

# MECHANICAL PROPERTIES OF ENGINEERING MATERIALS

## 1. Introduction

Often materials are subject to forces (loads) when they are used. Mechanical engineers calculate those forces and material scientists how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions.

Materials scientists learn about these mechanical properties by testing materials. Results from the tests depend on the size and shape of material to be tested (specimen), how it is held, and the way of performing the test. That is why we use common procedures, or *standards*.

The engineering tension test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. In the tension test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. The parameters, which are used to describe the stress-strain curve of a metal, are the tensile strength, yield strength or yield point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility.

In the tension test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. An engineering stress-strain curve is constructed from the load elongation measurements.

The tensile test is probably the simplest and most widely used test to characterize the mechanical properties of a material. The test is performed using a loading apparatus such as the Tinius Olsen machine. The capacity of this machine is 10,000 pounds (tension and compression). The specimen of a given material (i.e. steel, aluminum, cast iron) takes a cylindrical shape that is 2.0 in. long and 0.5 in. in diameter in its undeformed (with no permanent strain or residual stress), or original shape.

The results from the tensile test have direct design implications. Many common engineering structural components are designed to perform under tension. The truss is probably the most common example of a structure whose members are designed to be in tension (and compression).

## **2. Concepts of Stress and Strain**

Stress can be defined by ratio of the perpendicular force applied to a specimen divided by its original cross sectional area, formally called engineering stress

To compare specimens of different sizes, the load is calculated per unit area, also called normalization to the area. Force divided by area is called stress. In tension and compression tests, the relevant area is that perpendicular to the force. In shear or torsion tests, the area is perpendicular to the axis of rotation. The stress is obtained by dividing the load ( $F$ ) by the original area of the cross section of the specimen ( $A_0$ ).

$$\sigma = \frac{F}{A_0}$$

The unit is the Megapascal =  $10^6$  Newtons/m<sup>2</sup>.

There is a change in dimensions, or deformation elongation,  $\Delta L$  as a result of a tensile or compressive stress. To enable comparison with specimens of different length, the elongation is also normalized, this time to the length  $l_o$ . This is called strain. So, Strain is the ratio of change in length due to deformation to the original length of the specimen, formally called engineering strain. strain is unitless, but often units of m/m (or mm/mm) are used

The strain used for the engineering stress-strain curve is the average linear strain, which is obtained by dividing the elongation of the gage length of the specimen, by its original length.

$$\epsilon = \frac{l_i - l_o}{l_o} = \frac{\Delta l}{l_o}$$

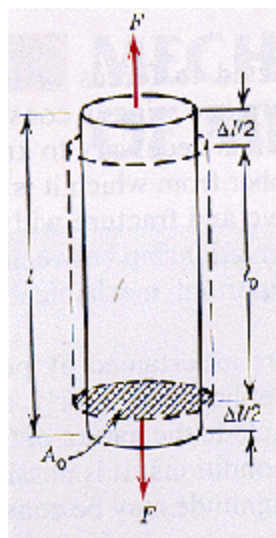
Since both the stress and the strain are obtained by dividing the load and elongation by constant factors, the load-elongation curve will have the same shape as the engineering stress-strain curve. The two curves are frequently used interchangeably.

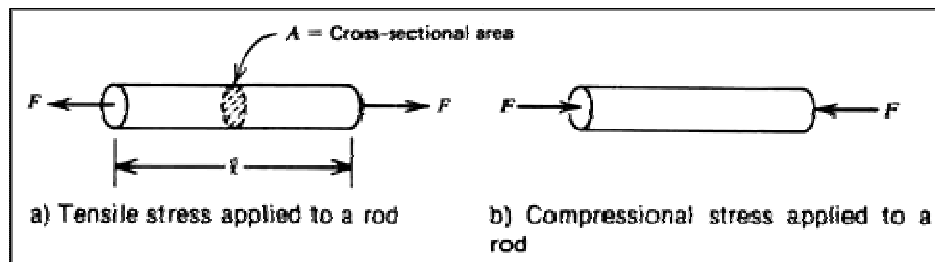
The shape and magnitude of the stress-strain curve of a metal will depend on its composition, heat treatment, prior history of plastic deformation, and the strain rate, temperature, and state of stress imposed during the testing. The parameters used to describe stress-strain curve are tensile strength, yield strength or yield

point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility.

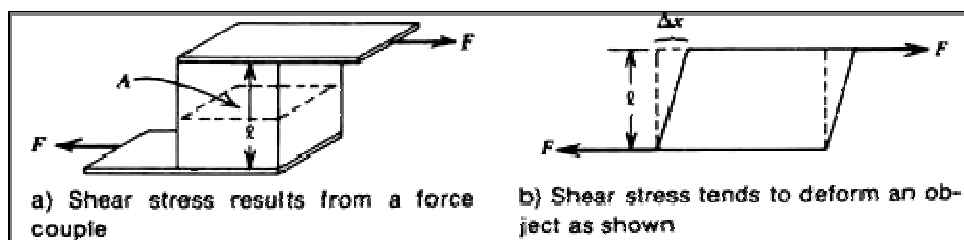
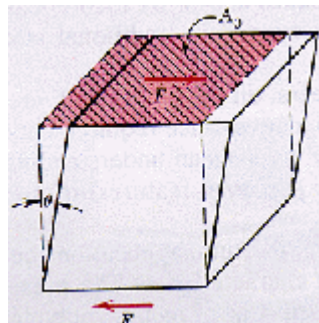
The general shape of the engineering stress-strain curve requires further explanation. In the elastic region stress is linearly proportional to strain. When the load exceeds a value corresponding to the yield strength, the specimen undergoes gross plastic deformation. It is permanently deformed if the load is released to zero. The stress to produce continued plastic deformation increases with increasing plastic strain, i.e., the metal strain-hardens. The volume of the specimen remains constant during plastic deformation,  $A \cdot L = A_0 \cdot L_0$  and as the specimen elongates, it decreases uniformly along the gage length in cross-sectional area.

Initially the strain hardening more than compensates for this decrease in area and the engineering stress (proportional to load  $P$ ) continues to rise with increasing strain. Eventually a point is reached where the decrease in specimen cross-sectional area is greater than the increase in deformation load arising from strain hardening. This condition will be reached first at some point in the specimen that is slightly weaker than the rest. All further plastic deformation is concentrated in this region, and the specimen begins to neck or thin down locally. Because the cross-sectional area now is decreasing far more rapidly than strain hardening increases the deformation load, the actual *load* required to deform the specimen falls off and the engineering stress likewise continues to decrease until fracture occurs.

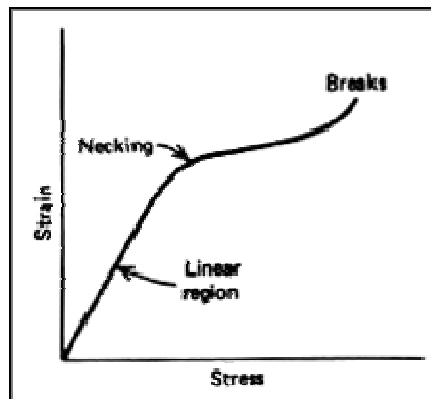
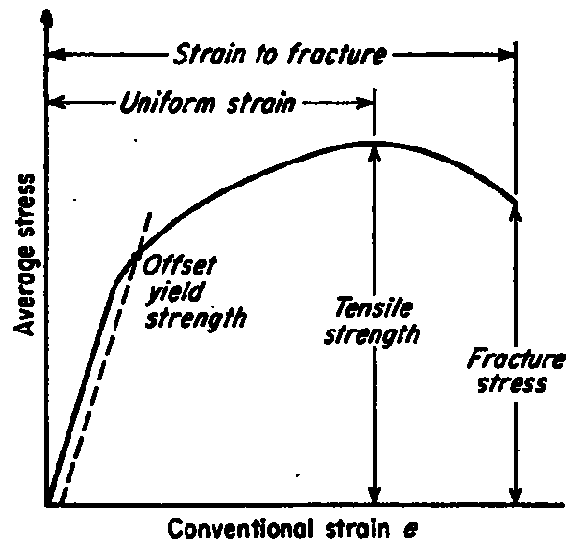




**Tensile and compressional stress can be defined in terms of forces applied to a uniform rod.**



**Shear stress is defined in terms of a couple that tends to deform a joining member**



A typical stress-strain curve showing the linear region, necking and eventual break.

Shear strain is defined as the tangent of the angle  $\theta$ , and, in essence, determines to what extent the plane was displaced. In this case, the force is applied as a *couple* (that is, *not* along the same line), tending to shear off the solid object that separates the force arms.

$$\text{shear strain} = \frac{\Delta x}{l}$$

where ,

$Dx$  = deformation in m

$l$  = width of a sample in m

In this case, the force is applied as a *couple* (that is, *not* along the same line), tending to shear off the solid object that separates the force arms. In this case, the stress is again  $\tau$ . The strain in this case is defined as the fractional change in dimension of the sheared member.

### 3. Stress—Strain Behavior

#### 3.1. Hooke's Law

- for materials stressed in tension, at relatively low levels, stress and strain are proportional through:

$$\sigma = E\varepsilon$$

- constant  $E$  is known as the modulus of elasticity, or Young's modulus.
  - Measured in MPa and can range in values from  $\sim 4.5 \times 10^4$  -  $40 \times 10^7$  MPa

The engineering stress strain graph shows that the relationship between stress and strain is linear over some range of stress. If the stress is kept within the linear region, the material is essentially *elastic* in that if the stress is removed, the deformation is also gone. But if the elastic limit is exceeded, permanent deformation results. The material may begin to "neck" at some location and finally

break. Within the linear region, a specific type of material will always follow the same curves despite different physical dimensions. Thus, it can say that the linearity and slope are a constant of the type of material only. In tensile and compressional stress, this constant is called the *modulus of elasticity* or *Young's modulus* ( $E$ ).

$$E = \frac{F/A}{\Delta L/L}$$

where stress =  $F/A$  in  $\text{N/m}^2$

strain =  $\Delta L/L$  unitless

$E$  = Modulus of elasticity in  $\text{N/m}^2$

The modulus of elasticity has units of stress, that is,  $\text{N/m}^2$ . The following table gives the modulus of elasticity for several materials. In an exactly similar fashion, the shear modulus is defined for shear stress-strain as modulus of elasticity.

Material	Modulus ( $\text{N/m}^2$ )
Aluminum	$6.89 \times 10^{10}$
Copper	$11.73 \times 10^{10}$ $20.70 \times 10^{10}$
Steel	$2.1 \times 10^8$

### 3.2 Stress-strain curve



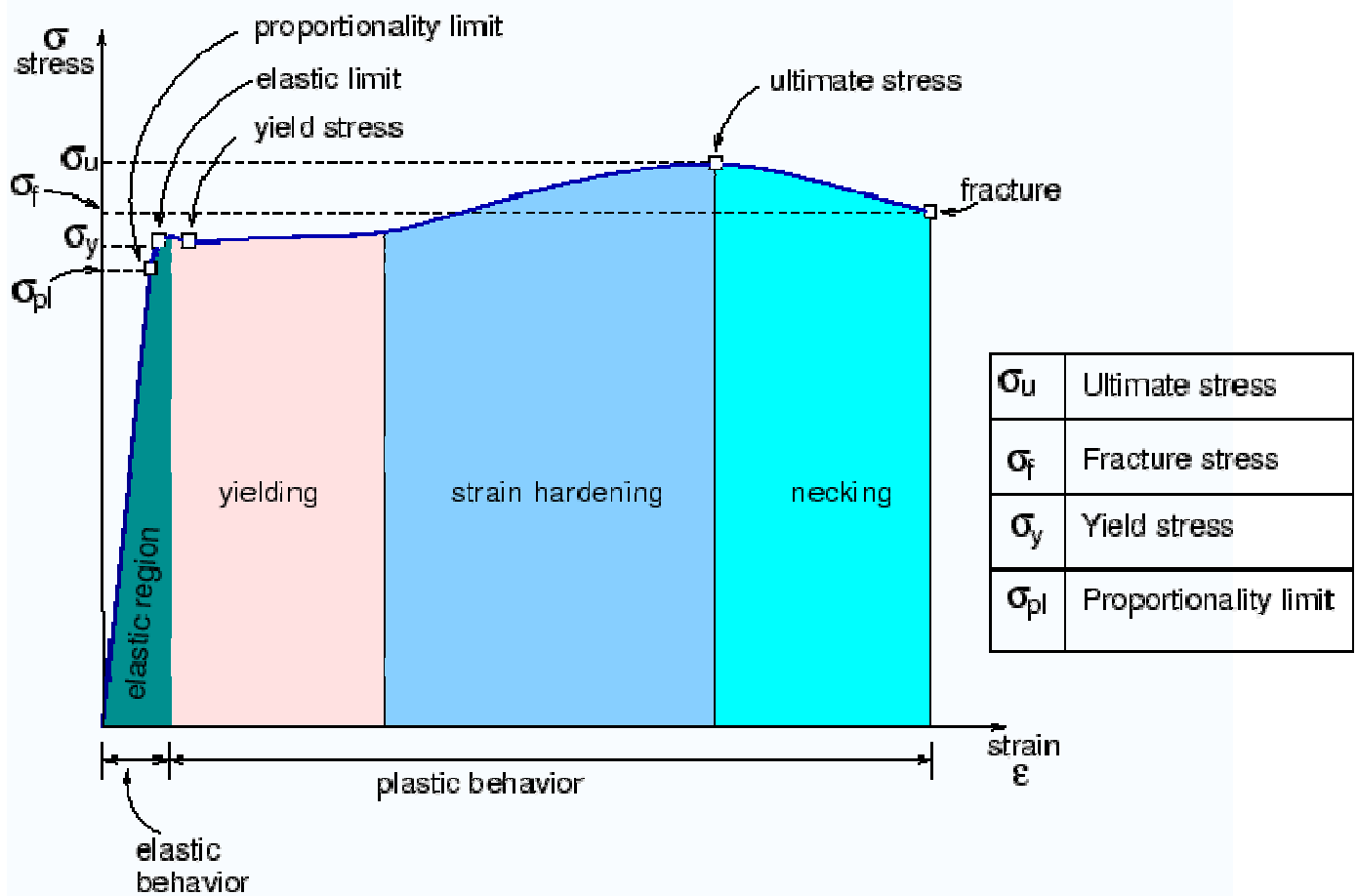
The stress-strain curve characterizes the behavior of the material tested. It is most often plotted using engineering stress and strain measures, because the reference length and cross-sectional area are easily measured. Stress-strain curves generated from tensile test results help engineers gain insight into the constitutive relationship between stress and strain for a particular material. The constitutive relationship can be thought of as providing an answer to the following question: Given a strain history for a specimen, what is the state of stress? As we shall see, even for the simplest of materials, this relationship can be very complicated.

In addition to providing quantitative information that is useful for the constitutive relationship, the stress-strain curve can also be used to qualitatively describe and classify the material. Typical regions that can be observed in a stress-strain curve are:

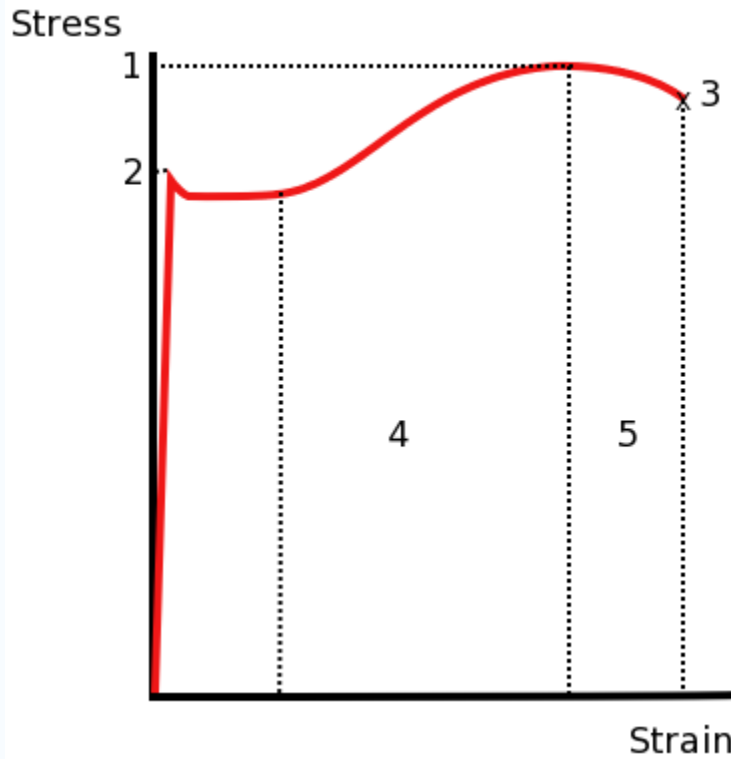
1. Elastic region
2. Yielding
3. Strain Hardening
4. Necking and Failure

A stress-strain curve with each region identified is shown below. The curve has been sketched using the assumption that the strain in the specimen is monotonically increasing - no unloading occurs. It should also be emphasized that a lot of variation from what's shown is possible with real materials, and each of the above regions will not always be so clearly delineated. It should be emphasized that the extent of each region in stress-strain space is material dependent, and that not all materials exhibit all of the above regions.

A stress-strain curve is a graph derived from measuring load (stress -  $\sigma$ ) versus extension (strain -  $\epsilon$ ) for a sample of a material. The nature of the curve varies from material to material. The following diagrams illustrate the stress-strain behaviour of typical materials in terms of the engineering stress and engineering strain where the stress and strain are calculated based on the original dimensions of the sample and not the instantaneous values. In each case the samples are loaded in tension although in many cases similar behaviour is observed in compression.



Various regions and points on the stress-strain curve.



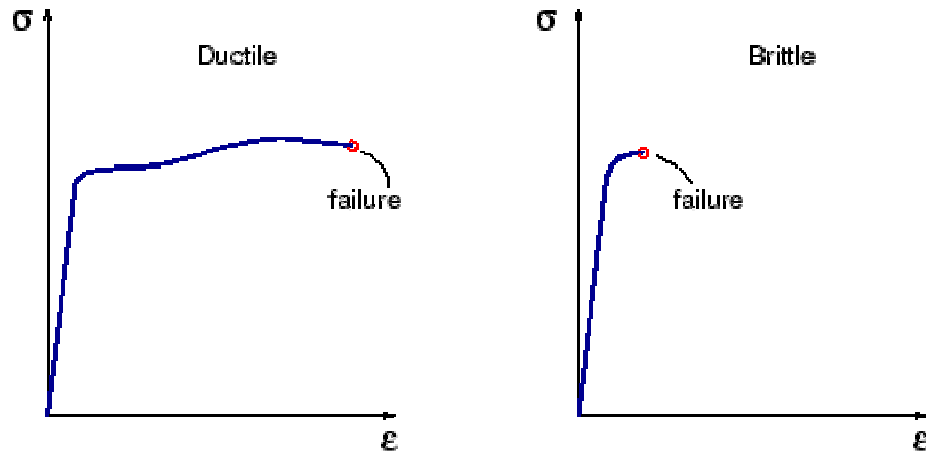
**Stress vs. Strain curve for mild steel (Ductile material).**

Reference numbers are:

- |                            |                   |            |
|----------------------------|-------------------|------------|
| 1- Ultimate strength       | 2- Yield Strength | 3- Rupture |
| 4- Strain hardening region | 5- Necking region |            |

### 3.3. Brittle and Ductile Behavior

The behavior of materials can be broadly classified into two categories; brittle and ductile. Steel and aluminum usually fall in the class of ductile materials. Glass, ceramics, plain concrete and cast iron fall in the class of brittle materials. The two categories can be distinguished by comparing the stress-strain curves, such as the ones shown in Figure.



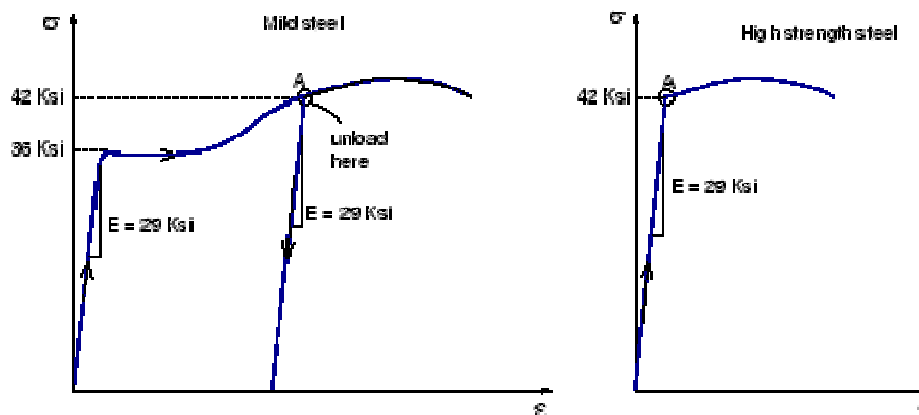
### Ductile and brittle material behavior

The material response for ductile and brittle materials are exhibited by both qualitative and quantitative differences in their respective stress-strain curves. Ductile materials will withstand large strains before the specimen ruptures; brittle materials fracture at much lower strains. The yielding region for ductile materials often takes up the majority of the stress-strain curve, whereas for brittle materials it is nearly nonexistent. Brittle materials often have relatively large Young's moduli and ultimate stresses in comparison to ductile materials.

These differences are a major consideration for design. Ductile materials exhibit large strains and yielding before they fail. On the contrary, brittle materials fail suddenly and without much warning. Thus ductile materials such as steel are a natural choice for structural members in buildings as we desire considerable warning to be provided before a building fails. The energy absorbed (per unit volume) in the tensile test is simply the area under the stress strain curve. Clearly, by comparing the curves in Figure., It can be observed that ductile materials are capable of absorbing much larger quantities of energy before failure.

Finally, it should be emphasized that not all materials can be easily classified as either ductile or brittle. Material response also depends on the operating environment; many ductile materials become brittle as the temperature is decreased. With advances in metallurgy and composite technology, other materials are advanced combinations of ductile and brittle constituents.

Often in structural design, structural members are designed to be in service below the yield stress. The reason being that once the load exceeds the yield limit, the structural members will exhibit large deformations (imagine for instance a roof sagging) that are undesirable. Thus materials with larger yield strength are preferable.

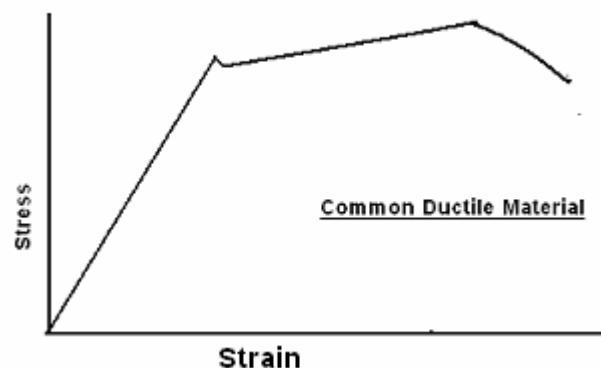


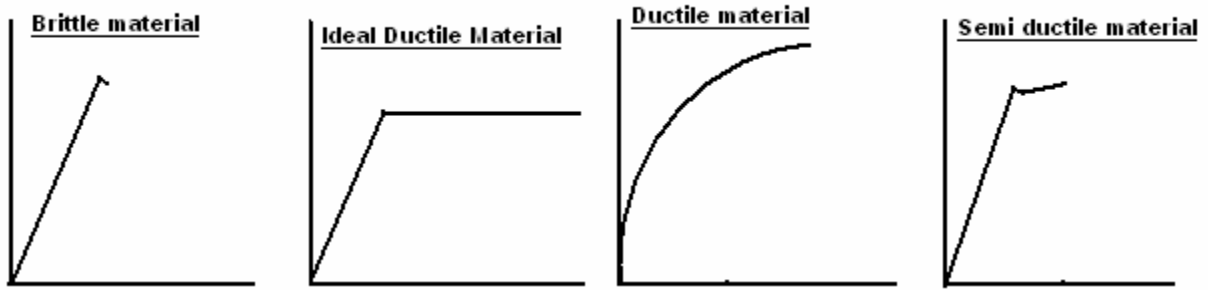
**After work hardening, the stress-strain curve of a mild steel (left) resembles that of high-strength steel (right).**

We will for now concentrate on steel, a commonly used structural material. Mild steels have a yield strength somewhere between 240 and 360 N/mm<sup>2</sup>. When work-hardened, the yield strength of this steel increases. Work hardening is the process of loading mild steel beyond its yield point and unloading as shown in Figure. When the material is loaded again, the linear elastic behavior now extends up to point A as shown. The negative aspect of work hardening is some loss in ductility of the material. It is noteworthy that mild steel is usually recycled. Because of this, the yield strength may be a little higher than expected for the mild steel specimens tested in the laboratory.

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Generally, the stress strain distribution varies from a material to another and could be in different forms as follows. Consequently, the type of material and fracture pattern can be defined and determined according to its stress-strain distribution diagram.





**Various stress-strain diagrams for different engineerin materials**

### 3.5. Yield strength

The yield point, is defined in engineering and materials science as the stress at which a material begins to plastically deform. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed some fraction of the deformation will be permanent and non-reversible. Knowledge of the yield point is vital when designing a component since it generally represents an upper limit to the load that can be applied. It is also important for the control of many materials production techniques such as forging, rolling, or pressing.

In structural engineering, **yield** is the permanent plastic deformation of a structural member under stress. This is a soft failure mode which does not normally cause catastrophic failure unless it accelerates buckling.

It is often difficult to precisely define yield due to the wide variety of stress-strain behaviours exhibited by real materials. In addition there are several possible ways to define the yield point in a given material.

Yield occurs when dislocations first begin to move. Given that dislocations begin to move at very low stresses, and the difficulty in detecting such movement, this definition is rarely used.

**Elastic Limit** - The lowest stress at which permanent deformation can be measured. This requires a complex interactive load-unload procedure and is critically dependent on the accuracy of the equipment and the skill of the operator.

**Proportional Limit** - The point at which the stress-strain curve becomes non-linear. In most metallic materials the elastic limit and proportional limit are essentially the same.

**Offset Yield Point (proof stress)** - Due to the lack of a clear border between the elastic and plastic regions in many materials, the yield point is often defined as the stress at some arbitrary plastic strain (typically 0.2%). This is determined by the intersection of a line offset from the linear region by the required strain. In some materials there is essentially no linear region and so a certain value of plastic strain is defined instead. Although somewhat arbitrary this method does allow for a consistent comparison of materials and is the most common.

### **Yield point.**

If the stress is too large, the strain deviates from being proportional to the stress. The point at which this happens is the *yield point* because there the material yields, deforming permanently (plastically).

**Yield stress.** Hooke's law is not valid beyond the yield point. The stress at the yield point is called *yield stress*, and is an important measure of the mechanical properties of materials. In practice, the yield stress is chosen as that causing a

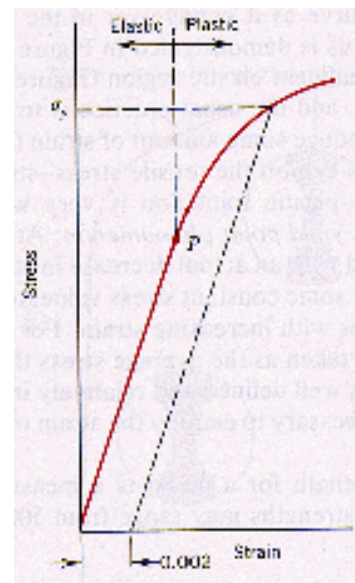


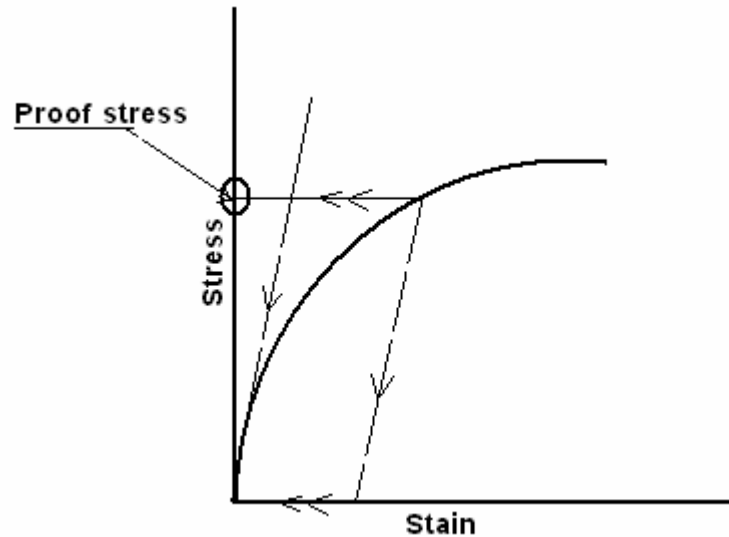
permanent strain of 0.002, which called as **proof stress**. The yield stress measures the resistance to plastic deformation.

The **yield strength** is the stress required to produce a small-specified amount of plastic deformation. The usual definition of this property is the **offset yield strength** determined by the stress corresponding to the intersection of the stress-strain curve and a line parallel to the elastic part of the curve offset by a specified strain. In the United States the offset is usually specified as a strain of 0.2 or 0.1 percent ( $e = 0.002$  or  $0.001$ ).

$$R_{p0.2} = \frac{P_{(\text{strain offset}=0.002)}}{A_0}$$

A good way of looking at offset yield strength is that after a specimen has been loaded to its 0.2 percent offset yield strength and then unloaded it will be 0.2 percent longer than before the test. The offset yield strength is often referred to in Great Britain as the **proof stress**, where offset values are either 0.1 or 0.5 percent. The yield strength obtained by an offset method is commonly used for design and specification purposes because it avoids the practical difficulties of measuring the elastic limit or proportional limit.



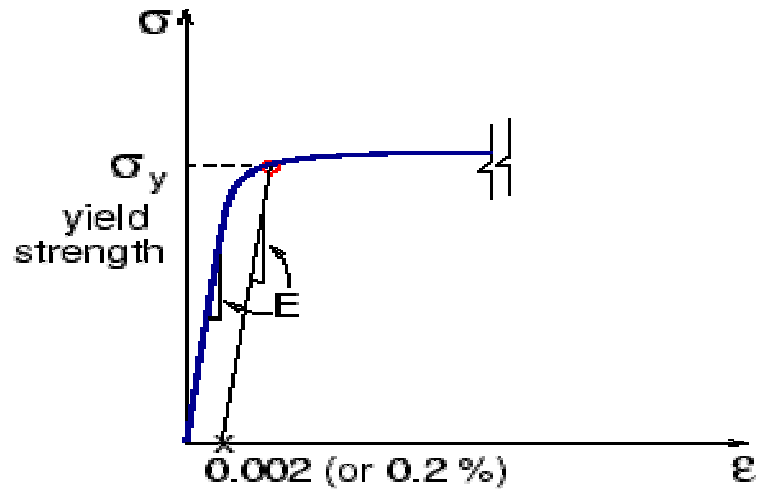


### Determination of proof stress

Some materials have essentially no linear portion to their stress-strain curve, for example, soft copper or gray cast iron. For these materials the offset method cannot be used and the usual practice is to define the yield strength as the stress to produce some total strain, for example,  $e = 0.005$ .

### Determination of Yield Strength in Ductile Materials

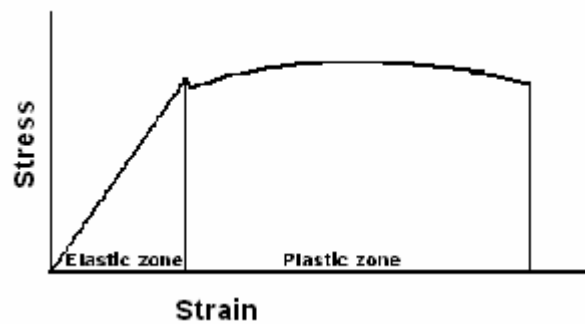
In many materials, the yield stress is not very well defined and for this reason a standard has been developed to determine its value. The standard procedure is to project a line parallel to the initial elastic region starting at 0.002 strain. The 0.002 strain point is often referred to as the **0.2 %** offset strain point. The intersection of this new line with the stress-strain curve then defines the *yield strength* as shown in Figure\_.



#### 4. Elastic Properties of Materials

When the stress is removed, the material returns to the dimension it had before the load was applied. Valid for small strains (except the case of rubbers).

Deformation is *reversible, non permanent*



Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the *Poisson's ratio*.

When a material is placed under a tensile stress, an accompanying strain is created in the same direction.

Poisson's ratio is the ratio of the lateral to axial strains.

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = \frac{\epsilon_y}{\epsilon_z}$$

The elastic modulus, shear modulus and Poisson's ratio are related by  $E = 2G(1 + \nu)$

$$\mathbf{E = 2G(1 + \nu)}$$

- Theoretically, isotropic materials will have a value for Poisson's ratio of 0.25.
- The maximum value of  $\nu$  is 0.5
- Most metals exhibit values between 0.25 and 0.35

## **9. Plastic deformation.**

When the stress is removed, the material does not return to its previous dimension but there is a *permanent*, irreversible deformation.

For metallic materials, elastic deformation only occurs to strains of about 0.005. After this point, plastic (non-recoverable) deformation occurs, and Hooke's Law is no longer valid.

On an atomic level, plastic deformation is caused by *slip*, where atomic bonds are broken by dislocation motion, and new bonds are formed.

## 5. Anelasticity

Here the behavior is elastic but not the stress-strain curve is not immediately reversible. It takes a while for the strain to return to zero. The effect is normally small for metals but can be significant for polymers.

## 6. Tensile strength.

When stress continues in the plastic regime, the stress-strain passes through a maximum, called the *tensile strength* ( $s_{TS}$ ), and then falls as the material starts to develop a *neck* and it finally breaks at the *fracture point*.

Note that it is called strength, not stress, but the units are the same, MPa.

For structural applications, the yield stress is usually a more important property than the tensile strength, since once the it is passed, the structure has deformed beyond acceptable limits.

The tensile strength, or ultimate tensile strength (UTS), is the maximum load divided by the original cross-sectional area of the specimen.

$$R_m = \frac{P_{max}}{A_0}$$

The tensile strength is the value most often quoted from the results of a tension test; yet in reality it is a value of little fundamental significance with regard to the strength of a metal. For ductile metals the tensile strength should be regarded as a measure of the maximum load, which a metal can withstand under the very restrictive conditions of uniaxial loading. It will be shown that this value bears little relation to the useful strength of the metal under the more complex conditions of stress, which are usually encountered.

For many years it was customary to base the strength of members on the tensile strength, suitably reduced by a factor of safety. The current trend is to the more rational approach of basing the static design of ductile metals on the yield strength.

However, because of the long practice of using the tensile strength to determine the strength of materials, it has become a very familiar property, and as such it is a very useful identification of a material in the same sense that the chemical composition serves to identify a metal or alloy.

Further, because the tensile strength is easy to determine and is a quite reproducible property, it is useful for the purposes of specifications and for quality control of a product. Extensive empirical correlations between tensile strength and properties such as hardness and fatigue strength are often quite useful. For brittle materials, the tensile strength is a valid criterion for design.

## **7. Ductility**

The ability to deform before breaking. It is the opposite of **brittleness**. Ductility can be given either as percent maximum elongation  $e_{\max}$  or maximum area reduction.

At our present degree of understanding, ductility is a qualitative, subjective property of a material. In general, measurements of ductility are of interest in three ways:

1. To indicate the extent to which a metal can be deformed without fracture in metal working operations such as rolling and extrusion.
2. To indicate to the designer, in a general way, the ability of the metal to flow plastically before fracture. A high ductility indicates that the material is "forgiving" and likely to deform locally without fracture should the designer err in the stress calculation or the prediction of severe loads.
3. To serve as an indicator of changes in impurity level or processing conditions. Ductility measurements may be specified to assess material quality even though no direct relationship exists between the ductility measurement and performance in service.

The conventional measures of ductility that are obtained from the tension test are the engineering strain at fracture  $e_f$  (usually called the *elongation*) and the *reduction of area* at fracture  $q$ . Both of these properties are obtained after fracture by putting the specimen back together and taking measurements of  $L_f$  and  $A_f$ .

$$e_f = \frac{L_f - L_0}{L_0}$$

$$q = \frac{A_0 - A_f}{A_0}$$

Because an appreciable fraction of the plastic deformation will be concentrated in the necked region of the tension specimen, the value of  $e_f$  will depend on the gage

length  $L_0$  over which the measurement was taken. The smaller the gage length the greater will be the contribution to the overall elongation from the necked region and the higher will be the value of  $e_f$ . Therefore, when reporting values of percentage elongation, the gage length  $L_0$  always should be given.

The reduction of area does not suffer from this difficulty. Reduction of area values can be converted into an equivalent **zero-gage-length elongation**  $e_0$ . From the constancy of volume relationship for plastic deformation  $A*L = A_0*L_0$ , we obtain

$$\frac{L}{L_0} = \frac{A_0}{A} = \frac{1}{1 - q}, \quad e_0 = \frac{L - L_0}{L_0} = \frac{A_0}{A} - 1 = \frac{1}{1 - q} - 1 = \frac{q}{1 - q}$$

This represents the elongation based on a very short gage length near the fracture.

Another way to avoid the complication from necking is to base the percentage elongation on the uniform strain out to the point at which necking begins. The uniform elongation  $e_u$  correlates well with stretch-forming operations. Since the engineering stress-strain curve often is quite flat in the vicinity of necking, it may be difficult to establish the strain at maximum load without ambiguity. In this case the method suggested by Nelson and Winlock is useful.

## 8. Resilience

The resilience of the material is the triangular area underneath the elastic region of the curve. **Resilience** generally means the ability to recover from (or to resist being affected by) some shock, insult, or disturbance. However, it is used quite differently in different fields.

In physics and engineering, **resilience** is defined as the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading to have



this energy recovered. In other words, it is the maximum energy per volume that can be elastically stored. It is represented by the area under the curve in the elastic region in the Stress-Strain diagram.

Modulus of Resilience,  $U_r$ , can be calculated using the following formula:

$$U_r = \frac{\sigma^2}{2E} = 0.5\sigma\epsilon = 0.5\sigma\left(\frac{\sigma}{E}\right),$$

where  $\sigma$  is yield stress,  $E$  is Young's modulus, and  $\epsilon$  is strain.

The ability of a material to absorb energy when deformed elastically and to return it when unloaded is called resilience. This is usually measured by the modulus of resilience, which is the strain energy per unit volume required to stress the material from, zero stress to the yield stress.

The ability of a material to absorb energy when deformed elastically and to return it when unloaded is called **resilience**. This is usually measured by the **modulus of resilience**, which is the strain energy per unit volume required to stress the material from, zero stress to the yield stress  $s$ . The strain energy per unit volume for uniaxial tension is

$$U_0 = \frac{1}{2} \sigma_x \epsilon_x$$

Table 1 gives some values of modulus of resilience for different materials.

**Table 1. Modulus of resilience for various materials**

<b>Material</b>	<b>E, psi</b>	<b>s<sub>0</sub>, psi</b>	<b>Modulus of resilience, U<sub>r</sub></b>
<b>Medium-carbon steel</b>	30×10 <sup>6</sup>	45000	33,7
<b>High-carbon spring steel</b>	30×10 <sup>6</sup>	140000	320
<b>Duraluminium</b>	10,5×10 <sup>6</sup>	18000	17,0
<b>Cooper</b>	16×10 <sup>6</sup>	4000	5,3
<b>Rubber</b>	150	300	300
<b>Acrylic polymer</b>	0,5×10 <sup>6</sup>	2000	4,0

## 9. Toughness

The area underneath the stress-strain curve is the toughness of the material- i.e. the energy the material can absorb prior to rupture.. It also can be defined as the resistance of a material to crack propagation.

In materials science and metallurgy, **toughness** is the resistance to fracture of a material when stressed. It is defined as the amount of energy that a material can absorb before rupturing, and can be found by finding the area (i.e., by taking the integral) underneath the stress-strain curve.

The ability of a metal to deform plastically and to absorb energy in the process before fracture is termed toughness. The emphasis of this definition should be placed on the ability to absorb energy before fracture. Recall that ductility is a measure of how much something deforms plastically before fracture, but just because a material is ductile does not make it tough. The key to toughness is a

good combination of strength and ductility. A material with high strength and high ductility will have more toughness than a material with low strength and high ductility. Therefore, one way to measure toughness is by calculating the area under the stress strain curve from a tensile test. This value is simply called “material toughness” and it has units of energy per volume. Material toughness equates to a slow absorption of energy by the material.

The toughness of a material is its ability to absorb energy in the plastic range. The ability to withstand occasional, stresses above the yield stress without fracturing is particularly desirable in parts such as freight-car couplings, gears, chains, and crane hooks. Toughness is a commonly used concept, which is difficult to pin down and define. One way of looking at toughness is to consider that it is the total area under the stress-strain curve. This area is an indication of the amount of work per unit volume, which can be done, on the material without causing it to rupture. The following Figure shows the stress-strain curves for high- and low-toughness materials. The high-carbon spring steel has a higher yield strength and tensile strength than the medium-carbon structural steel. However, the structural steel is more ductile and has a greater total elongation. The total area under the stress-strain curve is greater for the structural steel, and therefore it is a tougher material. This illustrates that toughness is a parameter that comprises **both** strength and ductility. The crosshatched regions in Figure indicate the modulus of resilience for each steel. Because of its higher yield strength, the spring steel has the greater resilience.

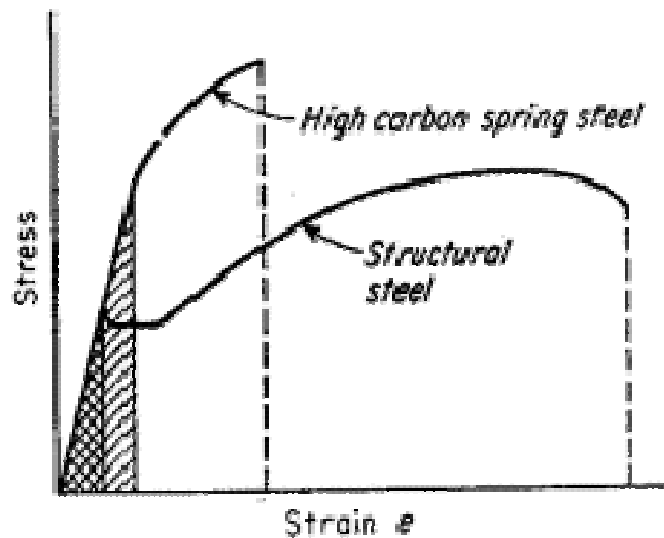
Several mathematical approximations for the area under the stress-strain curve have been suggested. For ductile metals that have a stress-strain curve like that of the structural steel, the area under the curve can be approximated by either of the following equations:

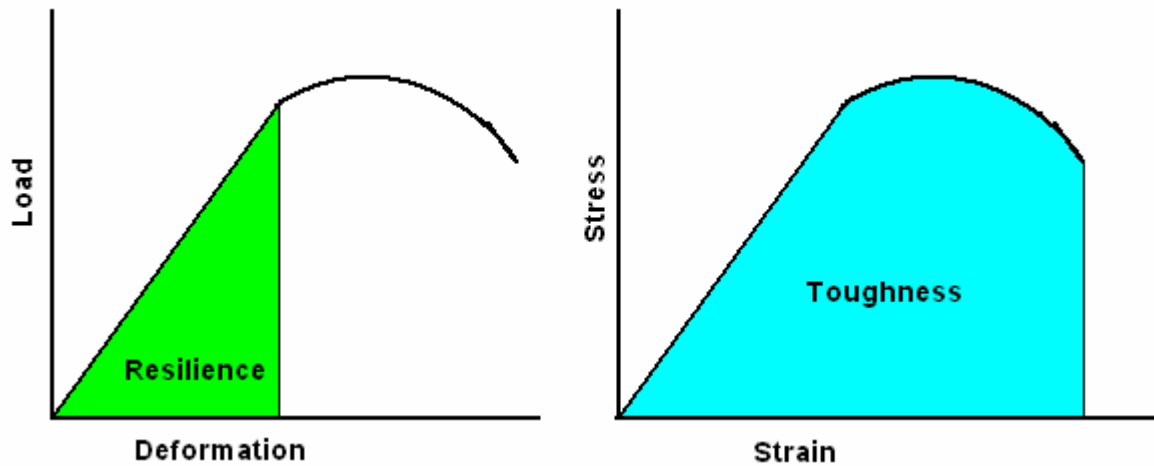
$$U_T \approx S_u e_f \qquad U_T \approx \frac{s_p + s_u}{2} \cdot e_f$$

For brittle materials the stress-strain curve is sometimes assumed to be a parabola, and the area under the curve is given by

$$U_T \approx \frac{2}{3} S_u e_f$$

All these relations are only approximations to the area under the stress-strain curves. Further, the curves do not represent the true behavior in the plastic range, since they are all based on the original area of the specimen.





### Comparison between resilience and toughness of metals

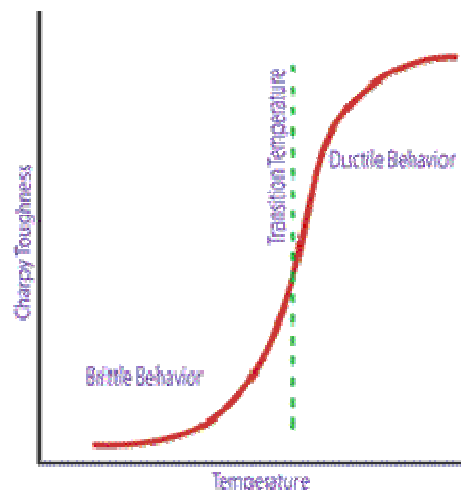
#### 9.1. Impact Toughness

Three of the toughness properties that will be discussed in more detail are 1) impact toughness, 2) notch toughness and 3) fracture toughness.

The impact toughness (AKA Impact strength) of a material can be determined with a Charpy or Izod test. These tests are named after their inventors and were developed in the early 1900's before fracture mechanics theory was available.

Impact properties are not directly used in fracture mechanics calculations, but the economical impact tests continue to be used as a quality control method to assess notch sensitivity and toughness of

for comparing the relative engineering materials.



The two tests use different specimens and methods of holding the specimens, but both tests make use of a pendulum-testing machine. For both tests, the specimen is broken by a single overload event due to the impact of the pendulum. A stop pointer is used to record how far the pendulum swings back up after fracturing the specimen. The impact toughness of a metal is determined by measuring the energy absorbed in the fracture of the specimen. This is simply obtained by noting the height at which the pendulum is released and the height to which the pendulum swings after it has struck the specimen. The height of the pendulum times the weight of the pendulum produces the potential energy and the difference in potential energy of the pendulum at the start and the end of the test is equal to the absorbed energy.

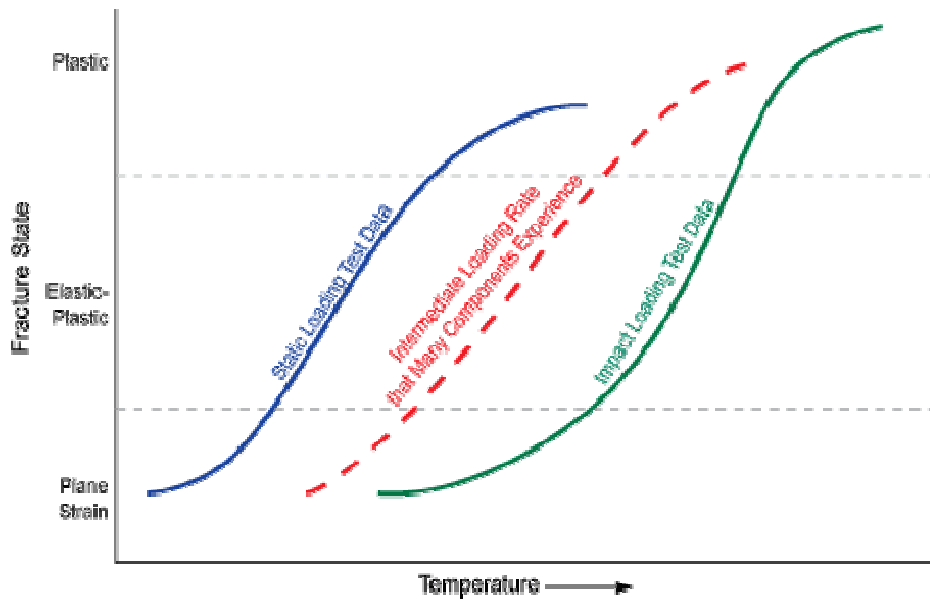
Since toughness is greatly affected by temperature, a Charpy or Izod test is often repeated numerous times with each specimen tested at a different temperature. This produces a graph of impact toughness for the material as a function of temperature. An impact toughness versus temperature graph for a steel is shown in the image. It can be seen that at low temperatures the material is more brittle and impact toughness is low. At high temperatures the material is more ductile and impact

toughness is higher. The transition temperature is the boundary between brittle and ductile behavior and this temperature is often an extremely important consideration in the selection of a material.

## **9.2 Notch-Toughness**

Notch toughness is the ability that a material possesses to absorb energy in the presence of a flaw. As mentioned previously, in the presence of a flaw, such as a notch or crack, a material will likely exhibit a lower level of toughness. When a flaw is present in a material, loading induces a triaxial tension stress state adjacent to the flaw. The material develops plastic strains as the yield stress is exceeded in the region near the crack tip. However, the amount of plastic deformation is restricted by the surrounding material, which remains elastic. When a material is prevented from deforming plastically, it fails in a brittle manner.

Notch-toughness is measured with a variety of specimens such as the Charpy V-notch impact specimen or the dynamic tear test specimen. As with regular impact testing the tests are often repeated numerous times with specimens tested at a different temperature. With these specimens and by varying the loading speed and the temperature, it is possible to generate curves such as those shown in the graph. Typically only static and impact testing is conducted but it should be recognized that many components in service see intermediate loading rates in the range of the dashed red line.



### 9.3. Fracture Toughness

In materials science, **fracture toughness** is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for virtually all design applications. It is denoted  $K_{1c}$  and has the units of  $MPa\sqrt{m}$ .

The subscript '1c' denotes mode 1 crack opening or plain strain, the material has to be too thick to shear, mode 2, or tear, mode 3.

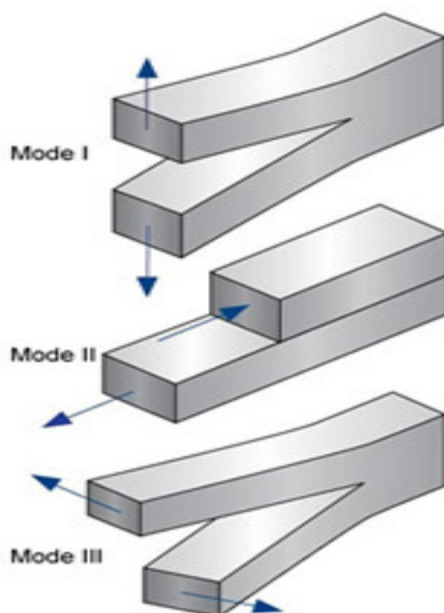
Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture when a crack is present. If a material has a large value of fracture toughness it will probably undergo ductile fracture. Brittle fracture is very characteristic of materials with a low fracture toughness value.



Fracture mechanics, which leads to the concept of fracture toughness, was largely based on the work of A. A. Griffith who, amongst other things, studied the behaviour of cracks in brittle materials.

Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of component

This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture.



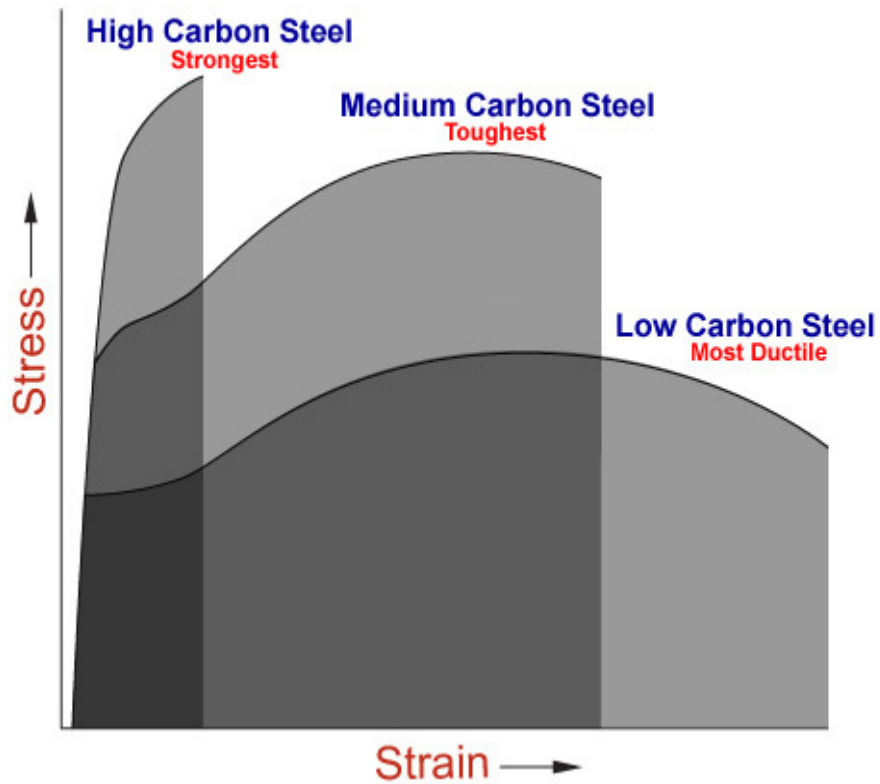
A parameter called the stress-intensity factor (K) is used to determine the fracture toughness of most materials. A Roman numeral subscript indicates the mode of fracture and the three modes of fracture are illustrated in the image to the right. Mode I fracture is the condition in which the crack plane is normal to the direction of largest tensile loading. This is the most commonly encountered mode and, therefore, for the remainder of the material we will consider  $K_I$

The stress intensity factor is a function of loading, crack size, and structural geometry. The stress intensity factor may be represented by

the following equation:

$$K_I = \sigma \sqrt{\pi a \beta}$$

- Where:
- $K_I$  is the fracture toughness in  $MPa\sqrt{m}$  ( $psi\sqrt{in}$ )
  - $\sigma$  is the applied stress in MPa or psi
  - $a$  is the crack length in meters or inches
  - $\beta$  is a crack length and component geometry factor that is different for each specimen and is dimensionless



There are several variables that have a profound influence on the toughness of a material. These variables are:

- Strain rate (rate of loading)
- Temperature
- Notch effect

A metal may possess satisfactory toughness under static loads but may fail under dynamic loads or impact. As a rule ductility and, therefore, toughness decrease as the rate of loading increases. Temperature is the second variable to have a major influence on its toughness. As temperature is lowered, the ductility and toughness

also decrease. The third variable is termed notch effect, has to do with the distribution of stress. A material might display good toughness when the applied stress is uniaxial; but when a multiaxial stress state is produced due to the presence of a notch, the material might not withstand the simultaneous elastic and plastic deformation in the various directions.

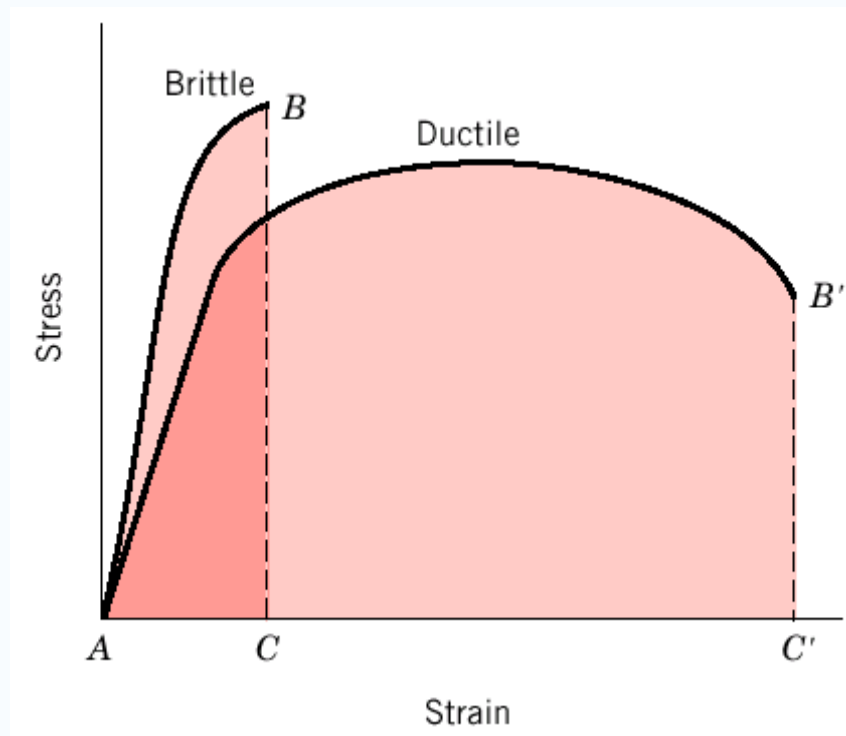
There are several standard types of toughness test that generate data for specific loading conditions and/or component design approaches.

## 10. Material Types

**Brittle materials** such as concrete or ceramics do not have a yield point. For these materials the rupture strength and the ultimate strength are the same.

**Ductile material** (such as steel) generally exhibits a very linear stress-strain relationship up to a well defined yield point. The linear portion of the curve is the elastic region and the slope is the modulus of elasticity or Young's Modulus. After the yield point the curve typically decreases slightly due to dislocations escaping from Cottrell atmospheres. As deformation continues the stress increases due to strain hardening until it reaches the ultimate strength. Until this point the cross-sectional area decreases uniformly due to Poisson contractions. However, beyond this point a *neck* forms where the local cross-sectional area decreases more quickly than the rest of the sample resulting in an increase in the true stress. On an engineering stress-strain curve this is seen as a decrease in the stress. Conversely, if the curve is plotted in terms of *true stress* and *true strain* the stress will continue to rise until failure. Eventually the neck becomes unstable and the specimen ruptures (fractures).

Most ductile metals other than steel do not have a well-defined yield point. For these materials the yield strength is typically determined by the "offset yield method", by which a line is drawn parallel to the linear elastic portion of the curve and intersecting the abscissa at some arbitrary value (most commonly .2%). The intersection of this line and the stress-strain curve is reported as the yield point.



**a- Ductile materials** - extensive plastic deformation and energy absorption (“toughness”) before fracture. Ductile materials can be classified into various classifications; 1- Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature., 2- Moderately ductile fracture, typical for ductile metals, 3- Brittle fracture, cold metals, ceramics.

**b- Brittle materials** – has a little plastic deformation and low energy absorption before fracture

## 11. True Stress and Strain

When one applies a constant tensile force the material will break after reaching the tensile strength. The material starts necking (the transverse area decreases) but the stress cannot increase beyond  $\sigma_{TS}$ . The ratio of the force to the initial area, what we normally do, is called the engineering stress. If the ratio is to the actual area (that changes with stress) one obtains the true stress.

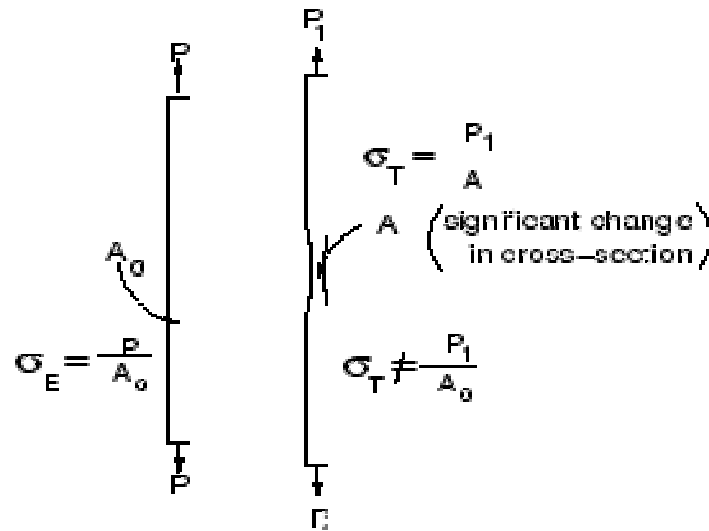
Stress has units of a force measure divided by the square of a length measure, and the average stress on a cross-section in the tensile test is the applied force divided by the cross-sectional area. Similarly, we may approximate the strain component along the long axis of the specimen as the change in length divided by the original reference length.

It sounds simple enough, but you should realize that there are still some choices to make. Specifically, what area should be used for the cross-sectional area? Should you use the original area or the current area as the load is applied? By the same token, should changes in length always be compared to the original length of the specimen?

The answer is that we will define different types of stress strain measures according to the way we perform the calculations. *Engineering* stress and strain measures are distinguished by the use of fixed reference quantities, typically the original cross-sectional area or original length. More precisely,

$$\sigma_E = \frac{P}{A_0}, \quad \epsilon_E = \frac{\Delta l}{l_0}.$$

In most engineering applications, these definitions are accurate enough, because the cross-sectional area and length of the specimen do not change substantially while loads are applied. In other situations (such as the tensile test), the cross-sectional area and the length of the specimen can change substantially. In such cases, the engineering stress calculated using the above definition (as the ratio of the applied load to the **undeformed** cross-sectional area) ceases to be an accurate measure. To overcome this issue alternative stress and strain measures are available. Below we discuss *true stress* and *true strain*.



**Engineering stress measures vs. true stress measures. The latter accounts for the change in cross-sectional area as the loads are applied.**

**True Stress:** The true stress is defined as the ratio of the applied load ( $P$ ) to the instantaneous cross-sectional area ( $A$ ):

True stress can be related to the engineering stress if we assume that there is no volume change in the specimen. Under this assumption, stress can be related to the engineering stress if we assume that there is no volume change in the specimen.

$$A \cdot l = A_0 \cdot l_0,$$

which leads to:

$$\sigma_T = \frac{P}{A} = \frac{P}{A_0} \cdot \frac{l}{l_0} = \sigma_E (1 + \epsilon_E).$$

**True Strain:** The true strain is defined as the sum of all the instantaneous engineering strains. Letting

$$d\epsilon = \frac{dl}{l},$$

the true strain is then

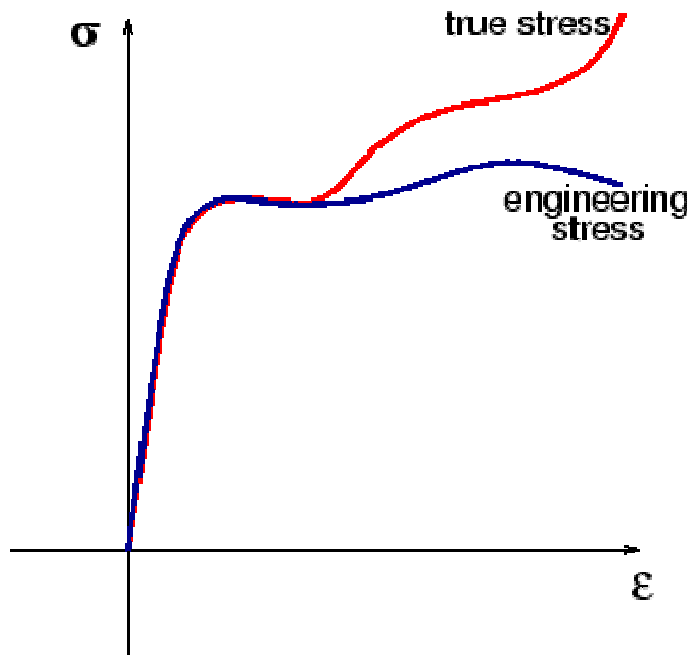
$$\epsilon_T = \int d\epsilon = \int_{l_0}^{l_f} \frac{dl}{l} = \epsilon_T = \int d\epsilon = \int_{l_0}^{l_f} \frac{dl}{l} = \ln \frac{l_f}{l_0} = \ln \frac{l_f}{l_0}.$$

where  $l_f$  is the final length when the loading process is terminated. True strain can also be related back to the engineering strain, through the manipulation where  $l_f$  is the final length when the loading process is terminated. True strain can also be related back to the engineering strain, through the manipulation



$$\epsilon_T = \ln \frac{l_f}{l_0} = \ln \frac{l_0 + \Delta l}{l_0} = \ln (1 + \epsilon_E)$$

In closing, you should note that the true stress and strain are practically indistinguishable from the engineering stress and strain at small deformations, as shown below in Figure 4. You should also note that as the strain becomes large and the cross-sectional area of the specimen decreases, the true stress can be much larger than the engineering stress.



**Engineering stress-strain curve vs. a true stress-strain curve**

### **True Stress - True Strain Curve**

The engineering stress-strain curve does not give a true indication of the deformation characteristics of a metal because it is based entirely on the original dimensions of the specimen, and these dimensions change continuously during the

test. Also, ductile metal which is pulled in tension becomes unstable and necks down during the course of the test. Because the cross-sectional area of the specimen is decreasing rapidly at this stage in the test, the load required continuing deformation falls off. The average stress based on original area like wise decreases, and this produces the fall-off in the stress-strain curve beyond the point of maximum load.

The engineering stress-strain curve does not give a true indication of the deformation characteristics of a metal because it is based entirely on the original dimensions of the specimen, and these dimensions change continuously during the test. Also, ductile metal which is pulled in tension becomes unstable and necks down during the course of the test. Because the cross-sectional area of the specimen is decreasing rapidly at this stage in the test, the load required continuing deformation falls off. The average stress based on original area likewise decreases, and this produces the fall-off in the stress-strain curve beyond the point of maximum load. Actually, the metal continues to strain-harden all the way up to fracture, so that the stress required to produce further deformation should also increase. If the true stress, based on the actual cross-sectional area of the specimen, is used, it is found that the stress-strain curve increases continuously up to fracture. If the strain measurement is also based on instantaneous measurements, the curve, which is obtained, is known as a **true-stress-true-strain curve**. This is also known as a flow curve since it represents the basic plastic-flow characteristics of the material. Any point on the flow curve can be considered the yield stress for a metal strained in tension by the amount shown on the curve. Thus, if the load is removed at this point and then reapplied, the material will behave elastically throughout the entire range of reloading. The true stress is expressed in terms of engineering stress  $s$  by

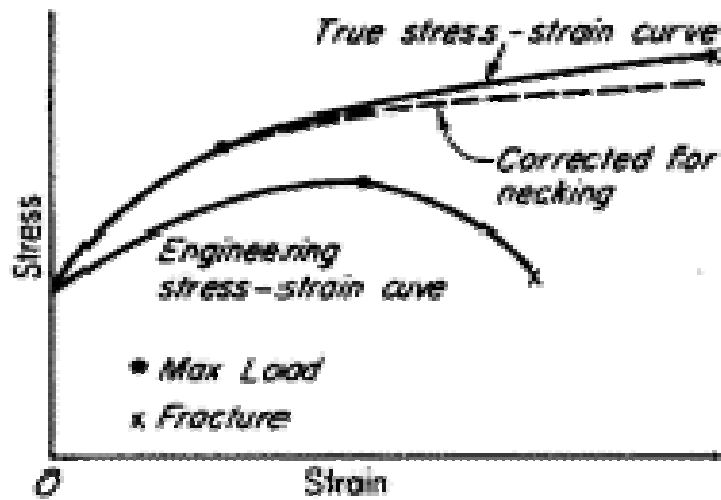
$$\sigma = \frac{P}{A_1} \cdot (e + 1) = s \cdot (e + 1)$$

The derivation of this Eq. assumes both constancy of volume and a homogenous distribution of strain along the gage length of the tension specimen. Thus, Eq. should only be used until the onset of necking. Beyond maximum load the true stress should be determined from actual measurements of load and cross-sectional area.

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

The true strain may be determined from the engineering or conventional strain  $e$  by

$$\epsilon = \ln (e + 1)$$



**Comparison of engineering and true stress-strain curves**

This equation is applicable only to the onset of necking for the reasons discussed above. Beyond maximum load the true strain should be based on actual area or diameter measurements.

$$\epsilon = \ln \frac{A_i}{A} = \ln \frac{(\pi/4)D_0^2}{(\pi/4)D^2} = 2 \ln \frac{D_0}{D}$$

The above Figure compares the true-stress-true-strain curve with its corresponding engineering stress-strain curve. Note that because of the relatively large plastic strains, the elastic region has been compressed into the y-axis. The true-stress-true-strain curve is always to the left of the engineering curve until the maximum load is reached. However, beyond maximum load the high-localized strains in the necked region that are used in last Equ far exceed the engineering strain calculated from first eq. Frequently the flow curve is linear from maximum load to fracture, while in other cases its slope continuously decreases up to fracture. The formation of a necked region or mild notch introduces triaxial stresses, which make it difficult to determine accurately the longitudinal tensile stress on out to fracture. The following parameters usually are determined from the true-stress-true-strain curve.

### **True Stress at Maximum Load**

The true stress at maximum load corresponds to the true tensile strength. For most materials necking begins at maximum load at a value of strain where the true stress equals the slope of the flow curve. Let  $\sigma_u$  and  $\epsilon_u$  denote the true stress and true strain at maximum load when the cross-sectional area of the specimen is  $A_u$ . The ultimate tensile strength is given by

$$s_u = \frac{P_{max}}{A_0}$$

$$\sigma_u = \frac{P_{max}}{A_u}$$

$$\epsilon_u = \ln \frac{A_0}{A_u}$$

Eliminating  $P_{max}$  yields

$$\sigma_u = s_u \frac{A_0}{A_u}$$

$$\sigma_u = s_u e^{\epsilon_u}$$

### **True Fracture Stress**

The true fracture stress is the load at fracture divided by the cross-sectional area at fracture. This stress should be corrected for the triaxial state of stress existing in the tensile specimen at fracture. Since the data required for this correction are often not available, true-fracture-stress values are frequently in error.

### **True Fracture Strain**

The true fracture strain  $\epsilon_f$  is the true strain based on the original area  $A_0$  and the area after fracture  $A_f$

$$\epsilon_f = \ln \frac{A_0}{A_f}$$

This parameter represents the maximum true strain that the material can withstand before fracture and is analogous to the total strain to fracture of the engineering stress-strain curve. Since Eq. (3) is not valid beyond the onset of necking, it is not possible to calculate  $\epsilon_f$  from measured values of  $\epsilon_f$ . However, for cylindrical tensile specimens the reduction of area  $q$  is related to the true fracture strain by the relationship

$$\epsilon_f = \ln \frac{1}{1 - q}$$

### **True Uniform Strain**

The true uniform strain is the true strain based only on the strain up to maximum load. It may be calculated from either the specimen cross-sectional area  $A_u$  or the gage length  $L_u$  at maximum load. The uniform strain is often useful in estimating the formability of metals from the results of a tension test.

$$\epsilon_u = \ln \frac{A_0}{A_u}$$

### **True Local Necking Strain**

The local necking strain is the strain required to deform the specimen from maximum load to fracture.

$$\epsilon = \ln \frac{A_u}{A_f}$$

The flow curve of many metals in the region of uniform plastic deformation can be expressed by the simple power curve relation

where  $n$  is the **strain-hardening exponent**  $\sigma = K \cdot \epsilon^n$

and  $K$  is the **strength coefficient**. A log-log plot of true stress and true strain up to maximum load will result in a straight-line. For most metals  $n$  has values between 0.10 and 0.50 (see the following Table.).

Table Values for  $n$  and  $K$  for metals at room temperature

<b>Metal</b>	<b>Condition</b>	<b>n</b>	<b>K, psi</b>
<b>0,05% C steel</b>	Annealed	0,26	77000
<b>SAE 4340 steel</b>	Annealed	0,15	93000
<b>0,60% C steel</b>	Quenched and tempered 1000°F	0,10	228000
<b>0,60% C steel</b>	Quenched and tempered 1300°F	0,19	178000
<b>Copper</b>	Annealed	0,54	46400
<b>70/30 brass</b>	Annealed	0,49	130000

## 12. Elastic Recovery During Plastic Deformation

If a material is taken beyond the yield point (it is deformed plastically) and the stress is then released, the material ends up with a permanent strain. If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point *that is higher than the original yield point* (strain hardening). The amount of

elastic strain that it will take before reaching the yield point is called *elastic strain recovery*.

### **13. Compressive, Shear, and Torsional Deformation**

Compressive and shear stresses give similar behavior to tensile stresses, but in the case of compressive stresses there is no maximum in the s-e curve, since no necking occurs.

### **14. Hardness**

**Hardness** is the resistance to plastic deformation (e.g., a local dent or scratch). Thus, it is a measure of *plastic* deformation, as is the tensile strength, so they are well correlated. Historically, it was measured on an empirically scale, determined by the ability of a material to scratch another, diamond being the hardest and talc the softer. Now we use standard tests, where a ball, or point is pressed into a material and the size of the dent is measured. There are a few different hardness tests: Rockwell, Brinell, Vickers, etc. They are popular because they are easy and non-destructive (except for the small dent).

Hardness is the resistance of a material to localized deformation. The term can apply to deformation from indentation, scratching, cutting or bending. In metals, ceramics and most polymers, the deformation considered is plastic deformation of the surface. For elastomers and some polymers, hardness is defined at the resistance to elastic deformation of the surface. The lack of a fundamental definition indicates that hardness is not be a basic property of a material, but rather a composite one with contributions from the yield strength, work hardening, true



tensile strength, modulus, and others factors. Hardness measurements are widely used for the quality control of materials because they are quick and considered to be nondestructive tests when the marks or indentations produced by the test are in low stress areas.

There are a large variety of methods used for determining the hardness of a substance. A few of the more common methods are introduced below.

### **Mohs Hardness Test**

One of the oldest ways of measuring hardness was devised by the German mineralogist Friedrich Mohs in 1812. The Mohs hardness test involves observing whether a materials surface is scratched by a substance of known or defined hardness. To give numerical values to this physical property, minerals are ranked along the Mohs scale, which is composed of 10 minerals that have been given arbitrary hardness values. Mohs hardness test, while greatly facilitating the identification of minerals in the field, is not suitable for accurately gauging the hardness of industrial materials such as steel or ceramics. For engineering materials, a variety of instruments have been developed over the years to provide a precise measure of hardness. Many apply a load and measure the depth or size of the resulting indentation. Hardness can be measured on the macro-, micro- or nano- scale.

### **Brinell Hardness Test**

The oldest of the hardness test methods in common use on engineering materials today is the Brinell hardness test. Dr. J. A. Brinell invented the Brinell test in

Sweden in 1900. The Brinell test uses a desktop machine to applying a specified load to a hardened sphere of a specified diameter. The Brinell hardness number, or simply the Brinell number, is obtained by dividing the load used, in kilograms, by the measured surface area of the indentation, in square millimeters, left on the test surface. The Brinell test is frequently used to determine the hardness metal forgings and castings that have a large grain structures. The Brinell test provides a measurement over a fairly large area that is less affected by the course grain structure of these materials than are Rockwell or Vickers tests.

A wide range of materials can be tested using a Brinell test simply by varying the test load and indenter ball size. In the USA, Brinell testing is typically done on iron and steel castings using a 3000Kg test force and a 10mm diameter ball. A 1500 kilogram load is usually used for aluminum castings. Copper, brass and thin stock are frequently tested using a 500Kg test force and a 10 or 5mm ball. In Europe Brinell testing is done using a much wider range of forces and ball sizes and it is common to perform Brinell tests on small parts using a 1mm carbide ball and a test force as low as 1kg. These low load tests are commonly referred to as baby Brinell tests. The test conditions should be reported along with the Brinell hardness number. A value reported as "60 HB 10/1500/30" means that a Brinell Hardness of 60 was obtained using a 10mm diameter ball with a 1500 kilogram load applied for 30 seconds.

### **Rockwell Hardness Test**

The Rockwell Hardness test also uses a machine to apply a specific load and then measure the depth of the resulting impression. The indenter may either be a steel ball of some specified diameter or a spherical diamond-tipped cone of 120° angle and 0.2 mm tip radius, called a brale. A minor load of 10 kg is first applied, which

causes a small initial penetration to seat the indenter and remove the effects of any surface irregularities. Then, the dial is set to zero and the major load is applied. Upon removal of the major load, the depth reading is taken while the minor load is still on. The hardness number may then be read directly from the scale. The indenter and the test load used determine the hardness scale that is used (A, B, C, etc).

For soft materials such as copper alloys, soft steel, and aluminum alloys a 1/16" diameter steel ball is used with a 100-kilogram load and the hardness is read on the "B" scale. In testing harder materials, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the "C" scale. There are several Rockwell scales other than the "B" & "C" scales, (which are called the common scales). A properly reported Rockwell value will have the hardness number followed by "HR" (Hardness Rockwell) and the scale letter. For example, 50 HRB indicates that the material has a hardness reading of 50 on the B scale.

### **Rockwell Superficial Hardness Test**

The Rockwell Superficial Hardness Tester is used to test thin materials, lightly carburized steel surfaces, or parts that might bend or crush under the conditions of the regular test. This tester uses the same indenters as the standard Rockwell tester but the loads are reduced. A minor load of 3 kilograms is used and the major load is either 15 or 45 kilograms depending on the indenter used. Using the 1/16" diameter, steel ball indenter, a "T" is added (meaning thin sheet testing) to the superficial hardness designation. An example of a superficial Rockwell hardness is

23 HR15T, which indicates the superficial hardness as 23, with a load of 15 kilograms using the steel ball.

### **Vickers and Knoop Microhardness Tests**

The Vickers and Knoop Hardness Tests are a modification of the Brinell test and are used to measure the hardness of thin film coatings or the surface hardness of case-hardened parts. With these tests, a small diamond pyramid is pressed into the sample under loads that are much less than those used in the Brinell test. The difference between the Vickers and the Knoop Tests is simply the shape of the diamond pyramid indenter. The Vickers test uses a square pyramidal indenter which is prone to crack brittle materials. Consequently, the Knoop test using a rhombic-based (diagonal ratio 7.114:1) pyramidal indenter was developed which produces longer but shallower indentations. For the same load, Knoop indentations are about 2.8 times longer than Vickers indentations.

An applied load ranging from 10g to 1,000g is used. This low amount of load creates a small indent that must be measured under a microscope. The measurements for hard coatings like TiN must be taken at very high magnification (i.e. 1000X), because the indents are so small. The surface usually needs to be polished. The diagonals of the impression are measured, and these values are used to obtain a hardness number (VHN), usually from a lookup table or chart. The Vickers test can be used to characterize very hard materials but the hardness is measured over a very small region.

The values are expressed like 2500 HK25 (or HV25) meaning 2500 Hardness Knoop at 25 gram force load. The Knoop and Vickers hardness values differ slightly, but for hard coatings, the values are close enough to be within the measurement error and can be used interchangeably.

## **Scleroscope and Rebound Hardness Tests**

The Scleroscope test is a very old test that involves dropping a diamond tipped hammer, which falls inside a glass tube under the force of its own weight from a fixed height, onto the test specimen. The height of the rebound travel of the hammer is measured on a graduated scale. The scale of the rebound is arbitrarily chosen and consists on Shore units, divided into 100 parts, which represent the average rebound from pure hardened high-carbon steel. The scale is continued higher than 100 to include metals having greater hardness. The Shore Scleroscope measures hardness in terms of the elasticity of the material and the hardness number depends on the height to which the hammer rebounds, the harder the material, the higher the rebound.

The Rebound Hardness Test Method is a recent advancement that builds on the Scleroscope. There are a variety of electronic instruments on the market that measure the loss of energy of the impact body. These instruments typically use a spring to accelerate a spherical, tungsten carbide tipped mass towards the surface of the test object. When the mass contacts the surface it has a specific kinetic energy and the impact produces an indentation (plastic deformation) on the surface which takes some of this energy from the impact body. The impact body will lose more energy and its rebound velocity will be less when a larger indentation is produced on softer material. The velocities of the impact body before and after impact are measured and the loss of velocity is related to Brinell, Rockwell, or other common hardness value.

## **Durometer Hardness Test**

A Durometer is an instrument that is commonly used for measuring the indentation hardness of rubbers/elastomers and soft plastics such as polyolefin, fluoropolymer, and vinyl. A Durometer simply uses a calibrated spring to apply a specific pressure to an indenter foot. The indenter foot can be either cone or sphere shaped. An indicating device measures the depth of indentation. Durometers are available in a variety of models and the most popular testers are the Model A used for measuring softer materials and the Model D for harder materials.

### **Barcol Hardness Test**

The Barcol hardness test obtains a hardness value by measuring the penetration of a sharp steel point under a spring load. The specimen is placed under the indenter of the Barcol hardness tester and a uniform pressure is applied until the dial indication reaches a maximum. The Barcol hardness test method is used to determine the hardness of both reinforced and non-reinforced rigid plastics and to determine the degree of cure of resins and plastics

## **14. Variability of Material Properties**

Tests do not produce exactly the same result because of variations in the test equipment, procedures, operator bias, specimen fabrication, etc. But, even if all those parameters are controlled within strict limits, a variation remains in the materials, due to uncontrolled variations during fabrication, non homogenous composition and structure, etc. The measured mechanical properties will show scatter, which is often distributed in a Gaussian curve (bell-shaped), that is characterized by the mean value and the standard deviation (width).

## **15. Design/Safety Factors**

To take into account variability of properties, designers use, instead of an average value of, say, the tensile strength, the probability that the yield strength is above the minimum value tolerable. This leads to the use of a *safety factor*  $N > 1$  (varies from 1.2 to 4). Thus, a working value for the tensile strength would be  $s_W = s_{TS} / N$ .

## 16. Theoretical strength and practical strength

The term of theoretical strength is used to express the state of stress of pure (ideal) material that does not contain any defects, such as flaws, cracks and pores. So, the maximum theoretical strength is corresponding to the amount of stresses required to separate atoms from each other, i.e. stress required to break the bond strength between adjacent atoms. The theoretical strength ( $\sigma_{th}$ ) of a material can be determined using the following Eq.

$$\sigma_{th} = \sqrt{\frac{E\gamma}{a}}$$

where: E is young Modulus

$\gamma$  is the surface energy of atoms

a is the equilibrium distance between atoms

It is clear from the above equation  $\sigma_{th}$  is dependent on material characteristics (E, a,  $\gamma$ ). This means that every material has its own theoretical strength.

On the other hand, the practical strength (actual strength) is used when the engineering material contains defects such as pore, flaws, and cracks. These defects could lead to decrease the material's theoretical strength dramatically, due

to stress concentration around the defects, causing rapid failure on some occasions. The practical strength ( $\sigma_p$ ) can be calculated using the following formula:

$$(\sigma_p) = \sqrt{\frac{EG}{\Pi c}}$$

Where E is the young modulus

G is the Fracture toughness

C is the crack length

It is clear from the above equation  $\sigma_{th}$  is dependent on material characteristics (E, G) and crack length. This means that material can undergo failure according to the presence of crack on its surface or inside it. So engineers have to minimize the amount of cracks to enhance the practical strength of engineering materials.



