K_B must also be a function of m .

Figure 32.21 is a plot of experimental data obtained by this author over a number of years that shows the relationships between the ratio K_B and the two variables strain-strengthening exponent m and diameter of the indentation, which is a function of the applied load. From these curves it is apparent that K_B varies directly with m and inversely with the load or diameter of the indentation d . The following examples will illustrate the applicability of these curves.

A test was conducted on a heat of alpha brass to see how accurately the tensile strength of a material could be predicted from a hardness test when the strain-strengthening exponent of the material is not known. Loads varying from 200 to 2000 kg were applied to a 10-mm ball, with the following results:

Load, kg	200	500	1000	1500	2000
Diameter, mm	2.53	3.65	4.82	5.68	6.30

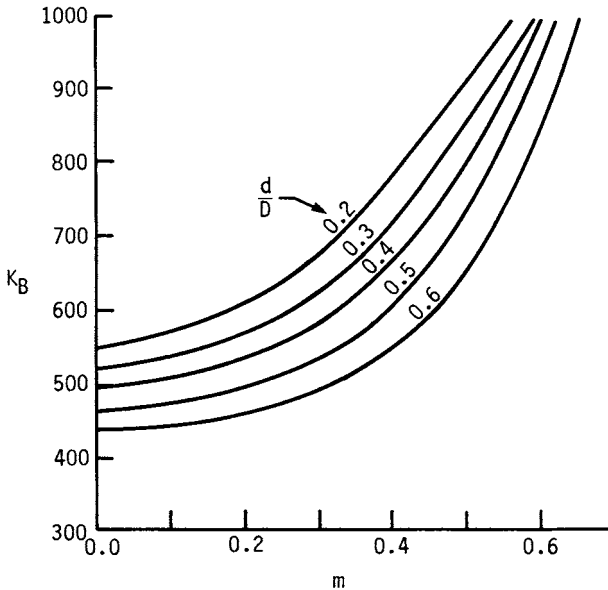


FIGURE 32.21 Relationships between the S_u/H_B ratio (K_B) and the strain-strengthening exponent m . D = diameter of the ball, and d = diameter of the indentation. Data are based on experimental results obtained by the author.

When plotted on log-log paper, these data fall on a straight line having a slope of 2.53, which is the Meyer strain-hardening exponent n . The equation for this straight line is

$$L = 18.8d^{2.53}$$

Since, for some metals, $m = n - 2$, the value of m is 0.53.

For ease in interpreting Fig. 32.21, the load corresponding to an indentation of 3 mm is calculated from Eq. (32.2) as 43. K_B can now be determined from Fig. 32.21 as 890. Thus the tensile strength is $S_u = K_B H_B = 890(43) = 38\,300$ psi. In a similar fashion, the load for a 5-mm diameter is 110 kg, and the corresponding Brinell hardness number is 53. From Fig. 32.21, the value of K_B is found to be 780, and the tensile strength is estimated as $S_u = K_B H_B = 780(53) = 41\,300$ psi. The average value of these two calculated tensile strengths is 39 800 psi. The experimentally determined value of the tensile strength for this brass was 40 500 psi, which is just 2 percent lower than the predicted value.

As another example, consider the estimation of tensile strength for a material when its typical strain-strengthening exponent is known. Annealed 3003 aluminum has an average m value of 0.28. What is the tensile strength of a heat that has a Brinell hardness number of 28 when measured with a 500-kg load? The diameter of the indentation for this hardness number is 4.65. Then from Fig. 32.21 the value of K_B is determined as 535. The tensile strength can then be calculated as $S_u = K_B H_B = 535(28) = 15\,000$ psi.

32.12 IMPACT STRENGTH

In some cases a structural part is subject to a single, large, suddenly applied load. A standard test has been devised to evaluate the ability of a material to absorb the impact energy through plastic deformation. The test can be described as a technological one, like the Rockwell hardness test, rather than as a scientific one. The values obtained by the impact test are relative rather than absolute. They serve as a basis of comparison and specification of the toughness of a material.

The *impact strength* is the energy, expressed in footpounds, required to fracture a standard specimen with a single-impact blow. The impact strength of a material is frequently referred to as being a measure of the toughness of the material, that is, its ability to absorb energy. The area under the tensile stress-strain curve is also a measure of the ability of a material to absorb energy (its toughness). Unfortunately, there is only a very general relationship between these two different measures of toughness; namely, if the material has a large area under its tensile stress-strain curve, it also has a relatively high impact strength.

Most impact-strength data are obtained with the two types of notched specimens shown in Fig. 32.22. Figure 32.22*a* illustrates the Charpy V-notch specimen as well as how the impact load is applied. Figure 32.22*b* does the same for the Izod V-notch specimen, and the details of the notch are shown in Fig. 32.22*c*. There are several modifications of the standard V-notch specimen. One is called the *keyhole notch* and another the *U-notch*. Both have a 1-mm radius at the bottom rather than the 0.25-mm radius of the V-notch. There is no correlation between the various types of notch-bar impact-strength values. However, the Charpy V-notch impact-strength value is considerably greater than the Izod V-notch value, particularly in the high toughness range.

The impact-testing machine consists of a special base mounted on the floor to support the specimen and a striking hammer that swings through an arc of about 32-in radius, much like a pendulum. When the hammer is “cocked” (raised to a locked elevation), it has a potential energy that varies between 25 and 250 ft · lb, depending on the mass of the hammer and the height to which it is raised. When the hammer is released and allowed to strike the specimen, a dial registers the energy that was absorbed by the specimen. The standards specify that the striking velocity must be in the range of 10 to 20 ft/s because velocities outside this range have an effect on the impact strength.

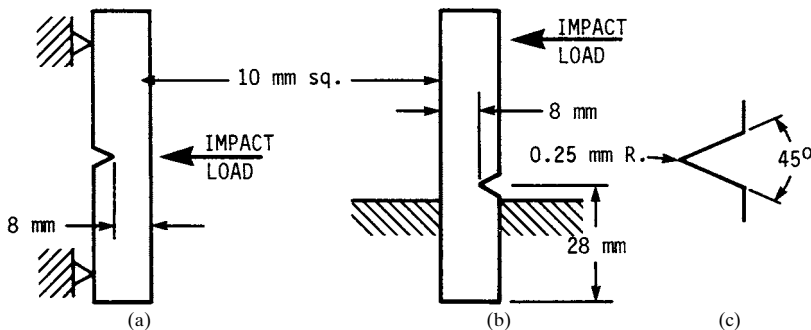


FIGURE 32.22 Impact tests and specimens. (a) Charpy $L = 55$ mm; (b) Izod $L = 75$ mm; (c) details of the notch.

The impact strengths of some materials, particularly steel, vary significantly with the testing temperature. Figure 32.23 shows this variation for a normalized AISI 1030 steel. At the low testing temperature the fracture is of the cleavage type, which has a bright, faceted appearance. At the higher temperatures the fractures are of the shear type, which has a fibrous appearance. The *transition temperature* is that temperature that results in 50 percent cleavage fracture and 50 percent shear fracture, or it may be defined as the temperature at which the impact strength shows a marked drop. The *nil-ductility temperature* is the highest temperature at which the impact strength starts to increase above its minimum value. These two temperatures are shown in Fig. 32.23.

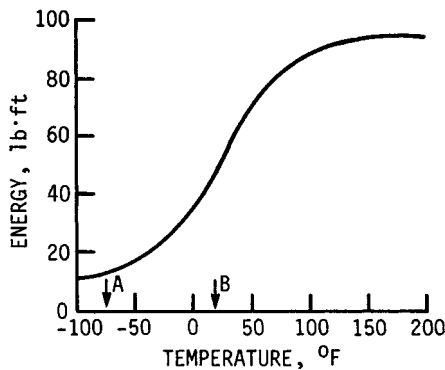


FIGURE 32.23 Charpy V-notch impact strength of 1030 steel versus temperature. *A* = nil-ductility temperature; *B* = transition temperature.

32.13 CREEP STRENGTH

A part may fail with a load that induced stresses in it that lie between the yield strength and the tensile strength of the material even if the load is steady and constant rather than alternating and repeating as in a fatigue failure. This type of constant loading causes the part to elongate or creep. The failure point may be when the part stretches to some specified length, or it may be when the part completely fractures.

The *creep strength* of a material is the value of nominal stress that will result in a specified amount of elongation at a specific temperature in a given length of time. It is also defined as the value of nominal stress that induces a specified creep rate at a specific temperature. The creep strength is sometimes called the *creep limit*. The *creep rate* is the slope of the strain-time creep curve in the steady-creep region, referred to as a *stage 2 creep*. It is illustrated in Fig. 32.24.

Most creep failures occur in parts that are exposed to high temperatures rather than room temperature. The stress necessary to cause creep at room temperature is considerably higher than the yield strength of a material. In fact, it is just slightly less than the tensile strength of a material. The stress necessary to induce creep at a temperature that is higher than the recrystallization temperature of a material, however, is very low.

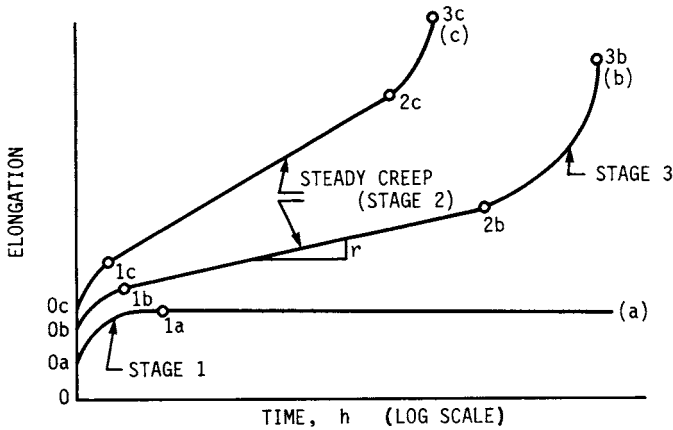


FIGURE 32.24 Creep data plotted on semilog coordinates. (a) Low stress (slightly above S_y) or low temperature (well below recrystallization); (b) moderate stress (midway between S_y and S_u) or moderate temperature (at recrystallization); (c) high stress (slightly below S_u) or high temperature (well above recrystallization). The elastic elongations are designated as $0a$, $0b$, and $0c$.

The specimens used for creep testing are quite similar to round tensile specimens. During the creep test the specimen is loaded with a dead weight that induces the required nominal stress applied throughout the entire test. The specimen is enclosed in a small round tube-type furnace to maintain a constant temperature throughout the test, and the gauge length is measured after various time intervals. Thus the three variables that affect the creep rate of the specimen are (1) nominal stress, (2) temperature, and (3) time.

Figure 32.24 illustrates the most common method of presenting creep-test data. Three different curves are shown. Curve (a) is typical of a creep test conducted at a temperature well below the recrystallization temperature of the material (room temperature for steel) and at a fairly high stress level, slightly above the yield strength. Curve (a) is also typical of a creep test conducted at a temperature near the recrystallization temperature of a material but at a low stress level. Curve (c) is typical of either a high stress level, such as one slightly below S_u , at a low temperature, or else a low stress level at a temperature significantly higher than the recrystallization temperature of the material. Curve (b) illustrates the creep rate at some intermediate combination of stress and temperature.

A creep curve consists of four separate parts, as illustrated with curve (b) in Fig. 32.24. These are explained as follows:

1. An initial elastic extension from the origin 0 to point $0b$.
2. A region of primary creep, frequently referred to as *stage 1 creep*. The extension occurs at a decreasing rate in this portion of the creep curve.
3. A region of secondary creep, frequently called *stage 2 creep*. The extension occurs at a constant rate in this region. Most creep design is based on this portion of the creep curve, since the creep rate is constant and the total extension for a given number of hours of service can be easily calculated.
4. A region of tertiary creep or *stage 3 creep*. The extension occurs at an increasing rate in this region until the material fractures.

Another practical way of presenting creep data is illustrated in Fig. 32.25, which is a log-log plot of nominal stress versus the second-stage creep rate expressed as percent per hour with the temperature as a parameter. Figure 32.26 illustrates still another type of plot that is used to present creep data where both the stress and temperature are drawn on cartesian coordinates.

The mechanism of creep is very complex inasmuch as it involves the movements of vacancies and dislocations, strain hardening, and recrystallization, as well as grain-boundary movements. At low temperatures, creep is restricted by the pile-up of dislocations at the grain boundaries and the resulting strain hardening. But at higher temperatures, the dislocations can climb out of the original slip plane and thus permit further creep. In addition, recrystallization, with its resulting lower strength, permits creep to occur readily at high temperatures.

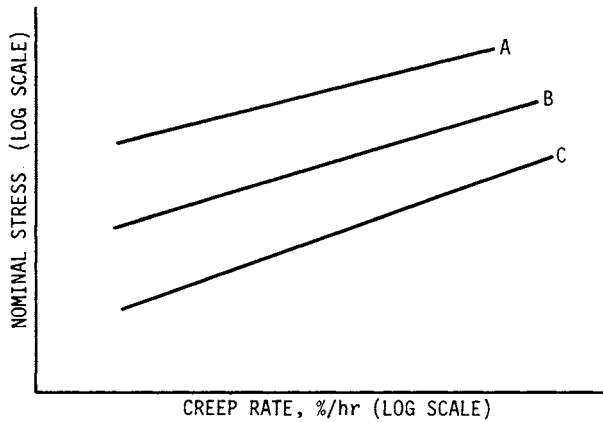


FIGURE 32.25 Second-stage creep rate versus nominal stress. A, B, and C are for low, medium, and high temperatures, respectively.

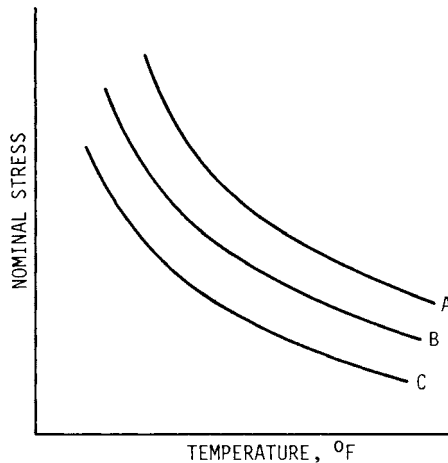


FIGURE 32.26 Second-stage creep rate versus temperature and nominal stress. A, 1%/h creep rate; B, 0.1%/h creep rate; C, 0.001%/h creep rate.

As explained in an earlier section, the grain-boundary material is stronger than the material at the interior portions at low temperatures, but the opposite is true at high temperatures. The temperature where these two portions of the grains are equal is called the *equicohesive temperature*. Consequently, parts that are exposed to high temperatures have lower creep rates if they are originally heat-treated to form coarse grains.

32.14 MECHANICAL-PROPERTY DATA

The number of different combinations of thermal and mechanical treatments for each family of materials plus the large number of individual material compositions within one family makes it impossible to compile a complete listing in one handbook. For more information on the typical values of the mechanical properties of a specific material, you should consult the engineering manuals published by the various material manufacturers as well as the references at the end of this chapter. The total number of pages of mechanical-property data listed in all the sources cited at the end of this chapter runs into the thousands, making it impossible to include it all in one handbook. The mechanical properties are simply listed as the experimentally obtained values for each of the many conditions of a given metal.

This section includes some select mechanical-property data in tabular form for a variety of materials in Table 32.5. Both the format of the data and the actual mechanical properties listed are different from the traditional handbook presentations. There are several advantages to presenting the data in this manner. One of the main advantages is that it requires much less space. For example, as shown in Table 32.5, only five numbers have to be recorded for each metal in its original non-cold-worked condition. These numbers refer to the five primary mechanical properties. From these original values it is very easy to calculate the new strengths of the metal after any specific amount of cold work or to construct tables or graphs of strength versus percent cold work. This is in sharp contrast to the large amount of space required to store the tables or graphs in any handbook or manual of properties.

A second advantage of presenting the data in this manner is that it is possible to make use of the rules and relationships included in Chap. 33 to calculate both the compressive and tensile properties in all directions in a cold-worked part. This is extremely important because for some materials (those having a high strain-strengthening exponent m) it is possible to have a compressive yield strength for a given amount of cold work that is one-half the tensile yield strength that may be tabulated in a materials handbook.

Table 32.6 includes some of the properties of very-high-strength steels. To illustrate the versatility of documenting mechanical properties in the format of Table 32.5, consider the annealed 303 stainless steel listed in the table. In the annealed condition it has the following listed properties: $S_y = 35$ kpsi, $S_u = 87.3$ kpsi, strength coefficient $\sigma_0 = 205$ kpsi, strain-strengthening exponent $m = 0.51$, and fracture strain $\epsilon_f = 1.16$. In an upsetting operation, a 2-in-diameter bar is upset to a diameter of $2\frac{1}{2}$ in for a length of $1\frac{1}{2}$ in prior to having splines machined on the end. Since the splines are cantilevered beams subject to bending stresses in the circumferential or transverse direction, the strength of the material in this direction rather than in the axial or longitudinal direction is required. Also, the stresses are compressive on one side of the splines and tensile on the other. Therefore, the designer should know both the tensile and compressive strengths in the transverse direction. The following sample calculations will demonstrate how this can be done.

TABLE 32.5 Tensile Properties of Some Metals^a

Material	Condition	Strength			Strain- strengthening exponent m	Fracture strain ϵ_f
		Yield S_y , kpsi	Ultimate S_u , kpsi	Coefficient σ_0 , kpsi		
Carbon and alloy steels						
1002	1500°F @ 1 h, A 0.032 in	22.0	39.5	76.0	0.29	1.25
1002 ^a	1800°F @ 1 h, A	19.0	42.0	78.0	0.27	1.25
1008 DQ	As rec'd 0.024 in	25.0	39.0	70.0	0.24	1.20
1008 DQ	As above—trans	27.0	43.0	70.0	0.24	1.10
1008 DQ	1600°F @ 1 h A	26.5	40.0			
1010	0.024-in CD strip	33.2	47.5	84.0	0.23	1.20
1010	As above—trans	36.8	48.5	88.0	0.26	1.00
1010	1600°F @ 1 h A	28.6	44.2	82.0	0.23	1.20
1010	As above—trans	29.1	43.8	82.0	0.23	1.20
1018	A	32.0	49.5	90.0	0.25	1.05
1020	HR	42.0	66.2	115.0	0.22	0.90
1045	HR	60.0	92.5	140.0	0.14	0.58
1144	A	52.0	93.7	144.0	0.14	0.49
1144 ^b	A	50.0	93.7	144.0	0.14	0.05
1212	HR	28.0	61.5	110.0	0.24	0.85
4340	HR	132.0	151.0	210.0	0.09	0.45
52100	Spher. A	80.0	101.0	165.0	0.18	0.58
52100	1500°F A	131.0	167.0	210.0	0.07	0.40
Stainless steels						
18-8	1600°F @ 1 h A	37.0	89.5	210.0	0.51	1.08
18-8	1800°F @ 1 h A	37.5	96.5	230.0	0.53	1.38
302	1800°F @ 1 h A	34.0	92.4	210.0	0.48	1.20
303	A	35.0	87.3	205.0	0.51	1.16
304	A	40.0	82.4	185.0	0.45	1.67
202	1900°F @ 1 h A	55.0	105.0	195.0	0.30	1.00
17-4 PH	1100°F aged	240.0	246.0	260.0	0.01	0.65
17-4 PH	A	135.0	142.0	173.0	0.05	1.20
17-7 PH	1050°F aged	155.0	185.0	225.0	0.05	0.90
17-7 PH	900°F aged	245.0	255.0	300.0	0.04	0.50
440 C	Solution H T	63.5	107.0	153.0	0.11	0.36
440 C	A 1600°F–50°F/h	67.6	117.0	180.0	0.14	0.12
Aluminum alloys						
1100	900°F @ 1 h A	4.5	12.1	22.0	0.25	2.30
3003	800°F @ 1 h A	6.0	15.0	29.0	0.30	1.50
2024 ^c	T-351	52.0	68.8	115.0	0.20	0.37
2024	T-4	43.0	64.8	100.0	0.15	0.18
7075	800°F A	14.3	33.9	61.0	0.22	0.53
7075	T-6	78.6	86.0	128.0	0.13	0.18
2011	800°F @ 1 h A	7.0	25.2	41	0.18	0.35
2011	T-6	24.5	47.0	90	0.28	0.10

TABLE 32.5 Tensile Properties of Some Metals^a (Continued)

Material	Condition	Strength			Strain-strengthening exponent m	Fracture strain ϵ_f
		Yield S_y , kpsi	Ultimate S_u , kpsi	Coefficient σ_0 , kpsi		
Magnesium alloys						
HK31 XA	800°F @ 1 h A	19.0	25.5	49.5	0.22	0.33
HK31 XA	H-24	31.0	36.2	48.0	0.08	0.20
Copper alloys						
ETP Cu	100°F @ 1 h A	4.7	31.0	78.0	0.55	1.19
ETP Cu	1250°F @ 1 h A	4.6	30.6	72.0	0.50	1.21
ETP Cu	1500°F @ 1 h A	4.2	30.0	68.0	0.48	1.26
OFHC Cu	1250°F @ 1 h A	5.3	33.1	67.0	0.35	1.00
90-10 brass	As rec'd ^c	12.8	38.0	85.0	0.43	
90-10 brass	1200°F @ 1 h A	8.4	36.4	83.0	0.46	
90-10 brass	As above, 10% CW, 1200°F A	6.9	35.0	87.0	1.83	
80-20 brass	1200°F @ 1 h A	7.2	35.8	84.0	0.48	
80-20 brass	As above, 10% CW, 1200°F A	6.4	34.6	85.0	0.51	1.83
70-30 brass	1200°F @ 1 h A	12.1	44.8	112.0	0.59	
70-30 brass	As above, 10% CW, 1200°F A	10.7	43.4	107.0	0.59	1.62
70-30 brass ^b	1000°F @ 1 h A	11.5	45.4	110.0	0.56	1.50
70-30 brass ^b	1200°F @ 1 h A	10.5	44.0	105.0	0.52	1.55
70-30 brass ^b	1400°F @ 1 h A	8.8	42.3	105.0	0.60	1.60
70-30 leaded brass	1250°F @ 1 h A	11.0	45.0	105.0	0.50	1.10
Naval brass ^d	1350°F @ $\frac{1}{2}$ h A	17.0	54.5	125.0	0.48	1.00
Naval brass ^d	1350°F @ $\frac{1}{2}$ h WQ	27.0	66.2	135.0	0.37	0.50
Naval brass ^d	850°F @ $\frac{1}{2}$ h A	17.5	56.0	125.0	0.48	0.90
Naval brass ^d	850°F @ $\frac{1}{2}$ h WQ	31.5	64.5	135.0	0.37	0.80
Naval brass ^d	1500°F @ 3 h A	11.0	48.0			0.74
Nickel alloys						
Ni 200	1700°F @ $\frac{1}{4}$ h WQ	16.2	72.1	150.0	0.375	1.805
99.44% Ni	CD, A	20.5	73.7	160.0	0.40	1.47
Monel 400	1700°F @ $\frac{1}{4}$ h WQ	26.5	77.7	157.0	0.337	1.184
Monel K500	1700°F @ $\frac{1}{4}$ h WQ	34.4	92.6	182.0	0.32	1.305
Inconel 600	1700°F @ $\frac{1}{4}$ h WQ	46.6	102.5	201.0	0.315	1.14
Inconel 625	1700°F @ $\frac{1}{2}$ h WQ	77.1	139.7	297.0	0.395	0.75
Inconel 718	1750°F @ 20 min AC	43.6	99.4	205.0	0.363	1.337
Inconel X750	2050°F @ 45 min WQ	36.4	106.4	230.0	0.415	1.27
Incoloy 800	2050°F @ 2 h AC	22.2	77.1	169.0	0.420	1.262
Incoloy 825	1700°F @ 20 min WQ	66.7	138.0	283.0	0.353	0.715
Ni, 2% Be	1800°F sol. T WQ	41.0	104.0	222.0	0.39	1.00

TABLE 32.5 Tensile Properties of Some Metals^a (Continued)

Material	Condition	Strength			Strain-strengthening exponent m	Fracture strain ϵ_f
		Yield S_y , kpsi	Ultimate S_u , kpsi	Coefficient σ_0 , kpsi		
Nickel alloys (Continued)						
Ni, 2% Be	As above + 1070°F @ 2 h aged	140.0	195.0	300.0	0.15	0.18
Ni, 15.8% Cr, 7.2% Fe	A	36.0	90.0	203.0	0.45	0.92
Special alloys						
Cobalt alloy ^f	2250°F solution HT	65.0	129.0	300.0	0.50	0.51
Cobalt alloy ^f	As above—trans ^c	65.0	129.0	300.0	0.50	0.40
Cobalt alloy ^{e,g}	As rec'd, annealed	62.8	119.5	283.0	0.52	0.75
Cobalt alloy ^{e,g}	Machined, 2250°F sol. HT	48.0	112.5	283.0	0.62	0.70
Cobalt alloy ^{e,g}	2250°F sol. HT, 925°F aged	48.0	107.5	270.0	0.63	1.00
Molybdenum	Extr'd A	49.5	70.7	106.0	0.12	0.38
Vanadium	A	45.0	63.0	97.0	0.17	1.10

^aAll values are for longitudinal specimens except as noted. These are values obtained from only one or two heats. The values will vary from heat to heat because of the differences in composition and annealing temperatures. The fracture strain may vary as much as 100 percent.

^b $\frac{3}{4}$ -in-diameter bar.

^cTensile specimen machined from a 4-in-diameter bar transverse to rolling direction.

^dSpecimens cut from $\frac{1}{2}$ -in hot-rolled plate.

^e $\frac{1}{2}$ -in-diameter bar.

^fHS 25 or L 605 alloy; 50 Co, 20 Cr, 15 W, 10 Ni, 3 Fe.

^gElgiloy; 50 Co, 20 Cr, 15 Ni, 7 Mo, 15 Fe.

SOURCE: From Datsko [32.1].

The strain associated with upsetting a 2-in-diameter bar to a 2½-in-diameter can be calculated by means of Eq. (32.12). Thus

$$\epsilon = -\ln \left(\frac{2}{2.5} \right)^2 = 0.45$$

The negative sign in front of the function is needed because Eq. (32.12) is for tensile deformation, whereas in this problem the deformation is axial compression. The equivalent amount of cold work can be calculated from Eq. (32.14) as 36.2 percent.

The axial compressive yield strength can be approximated by means of Eq. (32.23). Thus

$$(S_y)_c = \sigma_0(\epsilon_w)^m = 205(0.45)^{0.51} = 136 \text{ kpsi}$$

If one were to interpolate in a table of yield strength versus cold work in a hand-book, this value of 136 kpsi would be approximately the value that would be

TABLE 32.6 Properties of Some High-Strength Steels

AISI number	Processing ^a	Brinell hardness H_B	Modulus of elasticity E , Mpsi	Yield strength ^b S_y , kpsi	Ultimate strength S_u , kpsi	Reduction in area, %	True fracture strength σ_F , kpsi	True fracture ductility ^c ϵ_F	Strain-strengthening exponent m
1045	Q & T 80°F	705	29	265T ^d 300C ^d	300	2	310T 420C	0.02	0.186
1045	Q & T 360°F	595	30	270	325	41	430/ 395	0.52	0.071
1045	Q & T 500°F	500	30	245	265	51	370/ 330	0.71	0.047
1045	Q & T 600°F	450	30	220	230	55	345/ 305	0.81	0.041
1045	Q & T 720°F	390	30	185	195	59	315/ 270	0.89	0.044
4142	Q & T 80°F	670	29	235T 275C	355	6	375	0.06	0.136
4142	Q & T 400°F	560	30	245	325	27	405/ 385	0.31	0.091
4142	Q & T 600°F	475	30	250	280	35	340/ 315	0.43	0.048
4142	Q & T 700°F	450	30	230	255	42	320/ 290	0.54	0.043
4142	Q & T 840°F	380	30	200	205	48	295/ 265	0.66	0.051
4142 ^e	Q & D 550°F	475	29	275T 225C	295	20	310/ 300	0.22	0.101T 0.060C
4142	Q & D 650°F	450	29	270T 205C	280	37	330/ 305	0.46	0.016T 0.070C
4142	Q & D 800°F	400	29	210T ^f 175C	225	47	305/ 275	0.63	0.032T 0.085C

^aAISI 1045: Cold drawn to $\frac{1}{8}$ -in rounds from hot-rolled rod. Austenized 1500°F (oxidizing atmosphere) 20 min, water quenched at 70°F. AISI 4142: Cold-drawn to $\frac{1}{8}$ -in rounds from annealed rod. Austenized at 1500°F (neutral atmosphere), quenched in agitated oil at 180°F. AISI 4142 Def: Austenized at 1500°F, oil quenched. Reheated in molten lead, drawn 14 percent through die at reheating temperature to $\frac{1}{8}$ -in rods.

^b0.2 percent offset method.

^cBridgman's correction for necking.

^dT, tension; C, compression.

^eDeformed 14 percent.

^fProportional limit in tension.

SOURCE: Data from R. W. Landgraf, *Cyclic Deformation and Fatigue Behavior of Hardened Steels*, Report no. 320, Dept. of Theoretical and Applied Mechanics, University of Illinois, Urbana, 1968.

obtained for 36 percent cold work. And the handbook would not indicate whether it was a compressive or tensile yield strength, nor in what direction it was applied.

However, for this problem, the designer really needs both the tensile and compressive yield strengths in the transverse, i.e., circumferential, direction. These values can be closely approximated by means of Table 33.1. The tensile yield strength in the transverse direction is designated by the code $(S_y)_{iT}$, which is in group 2 of Table 33.1. Since the bar was given only one cycle of deformation (a single upset), ϵ_{qu} is 0.45 and the tensile yield strength is calculated to be 123 kpsi. The compressive yield strength in the transverse direction is designated by the code $(S_y)_{cT}$, which is in group 4 of Table 33.1. The compressive yield strength is then calculated to be $0.95(S_y)_{iT} = 0.95(123) = 117$ kpsi; this is 14 percent lower than the 136 kpsi that would normally be listed in a materials handbook.

In some design situations, the actual value of the yield strength in a given part for a specific amount of cold work may be 50 percent less than the value that would be listed in the materials handbook. In order to have a reliable design, the designer must be able to determine the strength of the material in a part in the direction and sense of the induced stresses. The information in this chapter and in Chap. 33 makes it possible for the design engineer to make a reasonable prediction of the mechanical properties of a fabricated part. However, it must be recognized that the original non-cold-worked properties of a given metal vary from heat to heat, and that the calculations are valid only for a part having the original properties that are used in the calculations.

32.15 NUMBERING SYSTEMS[†]

32.15.1 AISI and SAE Designation of Steel

Carbon and alloy steels are specified by a code consisting of a four-digit (sometimes five) number, as illustrated below with the substitution of the letters X, Y, and Z for the numbers. A steel specification of XYZZ (or XYZZZ) has the following meaning:

X indicates the type of alloy or alloys present.

Y indicates the total percent of the alloys present.

ZZ (or ZZZ) indicates the “points” of carbon in the steel (points of carbon equals the percent carbon times 100). For example, if ZZ is 40, then the steel has 0.40 percent carbon (C). If ZZZ is 120, then the steel has 1.20 percent carbon.

Table 32.7 identifies the number X corresponding to the alloy or alloys present. In addition, the following two special classes are included. A resulturized free-machining steel is identified as 11ZZ and 12ZZ. These steels have a high sulfur content, which combines with the manganese to form the compound manganese sulfide. It is the presence of this compound that makes the steel more machinable. The 13ZZ and 15ZZ groups are plain carbon steels that have high and moderate amounts of manganese, respectively.

[†] This section presents the numbering systems now in general use in order to correspond with those used in other sections of this handbook. See Ref. [32.2] for details of the unified numbering system (UNS).

TABLE 32.7 Alloy Designations for Steels

Number X	Alloying elements
1	None (plain carbon)
2	Nickel
3	Nickel-chromium
4	Molybdenum-nickel-chromium
5	Chromium
6	Chromium-vanadium
8	Nickel-chromium-molybdenum
9	Silicon-manganese

Some examples:

2130 is a steel with 1 percent nickel and 0.3 percent carbon.

4340 is a steel with a total of 3 percent Mo, Ni, and Cr and 0.4 percent C.

52100 is a steel with 2 percent Cr and 1 percent C.

32.15.2 Designation System for Aluminum Alloys

Wrought aluminum alloys are specified by a code consisting of four-digit numbers such as 1100, 2024, or 7075. To explain this code, the letters X Y Z Z are substituted for the four digits. The types of alloys present in the aluminum are identified by the letter X from Table 32.8.

The second digit in the code, Y, indicates alloy modifications. When Y is zero, it indicates the original alloy, or in the 1 Y Z Z series it indicates that the alloy is made to the standard impurity limits. When Y is any digit from 1 to 9, it indicates that a modification has been made to the original alloy and then designates which of the sequential changes were made. For example, 7075 refers to the original zinc alloy, whereas 7175 and 7475 refer to the first and fourth modifications made to it.

The third and fourth digits (Z Z in the code) have no numerical significance but simply relate to the chemical composition of the alloys.

TABLE 32.8 Alloy Designations for Wrought Aluminum Alloys

Number X	Alloying elements
1	None (99.00% Al min.)
2	Copper
3	Manganese
4	Silicon
5	Magnesium
6	Magnesium-silicon
7	Zinc

Temper Designation. The temper designation for aluminum alloys consists of a suffix which is a letter that may be followed by several digits. The suffix is separated from the alloy designation by a hyphen or dash. For example, 7075-T4 identifies both the alloy composition and its temper. The T in this suffix identifies the tempering treatment as a heat-treating process. Table 32.9 shows the letters used to identify the type of process used in the tempering treatment.

In addition to the T temper designations, other two- or three-digit numbers have been assigned to some specific treatments to certain special alloys or types of products.

32.15.3 Designation System for Copper Alloys

The designation system for copper alloys is not based on a coded system as those for steel and aluminum alloys are. It is simply a means of defining the chemical composition of the specific alloys. Table 32.10 identifies the principal alloying elements for the common classes of copper alloys.

Temper Designation. The temper designation for copper alloys refers to the amount of cold work given to the metal. Table 32.11 defines the amount of cold work associated with each temper designation.

TABLE 32.9 Tempering Processes and Designations for Aluminum Alloys

Designation	Process
F	As fabricated
O	Annealed
H	Strain hardened; the H is followed by two or more digits to indicate the amount of strain hardening
H1	Strain hardened only
H2	Strain hardened and partially annealed
H3	Strain hardened and stabilized
W	Solution heat treated
T	Heat treated; the T is always followed by one or more digits to specify the particular process used
T1	Cooled from a high-temperature forming process and naturally aged
T2	Cooled from a high-temperature forming process, cold worked, and naturally aged
T3	Solution heat treated, cold worked, and naturally aged
T4	Solution heat treated and naturally aged
T5	Cooled from a high-temperature forming process and artificially aged
T6	Solution heat treated and artificially aged
T7	Solution heat treated
T8	Solution heat treated, cold worked, and artificially aged
T9	Solution heat treated, artificially aged, and cold worked
T10	Cooled from a high-temperature forming process, cold worked, and artificially aged

TABLE 32.10 Designation of Copper Alloys

UNS Number	Alloy	Class or name
C10000-C13000	None	Commercially pure (ETP or OFHC)
C21000	Zn	Gilding brass (95% Cu)
C22000	Zn	Commercial bronze (90% Cu)
C23000	Zn	Red brass (85% Cu)
C24000	Zn	Low brass (80% Cu)
C26000	Zn	Cartridge brass (70% Cu)
C28000	Zn	Muntz metal (60% Cu)
C50000	Sn	Phosphor bronze
C60600-C64200	Al	Aluminum bronze
C64700-C66100	Li	Silicon bronze
C70000	Ni	Copper-nickel

TABLE 32.11 Temper Designation of Copper Alloys

Temper	Percent cold work	
	Rolled sheet	Drawn wire
$\frac{1}{4}$ hard	10.9	20.7
$\frac{1}{2}$ hard	20.7	37.1
$\frac{3}{4}$ hard	29.4	50.1
Hard	37.1	60.5
Extra hard	50.1	75.1
Spring	60.5	84.4
Extra spring	68.6	90.2
Special spring	75.1	93.8

32.15.4 Designation System for Magnesium Alloys

The designation system for magnesium alloys consists of four parts that include a combination of letters and digits. A typical example is AZ31B-H24.

The first part of the designation consists of two letters representing the two main alloying elements in order of decreasing amounts. The 10 principal alloying elements are given the following letters: A, aluminum; E, rare earth; H, thorium; K, zirconium; L, lithium; M, manganese; Q, silver; S, silicon; T, tin; and Z, zinc. Thus, in the preceding alloy, the main element is aluminum and the second one is zinc.

The second part consists of two digits corresponding to rounded-off percentages of the two main alloying elements. In the preceding example the alloy contains 3 percent aluminum and 1 percent zinc.

The third part of the designation consists of a letter that indicates the chronologic order of when that particular composition became a standard one. In the preceding example the letter B indicates that this particular alloy is the second one, having 3 percent aluminum and 1 percent zinc, that became an industry standard.

The fourth part consists of a letter preceded by a hyphen and followed by a number. It indicates the specific condition or temper that the alloy is in. Table 32.12 specifies the symbols that are used for each temper.

TABLE 32.12 Temper Designation of Magnesium Alloys

Designation	Process
F	As fabricated
O	Annealed
H10, H11	Slightly strain hardened
H23, H24, H26	Strain hardened and partially annealed
T4	Solution heat treated
T5	Solution heat treated and artificially aged
T8	Solution heated treated, cold worked, and artificially aged

REFERENCES

- 32.1 J. Datsko, *Materials in Design and Manufacture*, J. Datsko Consultants, Ann Arbor, Mich., 1978.
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- 32.3 *Metals Handbook Desk Edition*, American Society for Metals (ASM), Metals Park, Ohio, 1984.
- 32.4 R. M. Brick, A. W. Pense, and R. B. Gordon, *Structure and Properties of Engineering Materials*, 4th ed., McGraw-Hill, New York, 1977.
- 32.5 M. M. Schwartz, *Composite Materials Handbook*, McGraw-Hill, New York, 1984.
- 32.6 L. H. Van Vlack, *Elements of Materials Science*, 4th ed., Addison-Wesley, Reading, Mass., 1980.

