

MECHANICAL PROPERTIES OF MATERIALS AT LOW TEMPERATURES

D. A. Wigley



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Preface

In writing this monograph, the aim has been to consider the mechanical properties of the wide range of materials now available in such a way as to start with the fundamental nature of these properties and to follow the discussion through to the point at which the reader is able to comprehend the significance or otherwise of the large amounts of data now available in design manuals and other compilations. In short, it is hoped that this volume will be used as a companion to these data compilations and as an aid to their interpretation.

In attempting to cover such a wide field, a large degree of selection has been necessary, as complete volumes have been written on topics which here have had to be covered in a few pages or less. It is inevitable that not everyone will agree with the choice made, especially if it is his own subject which has been discussed rather briefly, and the author accepts full responsibility for the selection made. The book is written at a level which should be easily followed by a university graduate in science or engineering, although, if his background has not included a course in materials science, some groundwork may be lacking. This omission can easily be corrected by the use of one of the excellent texts now available,^{1,2} in particular, experience in teaching a one-year master's degree course in cryogenics has shown that volumes 1 and 3 of the series edited by Wulff¹ are particularly suitable for this purpose.*

Although this book is entitled "The Mechanical Properties of Materials at Low Temperatures," it is in fact impossible to discuss the low-temperature properties in isolation, as in most cases they must be considered over the whole range of temperatures below ambient. For example, much equipment designed for use at low temperatures has to be built and tested at room temperature, and furthermore, the allowable stresses laid down by most design codes are based on the room-temperature properties of the materials concerned. Most of the materials likely to be of use in cryogenic engineering have been included but, despite the superiority of nonmetals for certain applications, it is a reflection of the major importance of metals that about 70% of the book is devoted to their deformation and fracture characteristics. Most plastics suffer from the fundamental disadvantage of

* The references cited in the Preface will be found at the end of Chapter 1.

undergoing a glass transition at some temperature below which they are relatively brittle; a few varieties such as PTFE are, however, less seriously affected and they have proved very valuable in certain applications. Although the science of low-temperature physics developed by using apparatus made of glass, its brittleness made it too delicate for general engineering use and the major use of glass is now in the form of finely divided fibers which reinforce plastics to produce composites. Such composites are already finding widespread application, especially in situations where their high strength/weight ratio is advantageous, and the recent availability of high-modulus carbon fibers is likely to accelerate the transition to this class of material.

Some indication of the mature state of the science of metallurgy may be gained from the large number of books which have been written on almost every aspect of the subject and from the almost overwhelming amount of data which has been generated. Many metallurgy textbooks^{6-7,8} include sections on the behavior of metals at low temperatures, particularly on the effect of temperature on the fundamental mechanism of plastic deformation in crystalline solids.⁹⁻¹¹ There are also a number of excellent reviews on this aspect of the subject.⁴¹⁻⁴⁶ Fracture is also well documented in books^{12,13} and reviews,⁴⁷ the work by Tetelman and McEvily¹³ being particularly worthy of note, as it attempts to bridge the gap which so often exists between the fundamental, microscopic aspects of the problem and the practical considerations which must be understood if structures are to be designed and built free from the risks of catastrophic brittle failure.

Most textbooks and reviews on the properties of plastics⁴ and composites^{5,40} deal mainly with their properties at room temperature and above, although some⁴ have sections on low-temperature properties. Most of the available data on the low-temperature mechanical properties of all of these materials is to be found in specialist monographs, conference proceedings, and review articles. These include some of the special Technical Publications of the American Society for Testing and Materials,^{14,15} while the proceedings of the annual Cryogenic Engineering Conferences, published as "Advances in Cryogenic Engineering",¹⁶ are a particularly rich source of information on all aspects of cryogenic engineering. There are also a number of valuable reviews on the more technological aspects of the cryogenic properties of materials,^{3,40-55} although many of them are rather heavily biased toward aerospace applications. Information on the more general facets of cryogenic engineering is to be found in a number of textbooks,^{17-21, 35, 36} the theoretical and practical aspects of low-temperature physics are covered in further volumes and journals,^{22-26, 37, 38} while individual topics of particular interest are to be found in other monographs in this series.^{27, 28} A recent bibliographical guide to cryogenics and refrigeration²⁹ is also of considerable value.

It is, however, in the "Cryogenic Materials Data Handbook",³² the UCRL "Cryogenic Data Book",³³ the manufacturers' data manuals,³⁴ and in a series of excellent monographs^{21, 29-31} published by the National Bureau of Standards that specific data are to be found. These cover most of the available alloys in a range of conditions, purities, and heat treatments but, as we shall attempt to demonstrate in the coming chapters, there are an extremely large number of variables which can influence the strength, ductility, and toughness of materials. It is, therefore, often necessary to carry out tests to measure the required properties of a particular material, and in chapter 3 the most important methods of determining toughness are discussed, while in chapter 5 a brief indication is given of the experimental arrangements used to carry out tensile tests at low temperatures.

In conclusion, I would like to extend my thanks to all those who have helped in the preparation of this monograph, to Dr. R. A. Farrar for reading the whole of the manuscript and for many helpful comments and criticisms, to Messrs. A. Monroe, F. P. Grimshaw and P. Halford for advice and criticism on certain of its sections. All sources of figures have been acknowledged as they occur and I would like to thank all those authors and publishers who have assisted in this way and to apologize to anyone whose work has been drawn upon and used without specific acknowledgment. I would especially like to thank the editor, Dr. K. Mendelssohn, F.R.S., for his patience in awaiting the completion of this volume, which took considerably longer than either of us had anticipated, Mrs. B. Smith for her efficient typing, my wife, Jill, for her valued assistance in the preparation of the manuscript, and finally my family for accepting the inconveniences caused by my involvement in this task.

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Chapter 1

Deformation Processes in Pure Metals

When a metal is loaded, the resultant deformation is initially elastic and the metal returns to its original state as the load is removed. If, however, the applied load exceeds the yield strength of the metal, it deforms plastically and the strain so produced is not recoverable when the load is released. In most metals, the stress necessary to cause plastic deformation increases with the strain because the material work-hardens, and for over 5000 years man has used this property to strengthen metals and make them more suitable for his needs. It is, however, only in the last few decades that the fundamental mechanisms responsible for these properties have begun to be understood, and even now there are a number of important details which remain to be elucidated. For example, the phenomenon of work-hardening is not yet fully explained.

Much of our present knowledge of the mechanical properties of metals stems from the study of the microscopic aspects of plastic deformation, which have revealed its essentially crystalline nature. Perhaps the most significant advances have come from an understanding of the ways in which dislocations move, multiply, and interact with each other and with other features of the crystal lattice, such as impurity atoms, point defects, grain boundaries, and the free surface of the material. In particular, it is possible to explain many of the effects of temperature on the deformation and failure characteristics of metals by its influence on the ease with which dislocations may move through the various lattice structures. Although some knowledge of these mechanisms should form the basis of any thorough comprehension of the mechanical properties of metals, bulk engineering materials are not specified by their dislocation densities but by parameters such as their yield and tensile strengths, elongation, and reduction in area. It is therefore important to be able to correlate these two approaches if the fullest use is to be made of the wide range of materials which is now available to a designer. The properties of pure metals will be considered in this chapter, while impure metals and alloys will be covered in chapter 2.

The present chapter starts with an introduction to the terminology used

in describing the various features of the deformation of a specimen in the uniaxial tensile test, as this is one of the most universal methods of determining the mechanical properties of a material. Elastic deformation is then considered briefly before the general aspects of plastic deformation are discussed, firstly in terms of the microscopic mechanisms involved, and then in relation to the yield and flow of single crystals and polycrystals. The effect of temperature on these properties is then considered separately for metals with the three common crystal structures, face-centered cubic, body-centered cubic, and hexagonal close-packed. In each case, the behavior of single crystals is considered first and this is then compared with the characteristics shown by polycrystals. The dislocation structures developed during deformation are then described, and this section could, if desired, be omitted by those readers less interested in the fundamental aspects of the problem. Each section is completed by a short discussion on the effect of temperature on the familiar parameters used to describe the characteristics of engineering materials, while in section 1.7 the main characteristics of these three classes of metal are compared and summarized.

Although creep is only important as a mode of failure at high temperatures, its study at low temperatures reveals details of the fundamental processes which control plastic deformation in metals and these are discussed in section 1.8. The chapter concludes with a brief indication of the relevance of recovery processes to the deformation of metals at low temperatures.

1.1. GLOSSARY OF TERMS RELEVANT TO THE TENSILE TEST

Many specialized tests have been devised to measure the suitability of a material for service under particular combinations of applied stress, temperature, strain rate, and other relevant variables. The uniaxial tensile test is still, however, the most widely used measurement of the mechanical properties of a material. There are a number of ways in which the results of these tests may be presented, and confusion can arise if the meanings of the various terms involved are not clearly understood: it is hoped that this short section will help to clarify the situation.

The *engineering stress* σ is the ratio of the instantaneous load on the specimen P to its original cross-sectional area A_0 , i.e.,

$$\sigma = \frac{P}{A_0} \quad (1.1)$$

The central uniform portion of a specimen between two reference marks is the *gauge length* l_0 , and the *engineering strain* ϵ is the ratio of the

instantaneous increase in length of this section, $\Delta l = l - l_0$, to the original length l_0 , i.e.,

$$\epsilon = \frac{\Delta l}{l_0} \quad (1.2)$$

A typical engineering stress-strain curve for a ductile metal is shown in Fig. 1.1. The relation between stress and strain is linear up to the *elastic limit*, the constant of proportionality being *Young's modulus*, $E = \sigma/\epsilon$.

Up to the elastic limit, the strain is fully recoverable on removal of the applied stress; beyond this point, permanent plastic deformation occurs. In some metals, the transition between elastic and plastic deformation occurs quite sharply and it is possible to define a unique *yield stress* σ_y . In many cases, including the one illustrated in Fig. 1.1, transition from elastic to plastic deformation takes place so smoothly that it is impossible to define a unique yield stress from macroscopic strain readings. On a microscopic scale and with sensitive strain-measuring equipment, it is, however, possible to detect the onset of plastic yielding at the *microyield stress*, which is the stress required for a strain of 10^{-5} .

For practical purposes, we require a less-sophisticated and more readily reproducible value for the yield process, and this need is satisfied by the definition of the "*proof*" stress (also known as the "*offset yield*" stress). Defined as the stress required to produce a certain degree of permanent plastic strain, usually 0.1, 0.2, or 0.5%, it is often determined in practice as shown in Fig. 1.2. A line is drawn from the relevant strain, say 0.2%, parallel to the elastic loading line until it intercepts the stress-strain curve. The 0.2% proof stress is then read off from the ordinate.

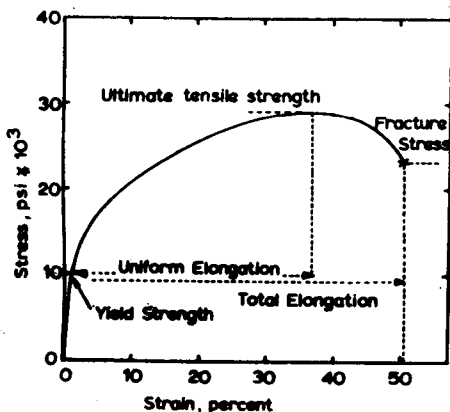


Fig. 1.1. Engineering stress-strain curve for a typical ductile metal such as copper.

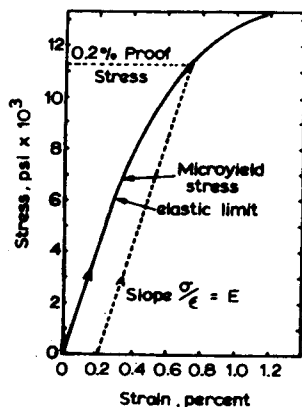


Fig. 1.2. Elastic and initial stages of plastic deformation shown enlarged to illustrate the method of determining the 0.2% proof stress.

In most tensile tests, the crosshead is driven at a constant strain rate and the stress developed in the specimen is measured as the dependent variable. Most metals have the capacity to *work-* or *strain-harden* and the stress needed to produce further plastic deformation increases as the plastic strain increases. The strain-hardening rate decreases with increasing strain until it is zero at the *ultimate tensile strength* (UTS, sometimes called simply the *tensile strength* TS), where the engineering stress is at a maximum. At this point, a neck starts to develop in the specimen because the metal can no longer strain-harden rapidly enough to compensate for the decrease in cross-sectional area. Further plastic deformation becomes concentrated in this localized region and the engineering stress decreases with increasing strain.

Fracture occurs at the *fracture stress* σ_f , which is lower than the ultimate tensile stress. The *reduction in area* RA is defined as the ratio of the minimum cross-sectional area at fracture, A_f , to the original cross-sectional area, A_0 , i.e.,

$$RA = \frac{A_f}{A_0} \quad (1.3)$$

The *fracture strain*, *ductility*, or *fracture elongation* is the amount of *plastic* strain produced before fracture and is thus the total strain measured at the instant of fracture minus the elastic strain. As, however, the elastic strain is typically a few tenths of 1%, while the plastic strain is a few tens per cent, the elastic strain is usually neglected and the total strain is used to represent the ductility. This is often measured by fitting together the two fracture halves and comparing the final value of the gauge length l_f , to the original value l_0 . Until necking starts, plastic deformation usually occurs uniformly along the specimen, and the *uniform elongation* is the amount of plastic strain occurring prior to the ultimate tensile stress.

During elastic deformation, there is a small change in volume of the specimen, but during plastic deformation, the volume remains constant. Thus, $A_0 l_0 = A_i l_i$, where A_i and l_i are the instantaneous values of cross-sectional area and gauge length, respectively. In the definition of engineering stress, this decrease in cross-sectional area is neglected and a more exact description of the stresses developed in a sample is obtained from the definition of the *true stress* σ_T . This is defined as the ratio of the load to the instantaneous minimum cross-sectional area supporting the load, i.e.,

$$\sigma_T = \frac{P}{A_i} \quad (1.4)$$

This definition of true stress accurately describes the stress in the necked region of the specimen, and it can be seen from Fig. 1.3 that the true stress increases right up to the instant of fracture, when its value is the *true fracture stress*.

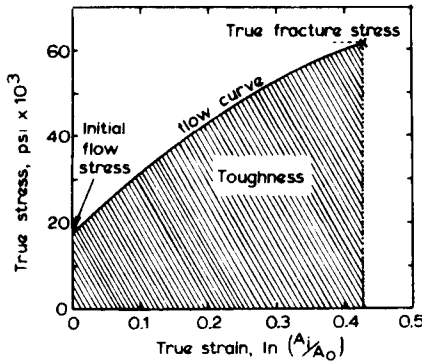


Fig. 1.3. True stress-strain curve for a ductile metal such as copper, showing true stress increasing continuously to fracture.

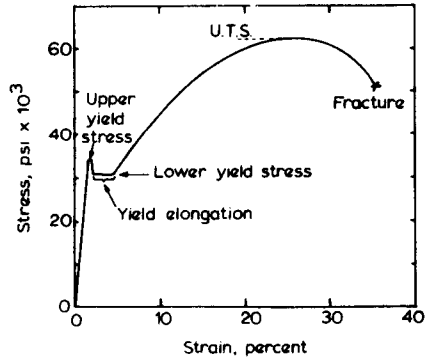


Fig. 1.4. Schematic stress-strain curve for mild steel, illustrating sharp yield phenomena.

True strain, sometimes known as *natural elongation*, may be defined in two ways. In the first, it is the definite integral of the ratio of an incremental change in length to the instantaneous length of the sample,

$$\epsilon = \int_{l_0}^{l_i} \frac{dl}{l} \quad (1.5)$$

On integration, this gives

$$\epsilon = \ln\left(\frac{l_i}{l_0}\right) \quad (1.6)$$

where l_i is the instantaneous length minus the small amount of elastic strain present. This definition is not valid after necking commences, and the second definition of true strain is needed, viz.

$$\epsilon = \ln\left(\frac{A_i}{A_0}\right) \quad (1.7)$$

A_i being the instantaneous minimum cross-sectional area. As the second definition of true strain is valid over the period of plastic deformation from yield to fracture, it is generally preferred.

The true-stress-true-strain curve shown in Fig. 1.3 is known as a *flow curve* and the stress for a particular strain is the *flow stress*. The *initial flow stress* is that stress required to initiate plastic deformation and is thus a synonym for yield stress. An important quantity also shown in this figure is the *toughness* of the material. This is a measure of the energy absorbed prior to fracture,

$$\int_{\epsilon_0}^{\epsilon_f} \sigma_T d\epsilon$$

and is given by the area under the flow curve.

As we shall see later in this chapter, plastic deformation in crystalline materials occurs by a shear mechanism and many results are presented in terms of *shear-stress-shear-strain* curves. Occasionally, materials are tested in such a way that values of shear stress and shear strain are obtained directly by measurement. In many cases, however, single crystalline specimens are tested in tension or compression and then the *resolved* shear stresses and strains are calculated from the geometry of the slip processes. Plastic yield occurs when the critical resolved shear stress is first exceeded on one of the possible slip systems. In the elastic region, the shear modulus G is the ratio of shear stress to shear strain.

In some metals, e.g., mild steel, yield occurs so suddenly that there is a sharp *yield drop* in the stress-strain curve as shown in Fig. 1.4. A small amount of plastic strain precedes the *upper yield* stress but macroscopic strains only occur after the stress has dropped to the *lower yield* stress. A period of *yield elongation* usually follows in which plastic deformation occurs at a more or less constant stress. This inhomogeneous deformation starts at a point of stress concentration, often near the grips, and propagates through the rest of the specimen. Its progress is accompanied by the formation of striations on the surface known as *Lüders bands* or *stretcher strains*, and once the deformation has propagated completely through the specimen, normal strain-hardening commences. The occurrence of sharp yield phenomena usually depends on the locking of dislocations by impurities and is discussed in more detail in section 2.4.

1.2. ELASTIC DEFORMATION

In metals and other crystalline solids, elasticity has its basis in the interatomic forces which act to restore displaced atoms to their equilibrium positions, and, as these forces are derived from strong primary bonds, the elastic moduli are high. In contrast, weaker, secondary bonds are responsible for the restoring forces in noncrystalline solids, the moduli are correspondingly lower, and there is often a nonlinear relationship between stress and strain.

A perfect crystal should theoretically show recoverable elastic strains of up to a few per cent, values of $\sim 5\%$ having in fact been found for whiskers which are minute, almost perfect, single crystals. In most metals, however, elastic behavior is limited to strains of about 0.1% by the onset of permanent plastic deformation. A further consequence of the crystalline nature of metals is that atoms are more closely packed in some directions than others: for example, the interatomic spacing along the body diagonal ($\langle 111 \rangle$ direction) of a fcc lattice is smaller than that along a cube edge ($\langle 100 \rangle$ direction). As stronger restoring forces act at smaller interatomic spacings, Young's modulus is largest along the most closely packed direc-