



INDUSTRIAL MATERIALS



METALS AND *Volume 1* ALLOYS

David A. Colling
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VOLUME 1

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Preface

Technology involves all phases of product development from design through delivery. Industrial practitioners must be well versed in all aspects of manufacture, including computer applications, manufacturing processes, quality control, production management, and organizational behavior, among others. Selection and processing of industrial materials are important, but students preparing for careers in industry do not need to first become proficient in materials science, as many of the good textbooks on materials available at present assume. To be successful, we feel that the authors should be specialists in materials first, but should also be well versed in product-oriented manufacturing processes, where making it right is the only practice that matters! For these reasons, this textbook is filled with case studies that illustrate industrial problems.

We also believe that teaching is important; the material in this textbook has been developed over many years of teaching industrial technology students, many of whom are now practicing in successful careers and some of whom have provided case studies that appear in the text. These students did not have rigorous mathematics backgrounds, so it was important to develop their understanding of concepts rather than their computational skills or theoretical knowledge. The thrust of this textbook is to define properties needed for applications, then relate these properties to the material properties for appropriate selection and control through processing.

It is impossible to cover all materials in a single one-semester course, yet curriculum demands do not always permit time for a two-course sequence. We have separated our treatment of materials into two volumes rather than including everything in a single cumbersome volume that might not be fully utilized. Where only a single course is required, your emphasis can be tailored to either metals and alloys

(Volume 1) or to polymers, ceramics, and composites (Volume 2), eliminating one volume or leaving it for an elective.

There is little new information provided in these two volumes—we have borrowed freely from other sources whose permission is acknowledged with appreciation. Our contribution is in the organization of the topics and their presentation in a logical fashion to establish a basis for optimum applications of materials in manufacturing.

Volume 1 is confined to metals and alloys. We begin the first four chapters by discussing properties related to these materials and their applications. We then build a basis for understanding the selection and control needed to satisfy the demands of these materials, beginning with brief treatments of atomic structure and bonding to form crystalline solids. Defects and their consequences provide the groundwork for single phase alloys, then binary and higher order alloys. Chapter 5 describes the making of metals and alloys and the microstructure and properties resulting from solidification. Chapter 6 emphasizes the proper heat treatment to use in making the material right for its application. In Chapters 7 and 8, the important ferrous and nonferrous alloys are described, along with ideas for their use. In Chapter 9, we emphasize what happens to metals during deformation and the metalworking methods for shaping metals by deforming them. Although we emphasize proper selection and control throughout the text, we describe metal joining in Chapter 10 because many products and properties are altered by joining or during application, particularly corrosion, which is presented in Chapter 11.

We would like to thank our students for their inspiration and our colleagues at the University of Massachusetts Lowell for their encouragement and support. Particular thanks are due Professor V. E. Simms, Jr., for his invaluable discussions and assistance in locating some of the photomicrographs. We would also like to thank all those who reviewed the final manuscript: David H. Devier, Ohio Northern University; Peter Stracener, South Plains College; C. J. Law, Western New Mexico University; Bill G. Cullins, Aims Community College; Thomas F. Kilduff, Thomas Nelson Community College; and Boyd Larson, University of Wisconsin–Platteville. Finally, we could not have completed the text without the sacrifice of our families and friends, particularly our wives, Dr. Jane Dreskin and Mrs. Helen Vasilos.

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1

Properties of Metals

The history of man can be measured by the development and applications of materials. It is with good reason that we refer to periods of human culture as the Stone Age, the Bronze Age, or the Iron Age because materials developments during these ages led to the production of weapons for hunting or warfare and to the production of cooking and storage utensils. Even today, our sophisticated technology is dependent on materials developments at work, at home, and at play. Enterprises such as the transportation, computer, electronics, communications, and aerospace industries are a result of our being able to study and learn about the materials needed to develop the dreams of entrepreneurs.

Our understanding of materials did not really begin until the late nineteenth century when the microscope and methods for testing materials were first developed. Up until then, materials development was purely empirical, thus limiting the technology of the time. For example, both the social and economic development of the United States was made possible by railroads. Prior to improved steelmaking by the Bessemer process, however, rails were too weak to sustain the constant travel of steam engines.

Today's materials can be classified as metals and alloys, as polymers or plastics, as ceramics, or as composites; composites, most of which are man-made, actually are combinations of different materials. Applications of these materials depend on their properties; therefore, we need to know what properties are required by the application and to be able to relate those specifications to the material. For example, a ladder must withstand a design load, the weight of a person using the ladder. However, the material property that can be measured is strength, which is affected by the load and design dimensions. Strength values must therefore be applied to determine the ladder dimensions to ensure safe use.

The properties that we will be using throughout this textbook are those of metals and alloys. They include **physical properties** such as density and melting point, **mechanical properties** such as strength and ductility, electrical and thermal properties such as conductivity, and magnetic properties. (Other properties of materials, such as optical properties, will be discussed in the second volume of this textbook on polymers, ceramics, and composites.)

The units for measurement of properties are supposedly uniform, with the International System of Units (SI units) universally acceptable. Nevertheless, conventional usage of British units in the United States has persisted in many disciplines. This mix really does not present a problem, however, because we can readily convert to SI units when measuring in British units. Table 1.1 compares the units of measurement and lists conversion factors.

Table 1.1
Measurements and material properties

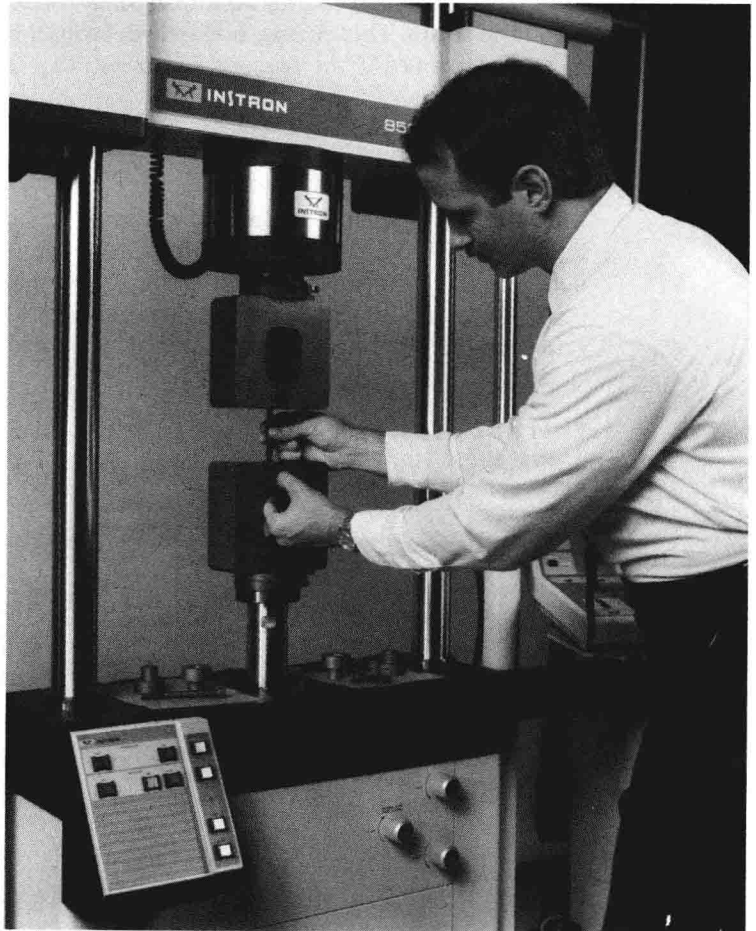
Property	SI unit	British unit	Conversion factors
Length	meter	inch, foot	1 in. = 2.54 cm = 25.4 mm 1 m = 39.37 in. 1 Å = 10^{-8} cm 1 mil (.001 in.) = .0394 mm
Mass	kilogram	pound mass (lbm)	1 kg = 2.204 lbm 1 lbm = 453.7 g
Force	newton (N)	pound force (lbf)	1 lbf = 4.44 N
Stress	pascal (Pa)	lbf/in. ² or psi	1 Pa = 1 N/m ² = $.145 \times 10^{-3}$ lbf/in. ² 1 lbf/in. ² = 6.89×10^3 Pa
Temperature	°C K (absolute)	°F °R (absolute)	°F = $\frac{9}{5}$ °C + 32 K = °C + 273 °R = °F + 460

1.1 Mechanical Properties

1.1.1 Tensile Properties

Mechanical properties are always specified in material selection for structural applications. Structural design, in turn, must provide the size that is appropriate for these properties. It is typical to specify tensile properties, which simply refer to the applied forces that stretch a shape. Tensile tests are performed in universal machines such as that shown in Figure 1.1. These machines can test materials under compression, shear, and flexure. In most cases, we will specify engineering properties, which are determined from a stress-strain curve of test results.

Figure 1.1
Universal testing machine
for mechanical property
measurement
(Courtesy of Instron
Corporation.)



Engineering **stress**, σ , is defined as

$$\sigma = \frac{P}{A_o}$$

where A_o is the original cross-sectional area and P is the force that is applied. This applied force will extend or elongate the metal, causing a **strain**, ϵ , which is given by

$$\epsilon = \frac{\ell - \ell_o}{\ell_o}$$

where ℓ is specimen length after force is applied and ℓ_o is the original specimen length.

When we load the specimen to failure, the stress-strain curve can be plotted, giving us useful data for specifications. Figure 1.2 shows a typical stress-strain curve for a metal sample tested to failure. Initially, there is a large *linear* increase in stress with little strain. This change is **elastic deformation** because the metal shape is completely recovered if the force is removed. The linear relation is described by the equation

$$\sigma = E\epsilon$$

where E is the **elastic modulus**, or Young's modulus. This equation is known as Hooke's law and introduces us to the most common example of a structure independent property. No matter what we do to the material, E remains unchanged. We have to change the temperature or composition to alter it. Structure sensitive properties, on the other hand, can be altered by either heat treatment or deformation.

Figure 1.2
Typical stress-strain curve for
metal sample tested to failure

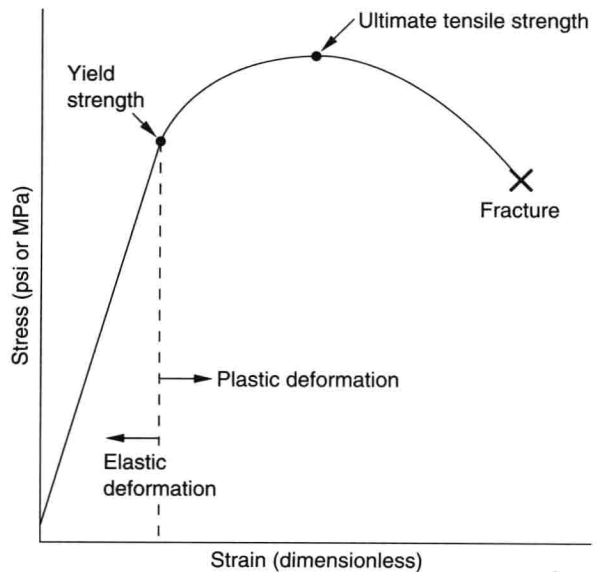
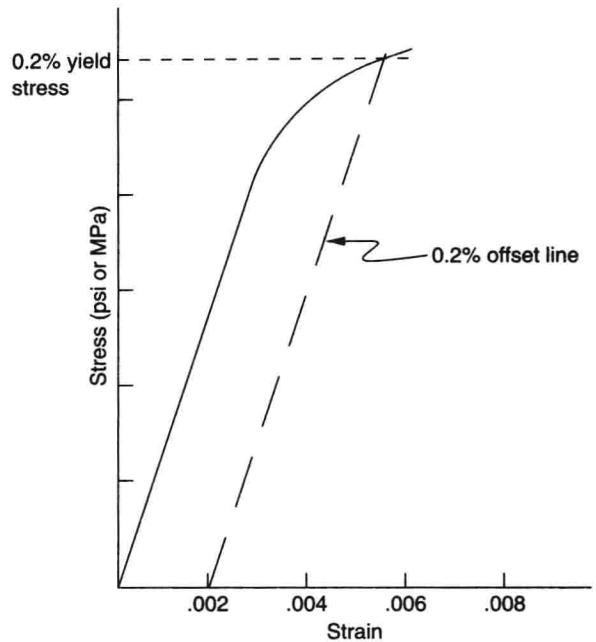


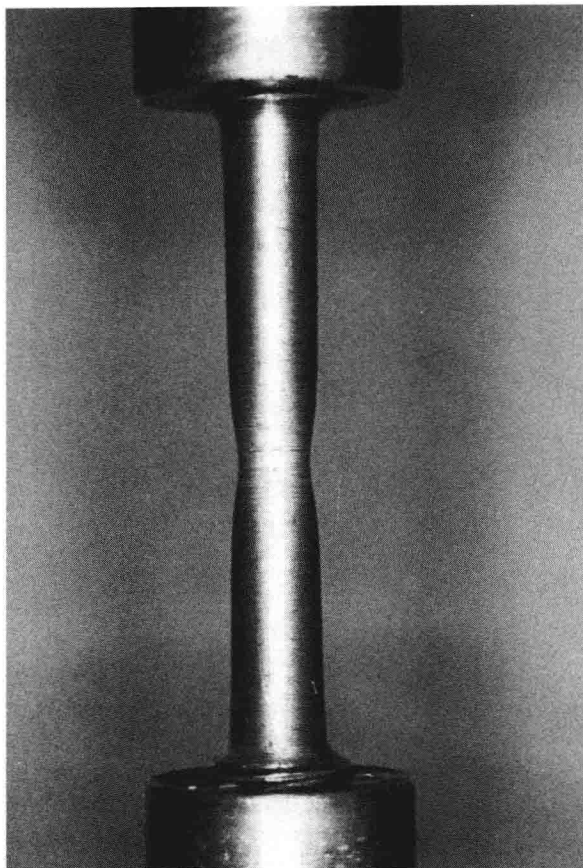
Figure 1.3
Method for determining
0.2% offset yield strength



The stress-strain curve of Figure 1.2 contains a great deal of information that we will use when specifying mechanical properties of materials used in manufacturing. Most applications cannot permit any permanent deformation, much less fracture of the material, so we must design for a stress below that where **plastic deformation** first occurs. We call this stress the **yield strength** or flow strength (also referred to as yield or flow stress). The exact value of the yield strength cannot be determined with any accuracy; therefore, we use the convention denoting the 0.2% offset yield strength. This is determined by selecting the strain value of 0.002 in./in. or mm/mm (0.2%) and drawing a line parallel to the elastic or linear portion of the stress-strain curve. The intersection of this line with the stress-strain curve, illustrated in Figure 1.3, is defined as the 0.2% yield strength.

The highest stress that a metal can withstand without breaking is termed the **ultimate tensile strength**, as indicated in Figure 1.2. When the ultimate tensile strength has been reached, the sample cross section is reduced by additional loading; we call this reduction **necking**. Figure 1.4 demonstrates the necking of a mild steel sample just prior to fracture. Therefore the reduction in engineering stress beyond the ultimate tensile strength is really an artifact because we continue to divide the load by the original cross-sectional area even though the cross section has been reduced by the necking (in Chapter 9, we will examine behavior in terms of true stress and true strain). We now have identified the elastic modulus and two strengths, the yield strength used for design purposes and the ultimate tensile strength, which is the maximum strength. Both yield strength and ultimate tensile strength are structure sensitive properties that can be affected by deformation or heat treatment.

Figure 1.4
Necking of mild steel sample
during testing



Ductility, which is a measure of deformability without breaking, cannot be easily determined from the stress-strain diagram. The high stresses and low strains of the elastic region are experimentally measured with extensometers or strain gauges; these cannot be used for high elongation values. Also, necking that occurs is a form of ductility that is not recorded on the stress-strain diagram. We therefore express ductility in terms of the percentage elongation to fracture or the percentage **reduction in area** (% RA). These are defined as

$$\% \text{ Elongation} = \frac{\ell_f - \ell_o}{\ell_o} \times 100$$
$$\text{and } \% \text{ RA} = \frac{A_o - A_f}{A_o} \times 100$$

A standard length is marked and measured both before (ℓ_o) and after (ℓ_f) testing, and the area before (A_o) and the area in the necked region after (A_f) testing are also determined to ascertain the property values. Both % elongation to fracture and the % RA are structure sensitive properties.

Sample Problem 1.1

Steel has a modulus of elasticity, E , of 29×10^6 psi (20×10^4 MPa).

a. What is the stress on a steel rod 0.125 in. in diameter and 12 in. long that is stretched 0.02 in.?

b. What is the force causing this stress?

Solution

$$\text{a. } \varepsilon = \frac{\ell - \ell_o}{\ell_o} = \frac{0.02 \text{ in.}}{12 \text{ in.}} = 1.67 \times 10^{-3} \text{ in./in.}$$

$$\begin{aligned} \sigma &= E\varepsilon = 29 \times 10^6 \text{ psi} \times 1.67 \times 10^{-3} \text{ in./in.} \\ &= 48.43 \times 10^3 \text{ psi} \\ &= 48,400 \text{ psi (333.8 MPa)}^* \end{aligned}$$

$$\text{b. } \sigma = \frac{P}{A}$$

$$48,400 \text{ psi} = \frac{P}{\pi(0.125 \text{ in.})^2 / 4}, \text{ since } A = \frac{\pi d^2}{4}$$

$$\begin{aligned} P &= 48,400 \text{ psi} \times \frac{\pi(0.125 \text{ in.})^2}{4} \\ &= 594 \text{ lbf (133.8 N)} \end{aligned}$$

Sample Problem 1.2

A yellow brass rod (Cu-30% Zn) 0.25 in. in diameter has a yield strength of 16,000 psi (110 MPa) and tensile strength of 48,000 psi (330 MPa). What is the maximum force that can be applied

a. without breaking the rod?

b. without deforming the rod permanently?

Solution

a. Using the ultimate tensile strength,

$$\begin{aligned} \frac{P}{A} &= 48,000 \text{ psi} \\ P &= \frac{48,000 \text{ psi}}{\pi(0.25 \text{ in.})^2 / 4} \\ &= 2360 \text{ lb (532 N)} \end{aligned}$$

* Values with more than three significant numbers cannot be supported by testing accuracy, so convention limits the answer to the rounded value of 48,400 psi.