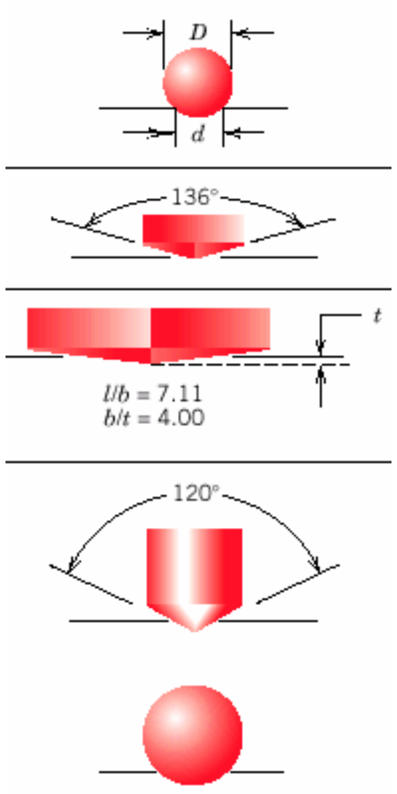
Hardness

Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch)

A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).



Different types of quantitative hardness test has been designed (Rockwell, Brinell, Vickers, etc.). Usually a small indenter (sphere, cone, or pyramid) is forced into the surface of a material under conditions of controlled magnitude and rate of loading. The depth or size of indentation is measured.

The tests somewhat approximate, but popular because they are easy and non-destructive (except for the small dent).

made by drawing a diamond stylus across the surface under a definite load. This is a useful tool for measuring the relative hardness of microconstituents, but it does not lend itself to high reproducibility or extreme accuracy.

In dynamic-hardness measurements the indenter is usually dropped onto the metal surface, and the hardness is expressed as the energy of impact. The Shore scleroscope, which is the commonest example of a dynamic-hardness tester, measures the hardness in terms of the height of rebound of the indenter.

9-2 BRINELL HARDNESS

The first widely accepted and standardized indentation-hardness test was proposed by J. A. Brinell in 1900. The Brinell hardness test consists in indenting the metal surface with a 10-mm-diameter steel ball at a load of 3,000 kg. For soft metals the load is reduced to 500 kg to avoid too deep an impression, and for very hard metals a tungsten carbide ball is used to minimize distortion of the indenter. The load is applied for a standard time, usually 30 s, and the diameter of the indentation is measured with a low-power microscope after removal of the load. The average of two readings of the diameter of the impression at right angles should be made. The surface on which the indentation is made should be relatively smooth and free from dirt or scale. The Brinell hardness number (BHN) is expressed as the load P divided by the *surface area* of the indentation. This is expressed by the formula[1]

$$\text{BHN} = \frac{P}{(\pi D/2)(D - \sqrt{D^2 - d^2})} = \frac{P}{\pi D t} \tag{9-1}$$

where P = applied load, kg
D = diameter of ball, mm
d = diameter of indentation, mm
t = depth of the impression, mm

It will be noticed that the units of the BHN are kilograms per square millimeter (1 kgf mm^{-2} = 9.8 MPa). However, the BHN is not a satisfactory physical concept since Eq. (9-1) does not give the mean pressure over the surface of the indentation.

From Fig. 9-1 it can be seen that $d = D \sin\phi$. Substitution into Eq. (9-1) gives an alternate expression for Brinell hardness number.

$$\text{BHN} = \frac{P}{(\pi/2) D^2 (1 - \cos\phi)} \tag{9-2}$$

In order to obtain the same BHN with a nonstandard load or ball diameter it is necessary to produce geometrically similar indentations. Geometric similitude is achieved so long as the included angle 2ϕ remains constant. Equation (9-2) shows

[1] Tables giving BHN as a function of d for standard loads may be found in most of the references in the Bibliography at the end of this chapter. See *ASTM* Standard E10-66.

MECHANICAL PROPERTIES OF MATERIALS

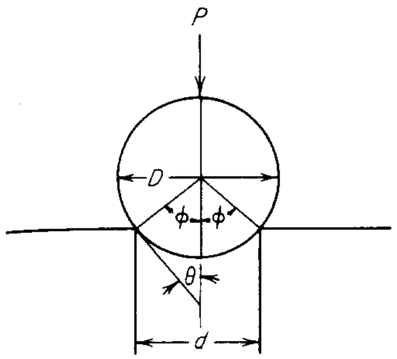


Figure 9-1 Basic parameters in Brinell test.

that for ϕ and BHN to remain constant the load and ball diameter must be varied in the ratio

$$\frac{P_1}{D_1^2} = \frac{P_2}{D_2^2} = \frac{P_3}{D_3^2} \tag{9-3}$$

Unless precautions are taken to maintain P/D^2 constant, which may be experimentally inconvenient, the BHN generally will vary with load. Over a range of loads the BHN reaches a maximum at some intermediate load. Therefore, it is not possible to cover with a single load the entire range of hardnesses encountered in commercial metals. The relatively large size of the Brinell impression may be an advantage in averaging out local heterogeneities. Moreover, the Brinell test is less influenced by surface scratches and roughness than other hardness tests. On the other hand, the large size of the Brinell impression may preclude the use of this test with small objects or in critically stressed parts where the indentation could be a potential site of failure.

9-3 MEYER HARDNESS

Meyer[1] suggested that a more rational definition of hardness than that proposed by Brinell would be one based on the *projected area* of the impression rather than the surface area. The mean pressure between the surface of the indenter and the indentation is equal to the load divided by the projected area of the indentation.

$$p_m = \frac{P}{\pi r^2}$$

Meyer proposed that this mean pressure should be taken as the measure of hardness. It is referred to as the *Meyer hardness*.

$$\text{Meyer hardness} = \frac{4P}{\pi d^2} \tag{9-4}$$

Like the Brinell hardness, Meyer hardness has units of kilograms per square

[1] E. Meyer, *Z. ver. Deut. Ing.*, vol. 52, pp. 645–654, 1908.

MECHANICAL BEHAVIOUR OF MATERIALS

millimeter. The Meyer hardness is less sensitive to the applied load than the Brinell hardness. For a cold-worked material the Meyer hardness is essentially constant and independent of load, while the Brinell hardness decreases as the load increases. For an annealed metal the Meyer hardness increases continuously with the load because of strain hardening produced by the indentation. The Brinell hardness, however, first increases with load and then decreases for still higher loads. The Meyer hardness is a more fundamental measure of indentation hardness; yet it is rarely used for practical hardness measurements.

Meyer proposed an empirical relation between the load and the size of the indentation. This relationship is usually called *Meyer's law*.

$$P = kd^{n'} \tag{9-5}$$

where P = applied load, kg
d = diameter of indentation, mm
n' = a material constant related to strain hardening of metal
k = a material constant expressing resistance of metal to penetration

The parameter n' is the slope of the straight line obtained when $\log P$ is plotted against $\log d$, and k is the value of P at $d = 1$. Fully annealed metals have a value of n' of about 2.5, while n' is approximately 2 for fully strain-hardened metals. This parameter is roughly related to the strain-hardening coefficient in the exponential equation for the true-stress–true-strain curve. The exponent in Meyer's law is approximately equal to the strain-hardening coefficient plus 2.

There is a lower limit of load below which Meyer's law is not valid. If the load is too small, the deformation around the indentation is not fully plastic and Eq. (9-5) is not obeyed. This load will depend on the hardness of the metal. For a 10-mm-diameter ball the load should exceed 50 kg for copper with a BHN of 100, and for steel with a BHN of 400 the load should exceed 1,500 kg. For balls of different diameter the critical loads will be proportional to the square of the diameter.

9-4 ANALYSIS OF INDENTATION BY AN INDENTER

The plastic zone beneath a hardness indentation is surrounded with elastic material which acts to hinder plastic flow in a manner similar to the die constraint forces in a closed-die forging. Therefore, the mean compressive stress required to cause plastic flow in the hardness test exceeds that in simple compression because of this constraint. The prediction of the load required to indent a solid is one of the classic problems in plasticity. Prandtl applied slip-line field theory to show that the constraint factor for plane-strain compression was 2.57 (see Sec. 3-12 and Fig. 3-13).

$$\frac{p_m}{\sigma} = 1 + \frac{\pi}{2} = 2.57$$

There is a very useful engineering correlation between the Brinell hardness and the ultimate tensile strength of heat-treated plain-carbon and medium-alloy steels (see Fig. 8-28).

$$\text{Ultimate tensile strength, in MPa} = 3.4(\text{BHN})$$

A brief consideration will show that this is in agreement with Tabor's results. If we make the simplifying assumption that this class of materials does not strain-harden, then the tensile strength is equal to the yield stress and Eq. (9-6) applies.

$$s_u = \tfrac{1}{3}p_m = 0.33p_m \text{ kgf mm}^{-2} = 3.23p_m \text{ MPa}$$

The Brinell hardness will be only a few percent less than the value of Meyer hardness p_m. It should now be apparent why the same relationship does not hold for other metals. For example, for annealed copper the assumption that strain hardening can be neglected will be grossly in error. For a metal with greater capability for strain hardening the "constant" of proportionality will be greater than that used for heat-treated steel.

9-6 VICKERS HARDNESS

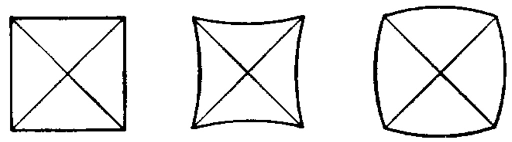
The Vickers hardness test uses a square-base diamond pyramid as the indenter. The included angle between opposite faces of the pyramid is 136°. This angle was chosen because it approximates the most desirable ratio of indentation diameter to ball diameter in the Brinell hardness test.[1] Because of the shape of the indenter, this is frequently called the *diamond-pyramid hardness test*. The diamond-pyramid hardness number (DPH), or Vickers hardness number (VHN, or VPH), is defined as the load divided by the surface area of the indentation. In practice, this area is calculated from microscopic measurements of the lengths of the diagonals of the impression. The DPH may be determined from the following equation

$$\text{DPH} = \frac{2P\sin(\theta/2)}{L^2} = \frac{1.854P}{L^2} \tag{9-9}$$

where P = applied load, kg
L = average length of diagonals, mm
θ = angle between opposite faces of diamond = 136°

The Vickers hardness test has received fairly wide acceptance for research work because it provides a continuous scale of hardness, for a given load, from very soft metals with a DPH of 5 to extremely hard materials with a DPH of

[1] In most Brinell tests d/D lies between 0.25 and 0.50. For the diamond-pyramid indenter a value of $d = 0.375D$ was used, which results in cone angle of 136°. As a result, DPH and BHN hardnesses are nearly identical so long as the Brinell impressions are of normal depth.



(a) (b) (c)

Figure 9-4 Types of diamond-pyramid tions. (*a*) Perfect indentation; (*b*) pincush ntation due to sinking in; (*c*) barreled in due to ridging.

1,500. With the Rockwell hardness test, described in Sec. 9-7, or the hardness test, it is usually necessary to change either the load or the ind some point in the hardness scale, so that measurements at one extreme scale cannot be strictly compared with those at the other end. Beca impressions made by the pyramid indenter are geometrically similar no what their size, the DPH should be independent of load. This is generall to be the case, except at very light loads. The loads ordinarily used with range from 1 to 120 kg, depending on the hardness of the metal to be te spite of these advantages, the Vickers hardness test has not been widely a for routine testing because it is slow, requires careful surface preparatio specimen, and allows greater chance for personal error in the determinatio diagonal length. The Vickers hardness test is described in ASTM S E92-72.

A perfect indentation made with a perfect diamond-pyramid indente be a square. However, anomalies corresponding to those described ea Brinell impressions are frequently observed with a pyramid indenter (F The pincushion indentation in Fig. 9-4*b* is the result of sinking in of th around the flat faces of the pyramid. This condition is observed with a metals and results in an overestimate of the diagonal length. The barrel indentation in Fig. 9-4*c* is found in cold-worked metals. It results from ri piling up of the metal around the faces of the indenter. The diagonal m ment in this case produces a low value of the contact area so that the h numbers are erroneously high. Empirical corrections for this effect ha proposed.[1]

9-7 ROCKWELL HARDNESS TEST

The most widely used hardness test in the United States is the Rockwell h test. Its general acceptance is due to its speed, freedom from person ability to distinguish small hardness differences in hardened steel, and tl size of the indentation, so that finished heat-treated parts can be tested damage. This test utilizes the depth of indentation, under constant lo measure of hardness. A minor load of 10 kg is first applied to seat the sp This minimizes the amount of surface preparation needed and redu tendency for ridging or sinking in by the indenter. The major load is then and the depth of indentation is automatically recorded on a dial gage in

[1] T. B. Crowe and J. F. Hinsely, *J. Inst. Met.*, vol. 72, p. 14, 1946.

arbitrary hardness numbers. The dial contains 100 divisions, each division representing a penetration of 0.002 mm. The dial is reversed so that a high hardness, which corresponds to a small penetration, results in a high hardness number. This is in agreement with the other hardness numbers described previously, but unlike the Brinell and Vickers hardness designations, which have units of kilograms per square millimeter (kgf mm^{-2}), the Rockwell hardness numbers are purely arbitrary.

One combination of load and indenter will not produce satisfactory results for materials with a wide range of hardness. A 120° diamond cone with a slightly rounded point, called a *Brale indenter*, and 1.6- and 3.2 mm-diameter steel balls are generally used as indenters. Major loads of 60, 100, and 150 kg are used. Since the Rockwell hardness is dependent on the load and indenter, it is necessary to specify the combination which is used. This is done by prefixing the hardness number with a letter indicating the particular combination of load and indenter for the hardness scale employed. A Rockwell hardness number without the letter prefix is meaningless. Hardened steel is tested on the C scale with the diamond indenter and a 150-kg major load. The useful range for this scale is from about R_C 20 to R_C 70. Softer materials are usually tested on the B scale with a 1.6 mm-diameter steel ball and a 100-kg major load. The range of this scale is from R_B 0 to R_B 100. The A scale (diamond penetrator, 60-kg major load) provides the most extended Rockwell hardness scale, which is usable for materials from annealed brass to cemented carbides. Many other scales are available for special purposes.[1]

The Rockwell hardness test is a very useful and reproducible one provided that a number of simple precautions are observed. Most of the points listed below apply equally well to the other hardness tests:

1. The indenter and anvil should be clean and well seated.
2. The surface to be tested should be clean and dry, smooth, and free from oxide. A rough-ground surface is usually adequate for the Rockwell test.
3. The surface should be flat and perpendicular to the indenter.
4. Tests on cylindrical surfaces will give low readings, the error depending on the curvature, load, indenter, and hardness of the material. Theoretical[2] and empirical[3] corrections for this effect have been published.
5. The thickness of the specimen should be such that a mark or bulge is not produced on the reverse side of the piece. It is recommended that the thickness be at least 10 times the depth of the indentation. Tests should be made on only a single thickness of material.
6. The spacing between indentations should be three to five times the diameter of the indentation.
7. The speed of application of the load should be standardized. This is done by adjusting the dashpot on the Rockwell tester. Variations in hardness can be

[1] See ASTM Standard E18-74.
[2] W. E. Ingerson, *Am. Soc. Test. Mater. Proc.*, vol. 39, pp. 1281–1291, 1939.
[3] R. S. Sutton and R. H. Heyer, *ASTM Bull.* 193, pp. 40–41, October, 1953.

appreciable in very soft materials unless the rate of load applica carefully controlled. For such materials the operating handle of the R tester should be brought back as soon as the major load has been fully a

9-8 MICROHARDNESS TESTS

Many metallurgical problems require the determination of hardness ov small areas.[1] The measurement of the hardness gradient at a carburized s the determination of the hardness of individual constituents of a microstr or the checking of the hardness of a delicate watch gear might be problems. The use of a scratch-hardness test for these purposes was mer earlier, but an indentation-hardness test has been found to be more useful development of the Knoop indenter by the National Bureau of Standards a introduction of the Tukon tester for the controlled application of loads d 25 g have made microhardness testing a routine laboratory procedure.

The Knoop indenter is a diamond ground to a pyramidal form that pr a diamond-shaped indentation with the long and short diagonals in the a mate ratio of 7 : 1 resulting in a state of plane strain in the deformed regio Knoop hardness number (KHN) is the applied load divided by the unrec projected area of the indentation.

$$KHN = \frac{P}{A_p} = \frac{P}{L^2C}$$

where P = applied load, kg
A_p = unrecovered projected area of indentation, mm^2
L = length of long diagonal, mm
C = a constant for each indenter supplied by manufacturer.

The special shape of the Knoop indenter makes it possible to place inden much closer together than with a square Vickers indentation, e.g., to me steep hardness gradient. Its other advantage is that for a given long di length the depth and area of the Knoop indentation are only about 15 per what they would be for a Vickers indentation with the same diagonal lengt is particularly useful when measuring the hardness of a thin layer (such electroplated layer), or when testing brittle materials where the tenden fracture is proportional to the volume of stressed material.

The low load used with microhardness tests requires that extreme c taken in all stages of testing. The surface of the specimen must be ca prepared. Metallographic polishing is usually required. Work hardening surface during polishing can influence the results. The long diagonal of the

[1] See ASTM Standard E334-69.
[2] For a review of microhardness testing see H. Bückle, *Metall. Rev.*, vol. 4, no. 3, pp. 1959.

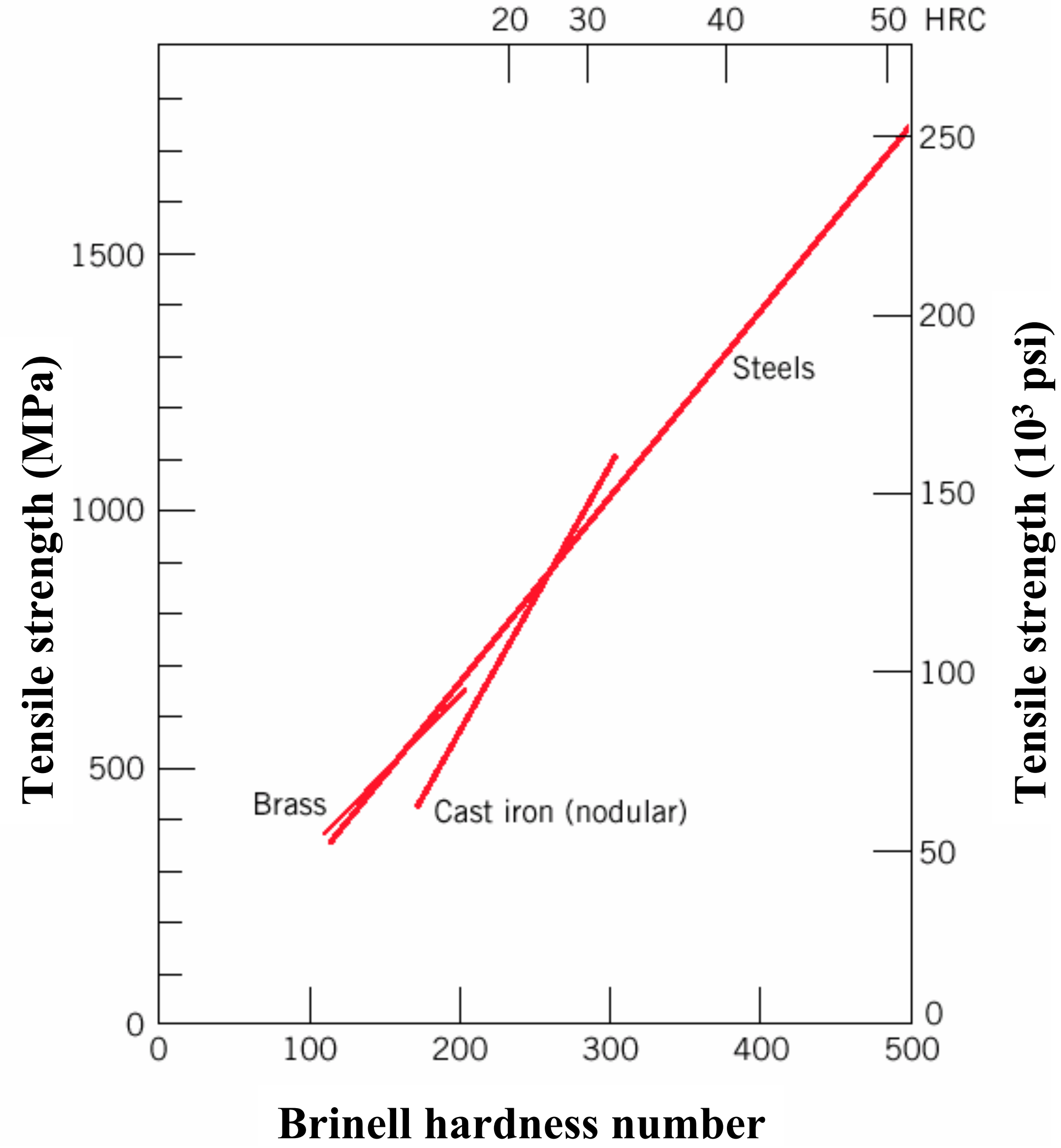
impression is essentially unaffected by elastic recovery for loads greater than about 300 g. However, for lighter loads the small amount of elastic recovery becomes appreciable. Further, with the very small indentations produced at light loads the error in locating the actual ends of the indentation become greater. Both these factors have the effect of giving a high hardness reading, so that it is usually observed that the Knoop hardness number increases as the load is decreased below about 300 g. Tarasov and Thibault[1] have shown that if corrections are made for elastic recovery and visual acuity the Knoop hardness number is constant with load down to 100 g.

9-9 HARDNESS-CONVERSION RELATIONSHIPS

From a practical standpoint it is important to be able to convert the results of one type of hardness test into those of a different test. Since a hardness test does not measure a well-defined property of a material and since all the tests in common use are not based on the same type of measurements, it is not surprising that no universal hardness-conversion relationships have been developed. It is important to realize that hardness conversions are empirical relationships. The most reliable hardness-conversion data exist for steel which is harder than 240 Brinell. The ASTM, ASM, and SAE (Society of Automotive Engineers) have agreed on a table[2] for conversion between Rockwell, Brinell, and diamond-pyramid hardness which is applicable to heat-treated carbon and alloy steel and to almost all alloy constructional steels and tool steels in the as-forged, annealed, normalized, and quenched and tempered conditions. However, different conversion tables are required for materials, with greatly different elastic moduli, such as tungsten carbide, or with greater strain-hardening capacity. Heyer[3] has shown that the indentation hardness of soft metals depends on the strain-hardening behavior of the material during the test, which in turn is dependent on the previous degree of strain hardening of the material before the test. As an extreme example of the care which is required in using conversion charts for soft metals, it is possible for Armco iron and cold-rolled aluminum each to have a Brinell hardness of 66; yet the former has a Rockwell B hardness of 31 compared with a hardness of R_B 7 for the cold-worked aluminum. On the other hand, metals, such as yellow brass and low-carbon sheet steel have a well-behaved Brinell-Rockwell conversion[4] relationship for all degrees of strain hardening. Special hardness-conversion tables for cold-worked aluminum, copper, and 18-8 stainless steel are given in the ASM Metals Handbook.

[1] L. P. Tarasov and N. W. Thibault, *Trans. Am. Soc. Met.*, vol. 38, pp. 331–353, 1947.
[2] This table may be found in ASTM Standard E-140-78, SAE Handbook, ASM Metals Handbook, and many other standard references.
[3] R. H. Heyer, *Am. Soc. Test. Mater. Proc.*, vol. 44, pp. 1027, 1944.
[4] The Wilson Mechanical Instrument Co. Chart 38 for metals softer than BHN 240 (see ASM Handbook, 1948 ed., p. 101) is based on tests on these metals.

Hardness-II



Both tensile strength and hardness may be regarded as degree of resistance to plastic deformation.

Hardness is proportional to the tensile strength - but note that the proportionality constant is different for different materials.

9-10 HARDNESS AT ELEVATED TEMPERATURES

Interest in measuring the hardness of metals at elevated temperatures has accelerated by the great effort which has gone into developing alloys improved high-temperature strength. Hot hardness gives a good indication potential usefulness of an alloy for high-temperature strength applications. degree of success has been obtained in correlating hot hardness with high-te ature strength properties. This will be discussed in Chap. 13. Hot-hardness i using a Vickers indenter made of sapphire and with provisions for test either vacuum or an inert atmosphere have been developed,[1] and a high-ten ture microhardness test has been described.[2]

In an extensive review of hardness data at different temperatures Westt showed that the temperature dependence of hardness could be express

$$H = Ae^{-BT}$$

where H = hardness, kgf mm^{-2}
T = test temperature, K
A, B = constants

Plots of log H versus temperature for pure metals generally yield two st lines of different slope. The change in slope occurs at a temperature wh about one-half the melting point of the metal being tested. Similar beha found in plots of the logarithm of the tensile strength against temperature. 9-5 shows this behavior for copper. It is likely that this change in slope is du change in the deformation mechanism at higher temperature. The const derived from the low-temperature branch of the curve can be considered to intrinsic hardness of the metal, that is, H at 0 K. This value would be ex to be a measure of the inherent strength of the binding forces of the l Westbrook correlated values of A for different metals with the heat content liquid metal at the melting point and with the melting point. This correlatio sensitive to crystal structure. The constant B, derived from the slope of the is the temperature coefficient of hardness. This constant was related in a complex way to the rate of change of heat content with increasing tempe With these correlations it is possible to calculate fairly well the hardness of metal as a function of temperature up to about one-half its melting point.

Hardness measurements as a function of temperature will show an change at the temperature at which an allotropic transformation occurs hardness tests on Co, Fe, Ti, U, and Zr have shown[4] that the body-centered lattice is always the softer structure when it is involved in an allotropic tra

[1] F. Garofalo, P. R. Malenock and G. V. Smith, *Trans. Am. Soc. Met.*, vol. 45, pp. 377–39 M. Semchyshen and C. S. Torgerson, *Trans. Am. Soc. Met.*, vol. 50, pp. 830–837, 1958.

[2] J. H. Westbrook, *Am. Soc. Test. Mater. Proc.*, vol. 57, pp. 873–897, 1957; *ASTM Bull.* 53–58, 1960.

[3] J. H. Westbrook, *Trans. Am. Soc. Met.*, vol. 45, pp. 221–248, 1953.

[4] W. Chubb, *Trans. AIME*, vol. 203, pp. 189–192, 1955.

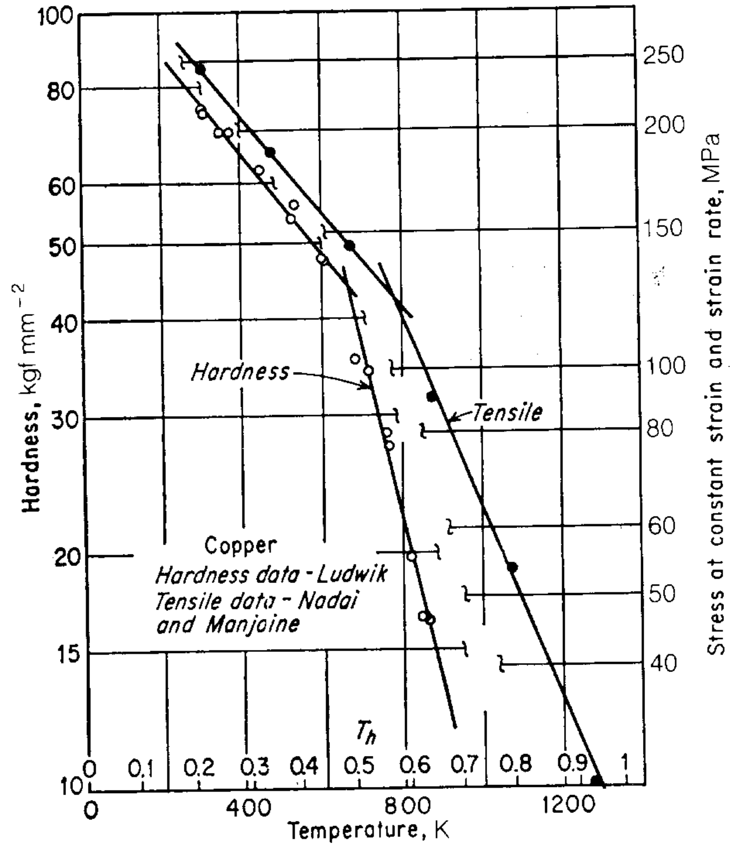


Figure 9-5 Temperature dependence of the hardness of copper. *(After J. H. Westbrook, Trans. Am. Soc. Met., vol. 45, p. 233, 1953.)*

mation. The face-centered cubic and hexagonal close-packed lattices have approximately the same strength, while highly complex crystal structures give even higher hardness. These results are in agreement with the fact that austenitic iron-based alloys have better high-temperature strength than ferritic alloys.

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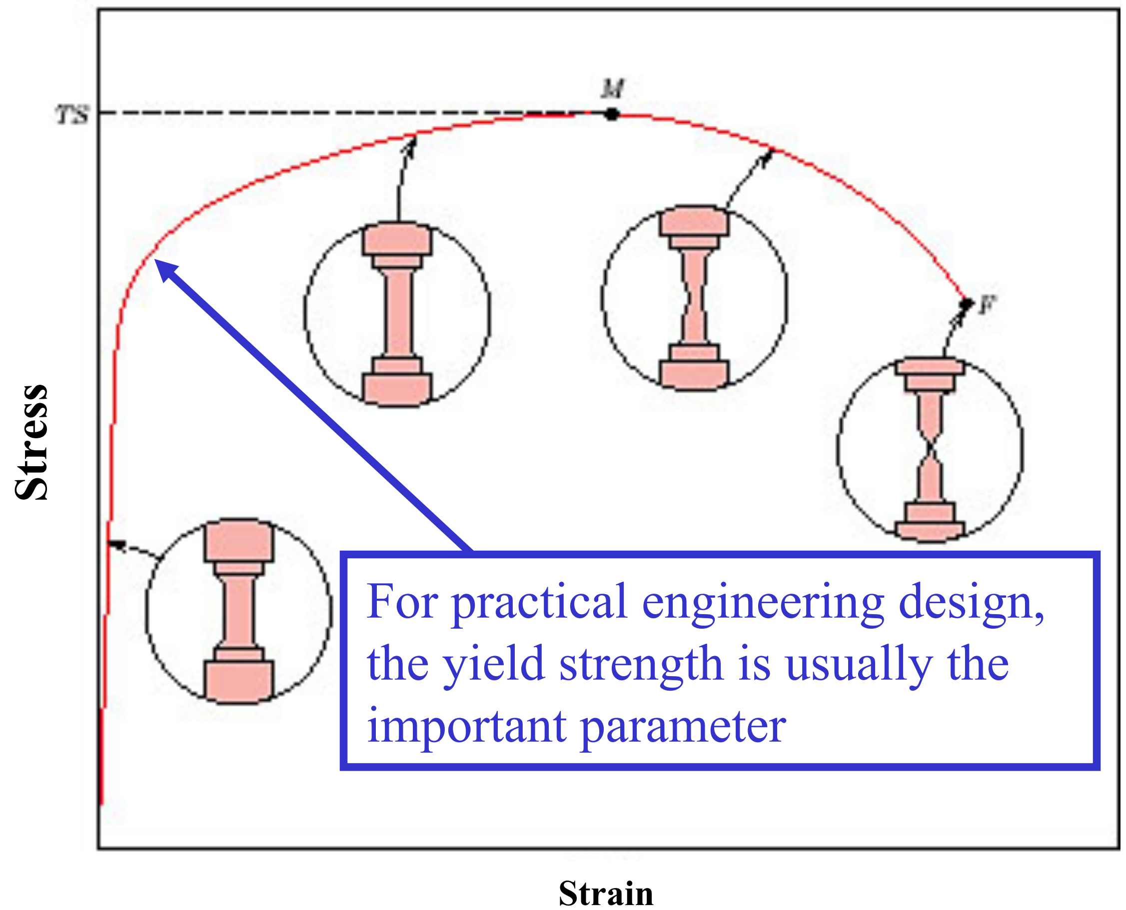
Limits of safe deformation



Design stress: $\sigma_d = N'\sigma_c$ where σ_c = maximum anticipated stress, N' is the "design factor" > 1. Want to make sure that $\sigma_d < \sigma_y$

Safe or working stress: $\sigma_w = \sigma_y/N$ where N is "factor of safety" > 1.

Summary

- **Stress** and **strain**: Size-independent measures of load and displacement, respectively.
- **Elastic** behavior: Reversible mechanical deformation, often shows a linear relation between stress and strain.
- Elastic deformation is characterized by **elastic moduli** (E or G). To minimize deformation, select a material with a large elastic moduli (E or G).
- **Plastic** behavior: Permanent deformation, occurs when the tensile (or compressive) uniaxial stress reaches the **yield strength** σ_y.
- **Tensile strength**: maximum stress supported by the material.
- **Toughness**: The energy needed to break a unit volume of material.
- **Ductility**: The plastic strain at failure.