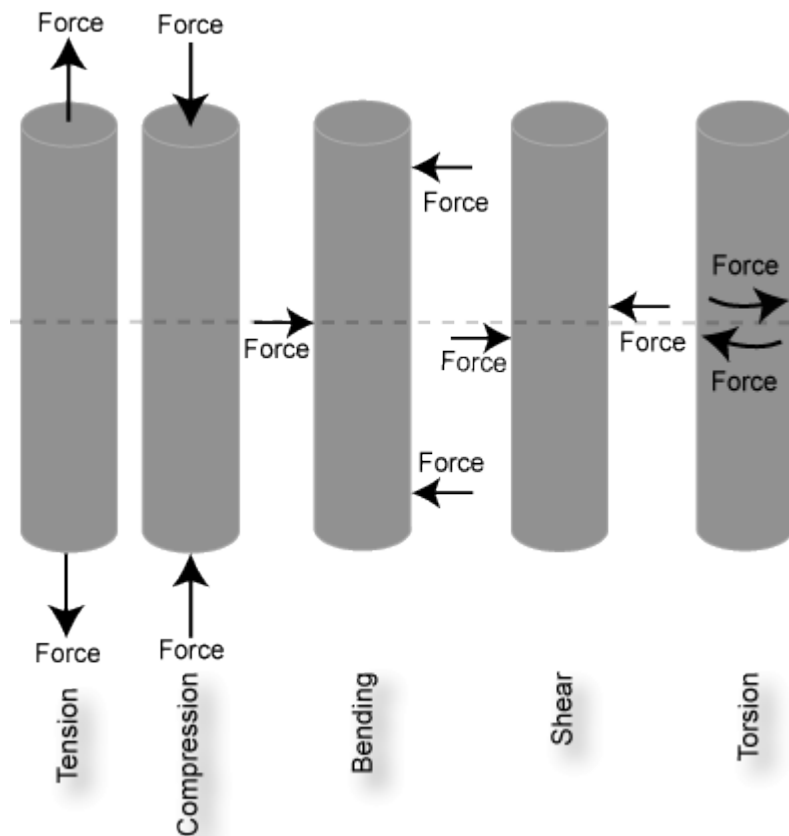


# Loading

<https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/Loading.htm>

The application of a force to an object is known as loading. Materials can be subjected to many different loading scenarios and a material's performance is dependant on the loading conditions. There are five fundamental loading conditions; tension, compression, bending, shear, and torsion. Tension is the type of loading in which the two sections of material on either side of a plane tend to be pulled apart or elongated. Compression is the reverse of tensile loading and involves pressing the material together. Loading by bending involves applying a load in a manner that causes a material to curve and results in compressing the material on one side and stretching it on the other. Shear involves applying a load parallel to a plane which caused the material on one side of the plane to want to slide across the material on the other side of the plane. Torsion is the application of a force that causes twisting in a material.



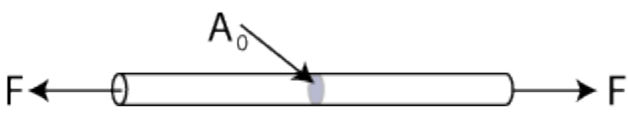
If a material is subjected to a constant force, it is called static loading. If the loading of the material is not constant but instead fluctuates, it is called dynamic or cyclic loading. The way a material is loaded greatly affects its mechanical properties and largely determines how, or if, a component will fail; and whether it will show warning signs before failure actually occurs.

# Stress and Strain

## Stress

The term stress ( $\sigma$ ) is used to express the loading in terms of force applied to a certain cross-sectional area of an object. From the perspective of loading, stress is the applied force or system of forces that tends to deform a body. From the perspective of what is happening within a material, stress is the internal distribution of forces within a body that balance and react to the loads applied to it. The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, a bar loaded in pure tension will essentially have a uniform tensile stress distribution. However, a bar loaded in bending will have a stress distribution that changes with distance perpendicular to the normal axis.

Simplifying assumptions are often used to represent stress as a vector quantity for many engineering calculations and for material property determination. The word "**vector**" typically refers to a quantity that has a "magnitude" and a "direction". For example, the stress in an axially loaded bar is simply equal to the applied force divided by the bar's cross-sectional area.



$$\text{Stress, } \sigma = \frac{\text{Force}}{\text{Cross-Sectional Area}} = \frac{F}{A_0}$$

Some common measurements of stress are:

Psi = lbs/in<sup>2</sup> (pounds per square inch)

ksi or kpsi = kilopounds/in<sup>2</sup> (one thousand or 10<sup>3</sup> pounds per square inch)

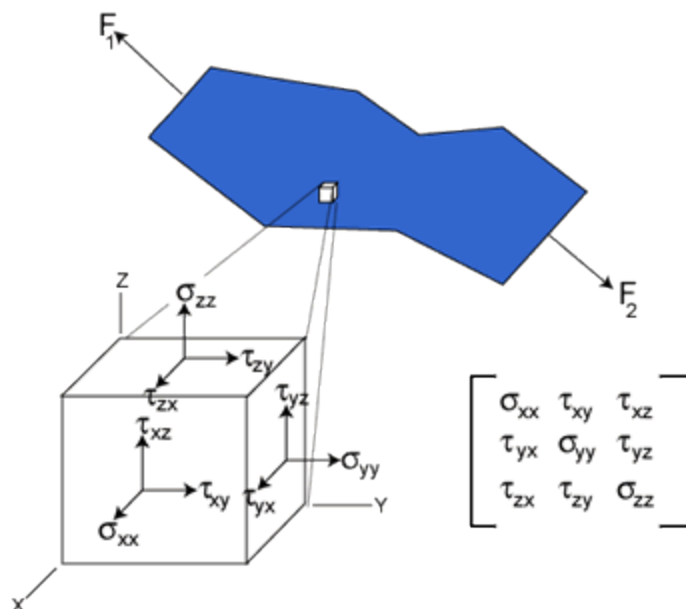
Pa = N/m<sup>2</sup> (Pascals or Newtons per square meter)

kPa = Kilopascals (one thousand or 10<sup>3</sup> Newtons per square meter)

GPa = Gigapascals (one million or 10<sup>6</sup> Newtons per square meter)

\*Any metric prefix can be added in front of psi or Pa to indicate the multiplication factor

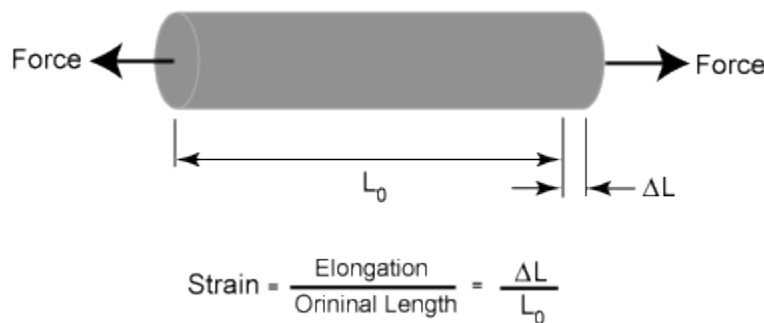
It must be noted that the stresses in most 2-D or 3-D solids are actually more complex and need be defined more methodically. The internal force acting on a small area of a plane can be resolved into three components: one normal to the plane and two parallel to



the plane. The normal force component divided by the area gives the normal stress ( $s$ ), and parallel force components divided by the area give the shear stress ( $t$ ). These stresses are average stresses as the area is finite, but when the area is allowed to approach zero, the stresses become stresses at a point. Since stresses are defined in relation to the plane that passes through the point under consideration, and the number of such planes is infinite, there appear an infinite set of stresses at a point. Fortunately, it can be proven that the stresses on any plane can be computed from the stresses on three orthogonal planes passing through the point. As each plane has three stresses, the stress tensor has nine stress components, which completely describe the state of stress at a point.

## Strain

Strain is the response of a system to an applied stress. When a material is loaded with a force, it produces a stress, which then causes a material to deform. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material. This results in a unitless number, although it is often left in the unsimplified form, such as inches per inch or meters per meter. For example, the strain in a bar that is being stretched in tension is the amount of elongation or change in length divided by its original length. As in the case of stress, the strain distribution may or may not be uniform in a complex structural element, depending on the nature of the loading condition.



If the stress is small, the material may only strain a small amount and the material will return to its original size after the stress is released. This is called elastic deformation, because like elastic it returns to its unstressed state. Elastic deformation only occurs in a material when stresses are lower than a critical stress called the yield strength. If a material is loaded beyond its elastic limit, the material will remain in a deformed condition after the load is removed. This is called plastic deformation.

## Engineering and True Stress and Strain

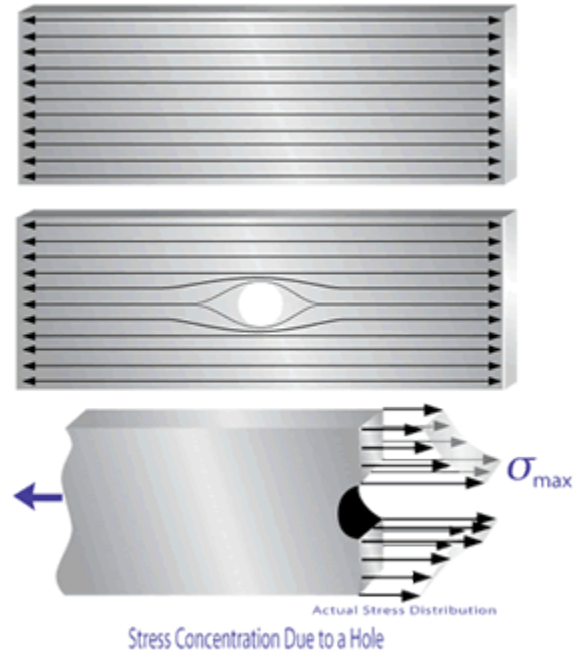
The discussion above focused on *engineering* stress and strain, which use the fixed, undeformed cross-sectional area in the calculations. *True* stress and strain measures account for changes in cross-sectional area by using the *instantaneous* values for the area. The engineering stress-strain curve 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 testing used to generate the data.

Engineering stress and strain data is commonly used because it is easier to generate the data and

the tensile properties are adequate for engineering calculations. When considering the stress-strain curves in the next section, however, it should be understood that metals and other materials continue to strain-harden until they fracture and the stress required to produce further deformation also increases.

### Stress Concentration

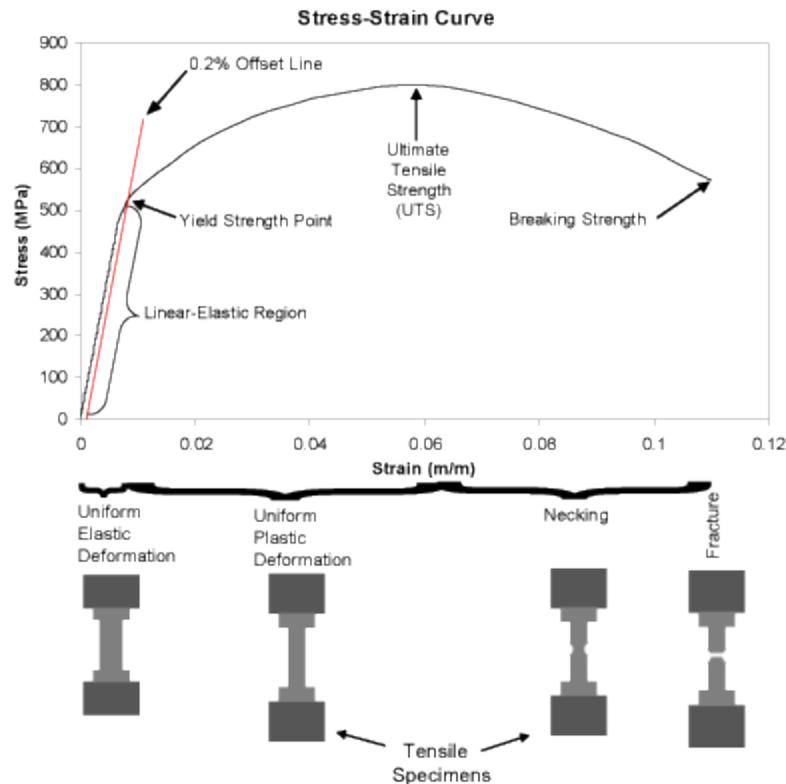
When an axial load is applied to a piece of material with a uniform cross-section, the normal stress will be uniformly distributed over the cross-section. However, if a hole is drilled in the material, the stress distribution will no longer be uniform. Since the material that has been removed from the hole is no longer available to carry any load, the load must be redistributed over the remaining material. It is not redistributed evenly over the entire remaining cross-sectional area but instead will be redistributed in an uneven pattern that is highest at the edges of the hole as shown in the image. This phenomenon is known as stress concentration.



### Tensile Properties

Tensile properties indicate how the material will react to forces being applied in tension. A tensile test is a fundamental mechanical test where a carefully prepared specimen is loaded in a very controlled manner while measuring the applied load and the elongation of the specimen over some distance. Tensile tests are used to determine the modulus of elasticity, elastic limit, elongation, proportional limit, reduction in area, tensile strength, yield point, yield strength and other tensile properties.

The main product of a tensile test is a load versus elongation curve which is then converted into a stress versus strain curve. Since both the engineering stress and the engineering strain are obtained by dividing the load and elongation by constant values (specimen geometry information), the load-elongation curve will have the same shape as the engineering stress-strain curve. The stress-strain curve relates the applied stress to the resulting strain and each material has its own unique stress-strain curve. A typical engineering stress-strain curve is shown below. 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.



### Linear-Elastic Region and Elastic Constants

As can be seen in the figure, the stress and strain initially increase with a linear relationship. This is the linear-elastic portion of the curve and it indicates that no plastic deformation has occurred. In this region of the curve, when the stress is reduced, the material will return to its original shape. In this linear region, the line obeys the relationship defined as **Hooke's Law** where the ratio of stress to strain is a constant.

The slope of the line in this region where stress is proportional to strain and is called the **modulus of elasticity** or **Young's modulus**. The modulus of elasticity ( $E$ ) defines the properties of a material as it undergoes stress, deforms, and then returns to its original shape after the stress is removed. It is a measure of the stiffness of a given material. To compute the modulus of elasticity, simply divide the stress by the strain in the material. Since strain is unitless, the modulus will have the same units as the stress, such as kpi or MPa. The modulus of elasticity applies specifically to the situation of a component being stretched with a tensile force. This modulus is of interest when it is necessary to compute how much a rod or wire stretches under a tensile load.

There are several different kinds of moduli depending on the way the material is being stretched, bent, or otherwise distorted. When a component is subjected to pure shear, for instance, a cylindrical bar under torsion, the shear modulus describes the linear-elastic stress-strain relationship.

Axial strain is always accompanied by lateral strains of opposite sign in the two directions mutually perpendicular to the axial strain. Strains that result from an increase in length are

designated as positive (+) and those that result in a decrease in length are designated as negative (-). **Poisson's ratio** is defined as the negative of the ratio of the lateral strain to the axial strain for a uniaxial stress state.

$$\nu = - \frac{\epsilon_{lateral}}{\epsilon_{axial}}$$

Poisson's ratio is sometimes also defined as the ratio of the absolute values of lateral and axial strain. This ratio, like strain, is unitless since both strains are unitless. For stresses within the elastic range, this ratio is approximately constant. For a perfectly isotropic elastic material, Poisson's Ratio is 0.25, but for most materials the value lies in the range of 0.28 to 0.33. Generally for steels, Poisson's ratio will have a value of approximately 0.3. This means that if there is one inch per inch of deformation in the direction that stress is applied, there will be 0.3 inches per inch of deformation perpendicular to the direction that force is applied.

Only two of the elastic constants are independent so if two constants are known, the third can be calculated using the following formula:

$$E = 2 (1 + \nu) G.$$

Where: E = modulus of elasticity (Young's modulus)  
n = Poisson's ratio  
G = modulus of rigidity (shear modulus).

A couple of additional elastic constants that may be encountered include the bulk modulus (K), and Lamé's constants (m and l). The bulk modulus is used to describe the situation where a piece of material is subjected to a pressure increase on all sides. The relationship between the change in pressure and the resulting strain produced is the bulk modulus. Lamé's constants are derived from modulus of elasticity and Poisson's ratio.

### Yield Point

In ductile materials, at some point, the stress-strain curve deviates from the straight-line relationship and Hooke's Law no longer applies as the strain increases faster than the stress. From this point on in the tensile test, some permanent deformation occurs in the specimen and the material is said to react plastically to any further increase in load or stress. The material will not return to its original, unstressed condition when the load is removed. In brittle materials, little or no plastic deformation occurs and the material fractures near the end of the linear-elastic portion of the curve.

With most materials there is a gradual transition from elastic to plastic behavior, and the exact point at which plastic deformation begins to occur is hard to determine. Therefore, various criteria for the initiation of yielding are used depending on the sensitivity of the strain measurements and the intended use of the data. (See Table) For most engineering design and specification applications, the yield strength is used. The yield strength is defined as the stress

required to produce a small, amount of plastic deformation. The offset yield strength is 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 US the offset is typically 0.2% for metals and 2% for plastics).

To determine the yield strength using this offset, the point is found on the strain axis (x-axis) of 0.002, and then a line parallel to the stress-strain line is drawn. This line will intersect the stress-strain line slightly after it begins to curve, and that intersection is defined as the yield strength with a 0.2% offset. 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. Even though the yield strength is meant to represent the exact point at which the material becomes permanently deformed, 0.2% elongation is considered to be a tolerable amount of sacrifice for the ease it creates in defining the yield strength.

In Great Britain, the yield strength is often referred to as the proof stress. The offset value is either 0.1% or 0.5%

Some materials such as gray cast iron or soft copper exhibit essentially no linear-elastic behavior. For these materials the usual practice is to define the yield strength as the stress required to produce some total amount of strain.

- **True elastic limit** is a very low value and is related to the motion of a few hundred dislocations. Micro strain measurements are required to detect strain on order of  $2 \times 10^{-6}$  in/in.
- **Proportional limit** is the highest stress at which stress is directly proportional to strain. It is obtained by observing the deviation from the straight-line portion of the stress-strain curve.
- **Elastic limit** is the greatest stress the material can withstand without any measurable permanent strain remaining on the complete release of load. It is determined using a tedious incremental loading-unloading test procedure. With the sensitivity of strain measurements usually employed in engineering studies ( $10^{-4}$  in/in), the elastic limit is greater than the proportional limit. With increasing sensitivity of strain measurement, the value of the elastic limit decreases until it eventually equals the true elastic limit determined from micro strain measurements.
- **Yield strength** is the stress required to produce a small-specified amount of plastic deformation. The yield strength obtained by an offset method is commonly used for engineering purposes because it avoids the practical difficulties of measuring the elastic limit or proportional limit.

### Ultimate Tensile Strength

The ultimate tensile strength (UTS) or, more simply, the tensile strength, is the maximum engineering stress level reached in a tension test. The strength of a material is its ability to withstand external forces without breaking. In brittle materials, the UTS will be at the end of the linear-elastic portion of the stress-strain curve or close to the elastic limit. In ductile materials, the UTS will be well outside of the elastic portion into the plastic portion of the stress-strain curve.

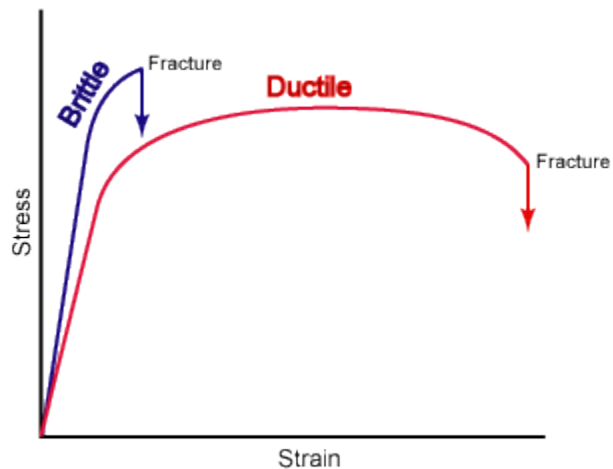


On the stress-strain curve above, the UTS is the highest point where the line is momentarily flat. Since the UTS is based on the engineering stress, it is often not the same as the breaking strength. In ductile materials strain hardening occurs and the stress will continue to increase until fracture occurs, but the engineering stress-strain curve may show a decline in the stress level before fracture occurs. This is the result of engineering stress being based on the original cross-section area and not accounting for the necking that commonly occurs in the test specimen. The UTS may not be completely representative of the highest level of stress that a material can support, but the value is not typically used in the design of components anyway. For ductile metals the current design practice is to use the yield strength for sizing static components. However, since the UTS is easy to determine and quite reproducible, it is useful for the purposes of specifying a material and for quality control purposes. On the other hand, for brittle materials the design of a component may be based on the tensile strength of the material.

### Measures of Ductility (Elongation and Reduction of Area)

The ductility of a material is a measure of the extent to which a material will deform before fracture. The amount of ductility is an important factor when considering forming operations such as rolling and extrusion. It also provides an indication of how visible overload damage to a component might become before the component fractures. Ductility is also used as a quality control measure to assess the level of impurities and proper processing of a material.

The conventional measures of ductility are the engineering strain at fracture (usually called the elongation) and the reduction of area at fracture. Both of these properties are obtained by fitting the specimen back together after fracture and measuring the change in length and cross-sectional area. Elongation is the change in axial length divided by the original length of the specimen or portion of the specimen. It is expressed as a percentage. Because an appreciable fraction of the plastic deformation will be concentrated in the necked region of the tensile specimen, the value of elongation will depend on the gage length over which the measurement is taken. The smaller the gage length the greater the large localized strain in the necked region will factor into the calculation. Therefore, when reporting values of elongation, the gage length should be given.



One way to avoid the complication from necking is to base the elongation measurement on the uniform strain out to the point at which necking begins. This works well at times but some engineering stress-strain curves are often quite flat in the vicinity of maximum loading and it is difficult to precisely establish the strain when necking starts to occur.

Reduction of area is the change in cross-sectional area divided by the original cross-sectional area. This change is measured in the necked down region of the specimen. Like elongation, it is usually expressed as a percentage.



As previously discussed, tension is just one of the way that a material can be loaded. Other ways of loading a material include compression, bending, shear and torsion, and there are a number of standard tests that have been established to characterize how a material performs under these other loading conditions. A very cursory introduction to some of these other material properties will be provided on the next page.

## **Compressive, Bearing, & Shear Properties**

### **Compressive Properties**

In theory, the compression test is simply the opposite of the tension test with respect to the direction of loading. In compression testing the sample is squeezed while the load and the displacement are recorded. Compression tests result in mechanical properties that include the compressive yield stress, compressive ultimate stress, and compressive modulus of elasticity.

Compressive yield stress is measured in a manner identical to that done for tensile yield strength. When testing metals, it is defined as the stress corresponding to 0.002 in./in. plastic strain. For plastics, the compressive yield stress is measured at the point of permanent yield on the stress-strain curve. Moduli are generally greater in compression for most of the commonly used structural materials.



Ultimate compressive strength is the stress required to rupture a specimen. This value is much harder to determine for a compression test than it is for a tensile test since many material do not exhibit rapid fracture in compression. Materials such as most plastics that do not rupture can have their results reported as the compressive strength at a specific deformation such as 1%, 5%, or 10% of the sample's original height.

For some materials, such as concrete, the compressive strength is the most important material property that engineers use when designing and building a structure. Compressive strength is also commonly used to determine whether a concrete mixture meets the requirements of the job specifications.

### **Bearing Properties**

Bearing properties are used when designing mechanically fastened joints. The purpose of a bearing test is to determine the the deformation of a hole as a function of the applied bearing stress. The test specimen is basically a piece of sheet or plate with a carefully prepared hole some standard distance from the edge. Edge-to-hole diameter ratios of 1.5 and 2.0 are common. A hardened pin is inserted through the hole and an axial load applied to the specimen and the pin. The bearing stress is computed by dividing the load applied to the pin, which bears against the edge of the hole, by the bearing area (the product of the pin diameter and the sheet or plate thickness). Bearing yield and ultimate stresses are obtained from bearing tests. BYS is computed from a bearing stress deformation curve by drawing a line parallel to the initial slope at an offset of 0.02 times the pin diameter. BUS is the maximum stress withstood by a bearing specimen.

## **Shear**

## **Properties**

A shearing stress acts parallel to the stress plane, whereas a tensile or compressive stress acts normal to the stress plane. Shear properties are primarily used in the design of mechanically fastened components, webs, and torsion members, and other components subject to parallel, opposing loads. Shear properties are dependant on the type of shear test and there is a variety of different standard shear tests that can be performed including the single-shear test, double-shear test, blanking-shear test, torsion-shear test and others. The shear modulus of elasticity is considered a basic shear property. Other properties, such as the proportional limit stress and shear ultimate stress, cannot be treated as basic shear properties because of “form factor” effects.

## **Hardness**

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 as the resistance to elastic deformation of the surface. The lack of a fundamental definition indicates that hardness is not a basic property of a material, but rather a composite one with contributions from the yield strength, work hardening, true tensile strength, modulus, and other 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 material's 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 of metal forgings and castings that have a large grain structure. The Brinell test provides a measurement

over a fairly large area that is less affected by the coarse 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.

- A -Cemented carbides, thin steel and shallow case hardened steel
- B -Copper alloys, soft steels, aluminum alloys, malleable iron, etc.
- C -Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than B 100
- D -Thin steel and medium case hardened steel and pearlitic malleable iron
- E -Cast iron, aluminum and magnesium alloys, bearing metals
- F -Annealed copper alloys, thin soft sheet metals
- G -Phosphor bronze, beryllium copper, malleable irons
- H -Aluminum, zinc, lead
- K, L, M, P, R, S, V -Bearing metals and other very soft or thin materials, including plastics.

### **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

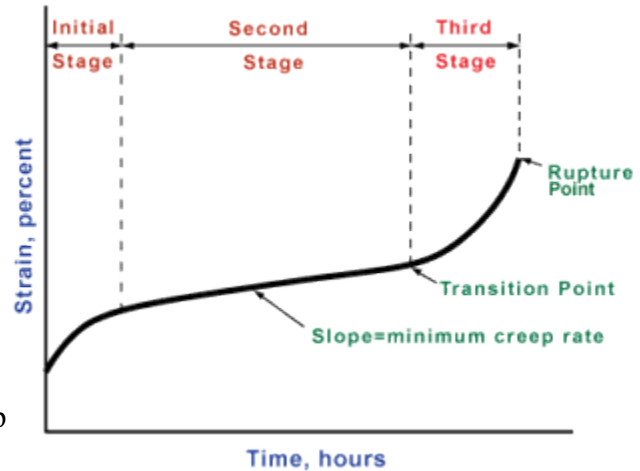
The Barcol hardness test obtains a hardness value by measuring the penetration of a sharp steel point under a spring load. The specimen is placed under the indenter of the Barcol hardness tester and a uniform pressure is applied until the dial indication reaches a maximum. The Barcol hardness test method 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.

## Creep and Stress Rupture Properties

### Creep Properties

Creep is a time-dependent deformation of a material while under an applied load that is below its yield strength. It most often occurs at elevated temperature, but some materials creep at room temperature. Creep terminates in rupture if steps are not taken to bring it to a halt.

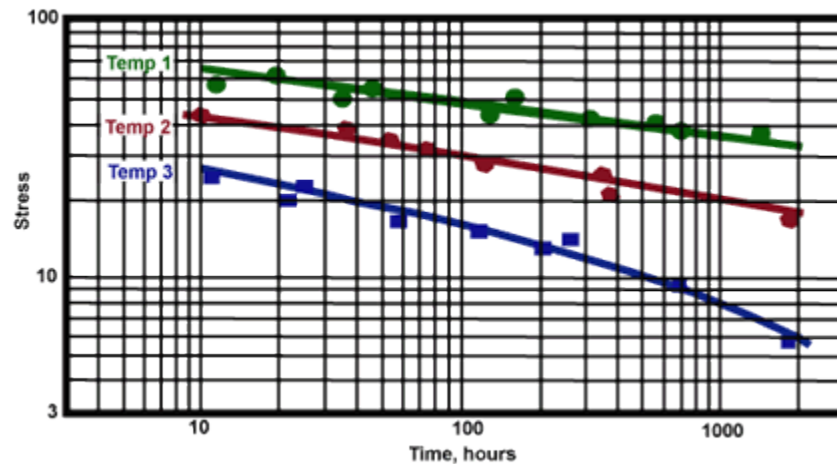
Creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature. Results of tests are usually plotted as strain versus time up to rupture. As indicated in the image, creep often takes place in three stages. In the initial stage, strain occurs at a relatively rapid rate but the rate gradually decreases until it becomes approximately constant during the second stage. This constant creep rate is called the minimum creep rate or steady-state creep rate since it is the slowest creep rate during the test. In the third stage, the strain rate increases until failure occurs.



Creep in service is usually affected by changing conditions of loading and temperature and the number of possible stress-temperature-time combinations is infinite. While most materials are subject to creep, the creep mechanisms are often different between metals, plastics, rubber, concrete.

## Stress Rupture Properties

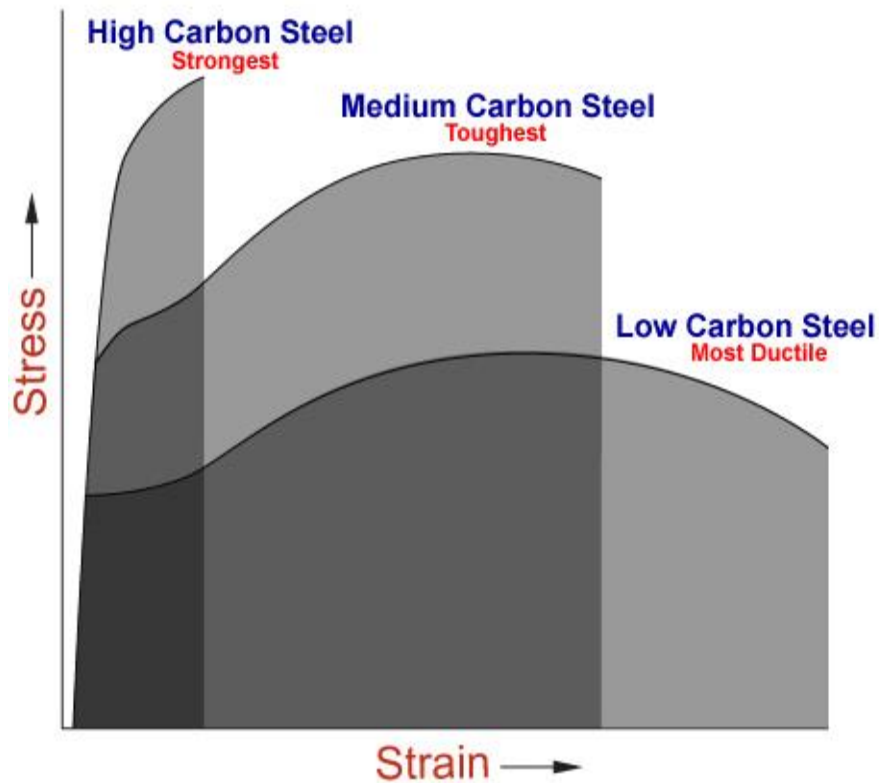
Stress rupture testing is similar to creep testing except that the stresses are higher than those used in a creep testing. Stress rupture tests are used to determine the time necessary to produce failure so stress rupture testing is always done until failure. Data is plotted log-log as in the chart above. A straight line or best fit curve is usually obtained at each temperature of interest. This information can then be used to extrapolate time to failure for longer times. A typical set of stress rupture curves is shown below.



## Toughness

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.





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.

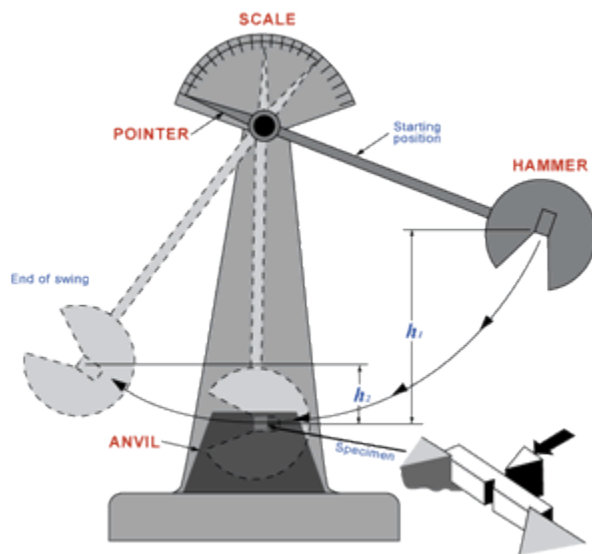
There are several standard types of toughness test that generate data for specific loading conditions and/or component design approaches. Three of the toughness properties that will be discussed in more detail are 1) impact toughness, 2) notch toughness and 3) fracture toughness.



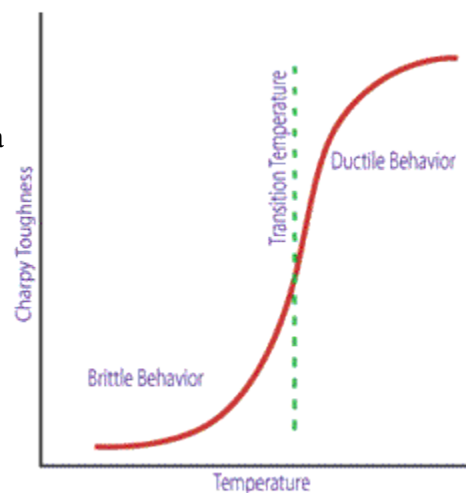
## Impact Toughness

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 for comparing the relative toughness of 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.

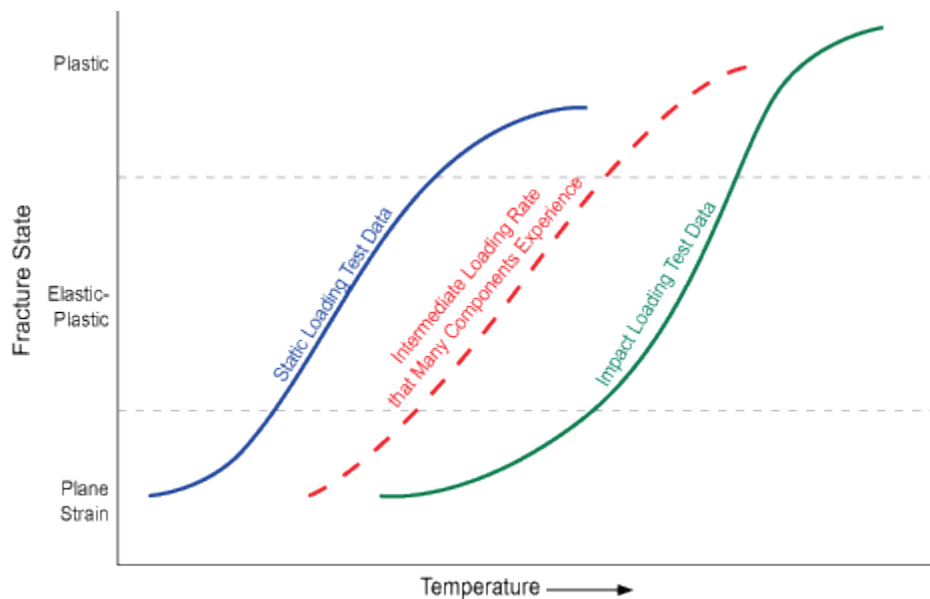


## Notch-Toughness

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.



## Fracture Toughness

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 components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. 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 ( $K_I$ ) 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:

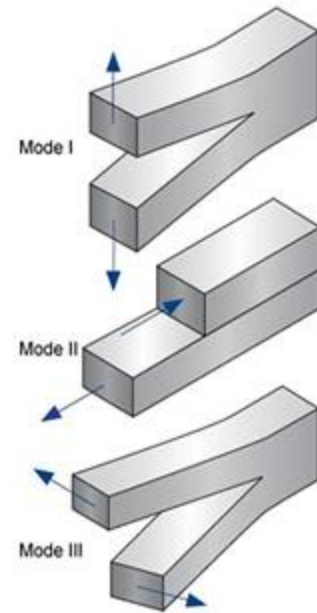
$$K_I = \sigma \sqrt{\pi a \beta}$$

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

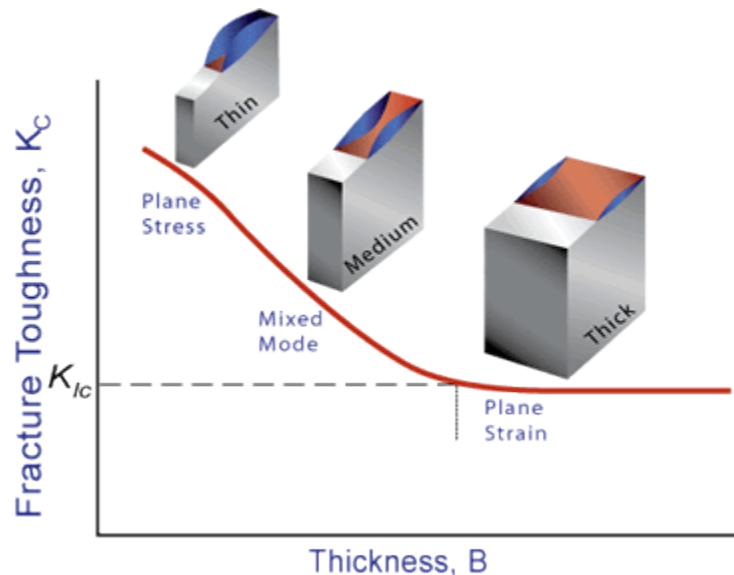
$\beta$  is a crack length and component geometry factor that is different for each specimen and is dimensionless.



### Role of Material Thickness

Specimens having standard proportions but different absolute size produce different values for  $K_I$ . This results because the stress states adjacent to the flaw changes with the specimen thickness ( $B$ ) until the thickness exceeds some critical dimension. Once the thickness exceeds the critical dimension, the value of  $K_I$  becomes relatively constant and this value,  $K_{IC}$ , is a true material property which is called the plane-strain fracture toughness. The relationship between stress intensity,  $K_I$ , and fracture toughness,  $K_{IC}$ , is similar to the relationship between stress and tensile stress.

The stress intensity,  $K_I$ , represents the level of “stress” at the tip of the crack and the fracture toughness,  $K_{IC}$ , is the highest value of stress intensity that a material under very specific (plane-strain) conditions that a material can withstand without fracture. As the stress intensity factor reaches the  $K_{IC}$  value, unstable fracture occurs. As with a material’s other mechanical properties,  $K_{IC}$  is commonly reported in reference books and other sources.



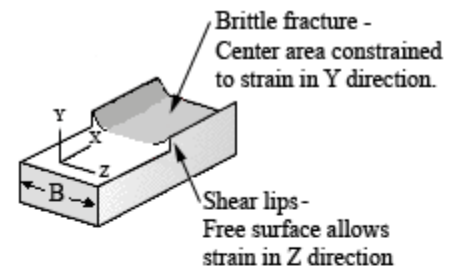
## Plane-Strain and Plane-Stress

When a material with a crack is loaded in tension, the materials develop plastic strains as the yield stress is exceeded in the region near the crack tip. Material within the crack tip stress field, situated close to a free surface, can deform laterally (in the z-direction of the image) because there can be no stresses normal to the free surface. The state of stress tends to be biaxial and the material fractures in a characteristic ductile manner, with a 45° shear lip being formed at each free surface. This condition is called “plane-stress” and it occurs in relatively thin bodies where the stress through the thickness cannot vary appreciably due to the thin section.

**Plane Strain** - a condition of a body in which the displacements of all points in the body are parallel to a given plane, and the values of these displacements do not depend on the distance perpendicular to the plane

**Plane Stress** – a condition of a body in which the state of stress is such that two of the principal stresses are always parallel to a given plane and are constant in the normal direction.

However, material away from the free surfaces of a relatively thick component is not free to deform laterally as it is constrained by the surrounding material. The stress state under these conditions tends to be triaxial and there is zero strain perpendicular to both the stress axis and the direction of crack propagation when a material is loaded in tension. This condition is called “plane-strain” and is found in thick plates. Under plane-strain conditions, materials behave essentially elastic until the fracture stress is reached and then rapid fracture occurs. Since little or no plastic deformation is noted, this mode fracture is termed brittle fracture.



Thin Section



Predominately ductile fracture due to biaxial stress state.

Shear lips occupy a large percentage of thickness.

Thick Section

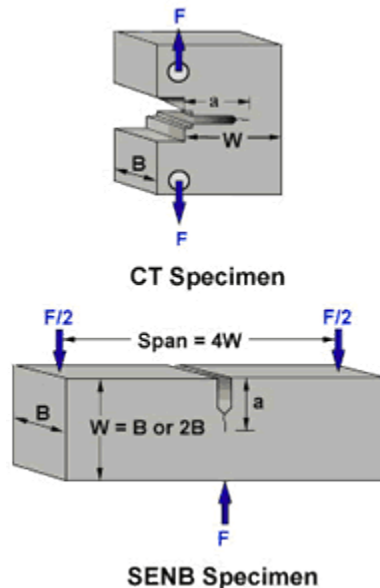


Predominately brittle fracture due to triaxial stress state

Shear lips occupy a small percentage of thickness

## Plane-Strain Fracture Toughness Testing

When performing a fracture toughness test, the most common test specimen configurations are the single edge notch bend (SENB) or three-point bend, and the compact tension (CT) specimens. From the above discussion, it is clear that an accurate determination of the plane-strain fracture whose thickness exceeds has shown that plane-strain



toughness requires a specimen some critical thickness (B). Testing conditions generally prevail when:

$$B \geq 2.5 \left( \frac{K_{IC}}{\sigma_y} \right)^2$$

Where: B is the minimum thickness that produces a condition where plastic

strain energy at the crack tip is minimal  
 $K_{IC}$  is the fracture toughness of the material  
 $s_y$  is the yield stress of material

When a material of unknown fracture toughness is tested, a specimen of full material section thickness is tested or the specimen is sized based on a prediction of the fracture toughness. If the fracture toughness value resulting from the test does not satisfy the requirement of the above equation, the test must be repeated using a thicker specimen. In addition to this thickness calculation, test specifications have several other requirements that must be met (such as the size of the shear lips) before a test can be said to have resulted in a  $K_{IC}$  value.

When a test fails to meet the thickness and other test requirement that are in place to insure plane-strain condition, the fracture toughness values produced is given the designation  $K_C$ . Sometimes it is not possible to produce a specimen that meets the thickness requirement. For example when a relatively thin plate product with high toughness is being tested, it might not be possible to produce a thicker specimen with plain-strain conditions at the crack tip.

### ***Plane-Stress and Transitional-Stress States***

For cases where the plastic energy at the crack tip is not negligible, other fracture mechanics parameters, such as the J integral or R-curve, can be used to characterize a material. The toughness data produced by these other tests will be dependant on the thickness of the product tested and will not be a true material property. However, plane-strain conditions do not exist in all structural configurations and using  $K_{IC}$  values in the design of relatively thin areas may result in excess conservatism and a weight or cost penalty. In cases where the actual stress state is plane-stress or, more generally, some intermediate- or transitional-stress state, it is more appropriate to use J integral or R-curve data, which account for slow, stable fracture (ductile tearing) rather than rapid (brittle) fracture.

### **Uses of Plane-Strain Fracture Toughness**

$K_{IC}$  values are used to determine the critical crack length when a given stress is applied to a component.

$$\sigma_c \leq \frac{K_{IC}}{Y\sqrt{\pi a}}$$

Where:  $s_c$  is the critical applied stress that will cause failure

$K_{IC}$  is the plane-strain fracture toughness

Y is a constant related to the sample's geometry

a is the crack length for edge cracks  
 or one half crack length for internal crack

$K_{IC}$  values are used also used to calculate the critical stress value when a crack of a given length is found in a component.

$$a_c = \frac{1}{\pi} \left( \frac{K_{IC}}{\sigma Y} \right)^2$$

Where:  $a$  is the crack length for edge cracks  
or one half crack length for internal crack

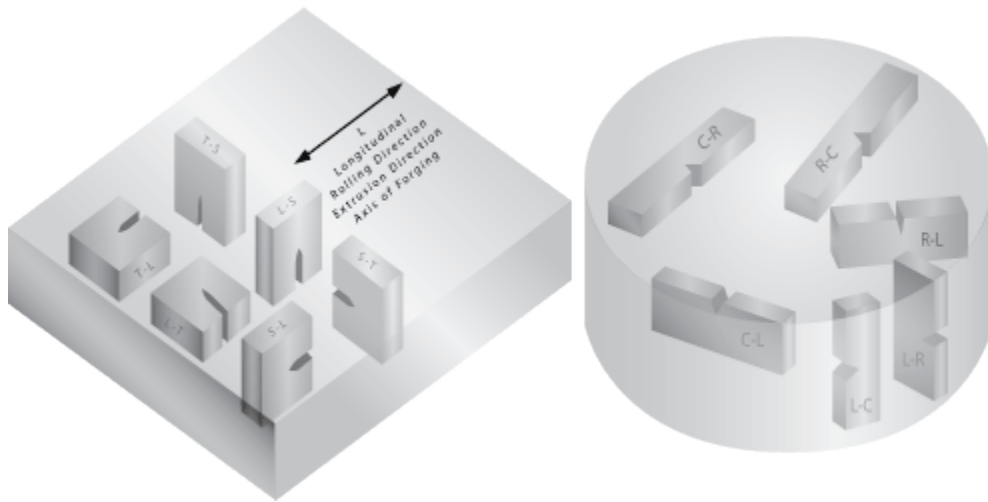
$s$  is the stress applied to the material

$K_{IC}$  is the plane-strain fracture toughness

$Y$  is a constant related to the sample's geometry

### Orientation

The fracture toughness of a material commonly varies with grain direction. Therefore, it is customary to specify specimen and crack orientations by an ordered pair of grain direction symbols. The first letter designates the grain direction normal to the crack plane. The second letter designates the grain direction parallel to the fracture plane. For flat sections of various products, e.g., plate, extrusions, forgings, etc., in which the three grain directions are designated (L) longitudinal, (T) transverse, and (S) short transverse, the six principal fracture path directions are: L-T, L-S, T-L, T-S, S-L and S-T.



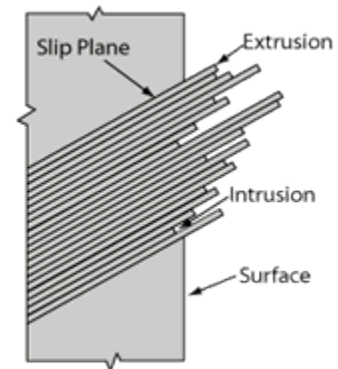
## Fatigue Properties

Fatigue cracking is one of the primary damage mechanisms of structural components. Fatigue cracking results from cyclic stresses that are below the ultimate tensile stress, or even the yield stress of the material. The name “fatigue” is based on the concept that a material becomes “tired” and fails at a stress level below the nominal strength of the material. The facts that the original bulk design strengths are not exceeded and the only warning sign of an impending fracture is an often hard to see crack, makes fatigue damage especially dangerous.



The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size. Therefore, it can be said that fatigue failure occurs in three stages – crack initiation; slow, stable crack growth; and rapid fracture.

As discussed previously, dislocations play a major role in the fatigue crack initiation phase. In the first stage, dislocations accumulate near surface stress concentrations and form structures called persistent slip bands (PSB) after a large number of loading cycles. PSBs are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes. This leaves tiny steps in the surface that serve as stress risers where tiny cracks can initiate. These tiny cracks (called microcracks) nucleate along planes of high shear stress which is often  $45^\circ$  to the loading direction.



In the second stage of fatigue, some of the tiny microcracks join together and begin to propagate through the material in a direction that is perpendicular to the maximum tensile stress. Eventually, the growth of one or a few crack of the larger cracks will dominate over the rest of the cracks. With continued cyclic loading, the growth of the dominate crack or cracks will continue until the remaining uncracked section of the component can no longer support the load. At this point, the fracture toughness is exceeded and the remaining cross-section of the material experiences rapid fracture. This rapid overload fracture is the third stage of fatigue failure.

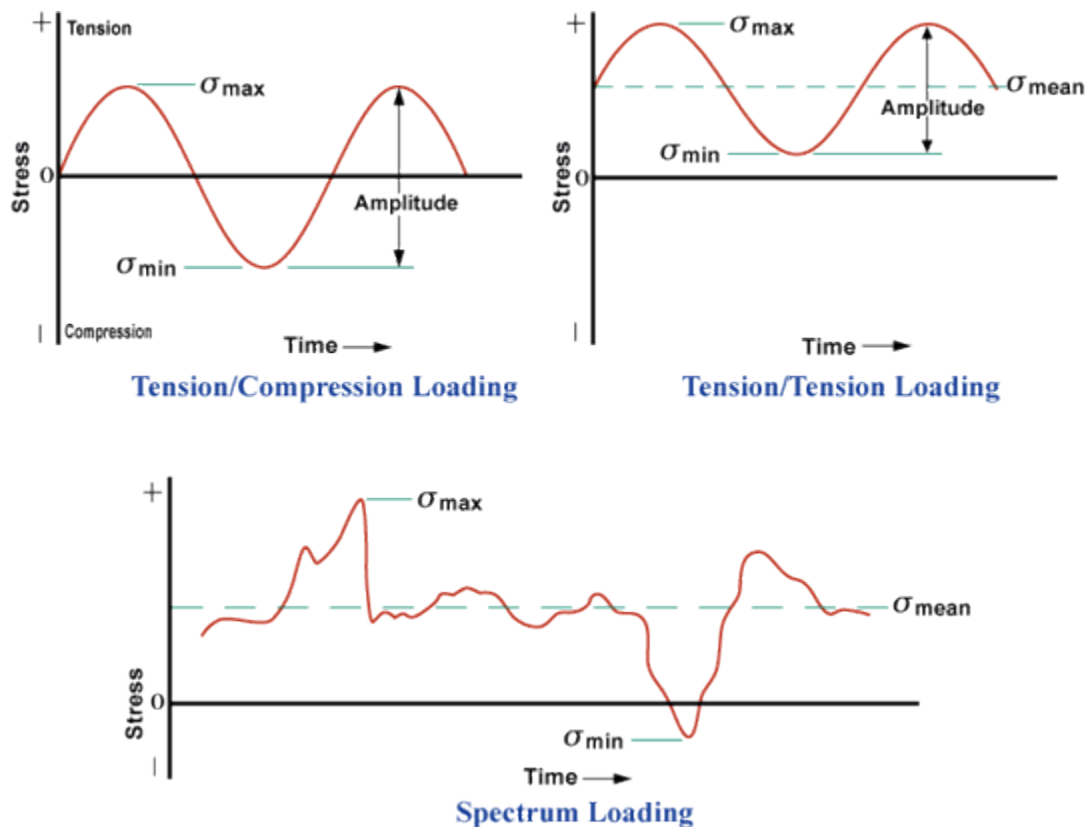
### Factors Affecting Fatigue Life

In order for fatigue cracks to initiate, three basic factors are necessary. First, the loading pattern must contain minimum and maximum peak values with large enough variation or fluctuation. The peak values may be in tension or compression and may change over time but the reverse loading cycle must be sufficiently great for fatigue crack initiation. Secondly, the peak stress levels must be of sufficiently high value. If the peak stresses are too low, no crack initiation will occur. Thirdly, the material must experience a sufficiently large number of cycles of the applied stress. The number of cycles required to initiate and grow a crack is largely dependant on the first to factors.

In addition to these three basic factors, there are a host of other variables, such as stress concentration, corrosion, temperature, overload, metallurgical structure, and residual stresses which can affect the propensity for fatigue. Since fatigue cracks generally initiate at a surface, the surface condition of the component being loaded will have an effect on its fatigue life. Surface roughness is important because it is directly related to the level and number of stress concentrations on the surface. The higher the stress concentration the more likely a crack is to nucleate. Smooth surfaces increase the time to nucleation. Notches, scratches, and other stress risers decrease fatigue life. Surface residual stress will also have a significant effect on fatigue life. Compressive residual stresses from machining, cold working, heat treating will oppose a



tensile load and thus lower the amplitude of cyclic loading

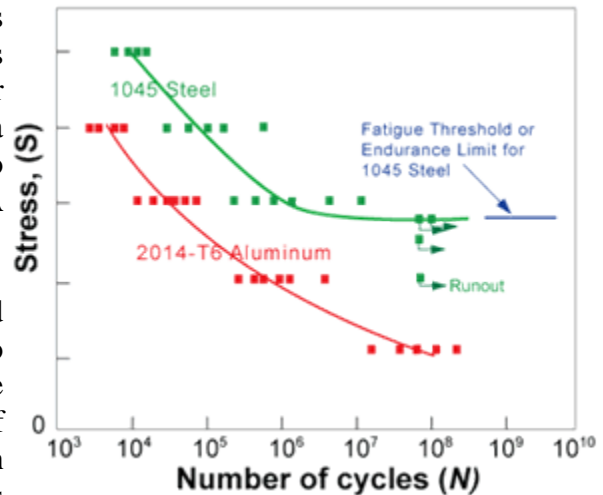


The figure shows several types of loading that could initiate a fatigue crack. The upper left figure shows sinusoidal loading going from a tensile stress to a compressive stress. For this type of stress cycle the maximum and minimum stresses are equal. Tensile stress is considered positive, and compressive stress is negative. The figure in the upper right shows sinusoidal loading with the minimum and maximum stresses both in the tensile realm. Cyclic compression loading can also cause fatigue. The lower figure shows variable-amplitude loading, which might be experienced by a bridge or airplane wing or any other component that experiences changing loading patterns. In variable-amplitude loading, only those cycles exceeding some peak threshold will contribute to fatigue cracking.

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## S-N Fatigue Properties

There are two general types of fatigue tests conducted. One test focuses on the nominal stress required to cause a fatigue failure in some number of cycles. This test results in data presented as a plot of stress (S) against the number of cycles to failure (N), which is known as an S-N curve. A log scale is almost always used for N.



The data is obtained by cycling smooth or notched specimens until failure. The usual procedure is to test the first specimen at a high peak stress where failure is expected in a fairly short number of cycles. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles, which is usually at least 10<sup>7</sup> cycles. The highest stress at which a runout (non-failure) occurs is taken as the fatigue threshold. Not all materials have a fatigue threshold (most nonferrous metallic alloys do not) and for these materials the test is usually terminated after about 10<sup>8</sup> or 5x10<sup>8</sup> cycles.

Since the amplitude of the cyclic loading has a major effect on the fatigue performance, the S-N relationship is determined for one specific loading amplitude. The amplitude is expressed as the R ratio value, which is the minimum peak stress divided by the maximum peak stress. ( $R = \sigma_{\min} / \sigma_{\max}$ ). It is most common to test at an R ratio of 0.1 but families of curves, with each curve at a different R ratio, are often developed.

A variation to the cyclic stress controlled fatigue test is the cyclic strain controlled test. In this test, the strain amplitude is held constant during cycling. Strain controlled cyclic loading is more representative of the loading found in thermal cycling, where a component expands and contracts in response to fluctuations in the operating temperature.

It should be noted that there are several shortcomings of S-N fatigue data. First, the conditions of the test specimens do not always represent actual service conditions. For example, components with surface conditions, such as pitting from corrosion, which differs from the condition of the test specimens will have significantly different fatigue performance. Furthermore, there is often a considerable amount of scatter in fatigue data even when carefully machined standard specimens out of the same lot of material are used. Since there is considerable scatter in the data, a reduction factor is often applied to the S-N curves to provide conservative values for the design of components.

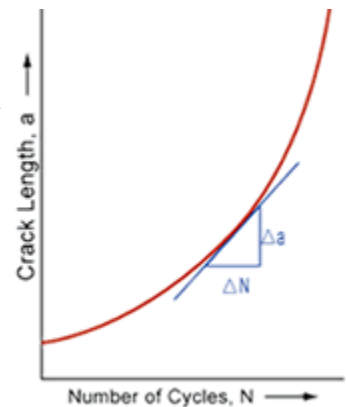
## Fatigue Crack Growth Rate Properties

For some components the crack propagation life is neglected in design because stress levels are high, and/or the critical flaw size small. For other components the crack growth life might be a substantial portion of the total life of the assembly. Moreover, preexisting flaws or sharp design

features may significantly reduce or nearly eliminate the crack initiation portion of the fatigue life of a component. The useful life of these components may be governed by the rate of subcritical crack propagation.

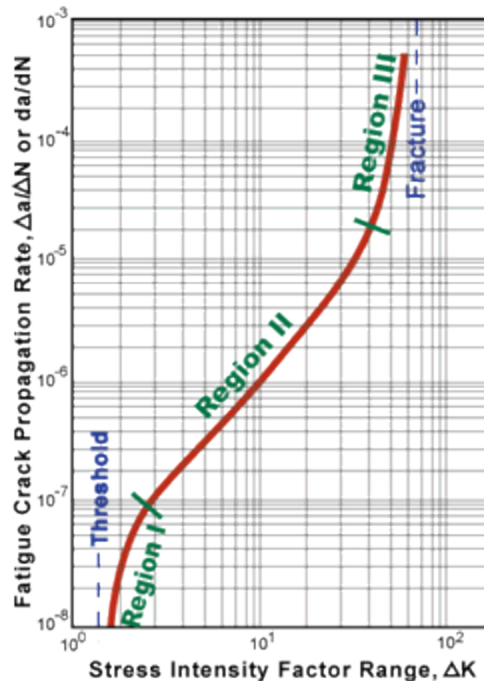
Aircraft fuselage structure is a good example of structure that is based largely on a slow crack growth rate design. Many years ago, the USAF reviewed a great number of malfunction reports from a variety of aircraft. The reports showed that the preponderance of structural failures occurred from 1) built-in preload stresses, 2) material flaws and 3) flaw caused by in-service usage. These facts led to a design approach that required the damage tolerance analysis to assume a material flaw exists in the worst orientation and at the most undesirable location. The analysis helps to ensure that structures are designed that will support slow stable crack growth until the crack reaches a length where it can reliably be detected using NDT methods.

The rate of fatigue crack propagation is determined by subjecting fatigue-cracked specimens, like the compact specimen used in fracture toughness testing, to constant-amplitude cyclic loading. The incremental increase in crack length is recorded along with the corresponding number of elapsed load cycles acquire stress intensity (K), crack length (a), and cycle count (N) data during the test. The data is presented in an “a versus N” curve as shown in the image to the right. Various a versus N curves can be generated by varying the magnitude of the cyclic loading and/or the size of the initial crack.



The data can be reduced to a the data in terms of crack loading ( $\Delta a / \Delta N$  or  $da/dN$ ) the stress-intensity factor at  $DK_I$  is representative of the and it incorporates the effect and the magnitude of the page on fracture toughness the stress-intensity factor.) presenting fatigue crack plot of  $da/dN$  versus  $DK_I$ .

The fatigue crack many materials can be as shown in the image. threshold region where the a crack. Region II



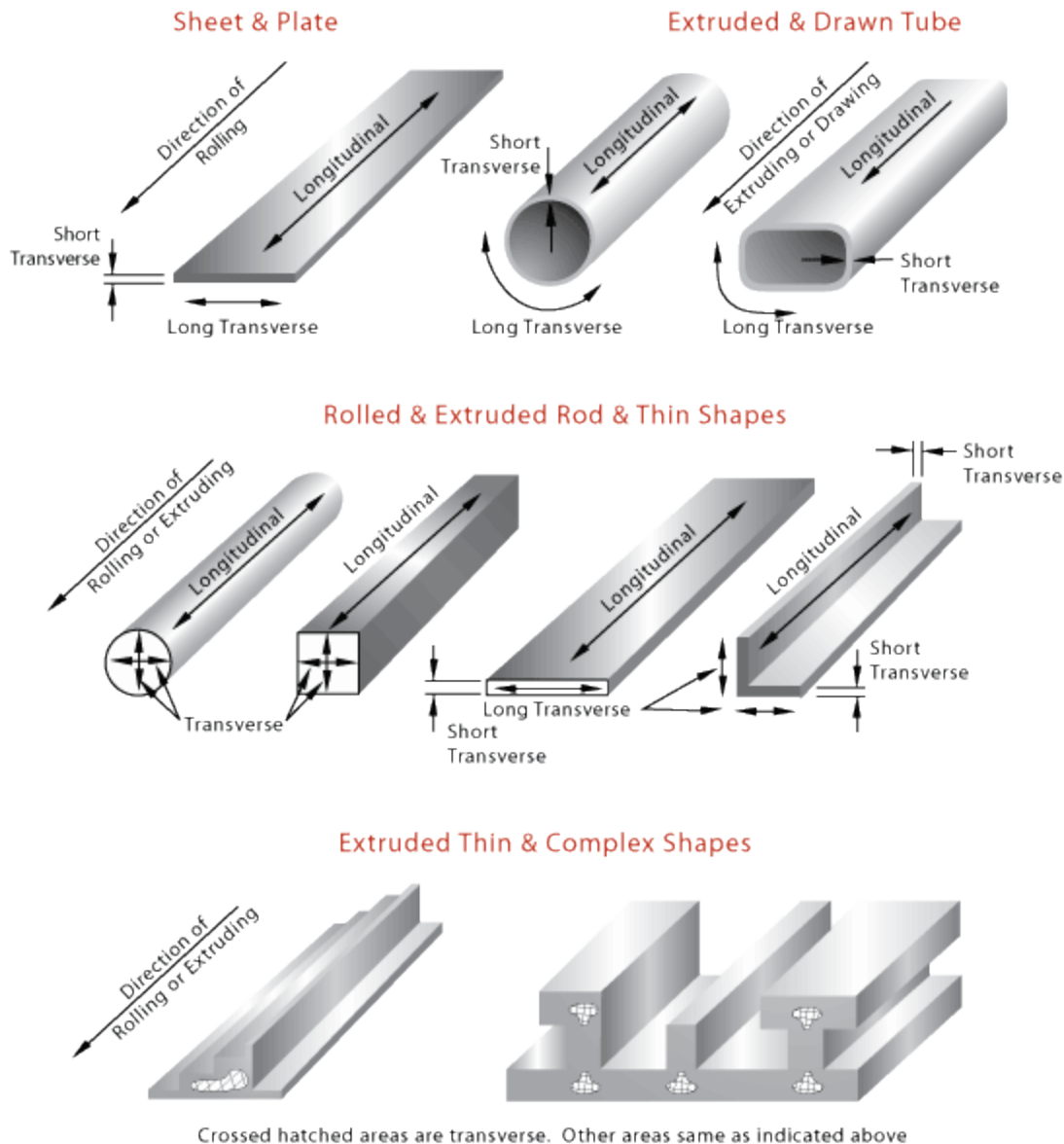
single curve by presenting growth rate per cycle of versus the fluctuation of the tip of the crack ( $DK_I$ ). mechanical driving force, of changing crack length cyclic loading. (See the for more information on The most common form of growth data is a log-log

propagation behavior of divided into three regions Region I is the fatigue  $Dk$  is too low to propagate encompasses data where the rate of crack growth changes roughly linearly with a change in stress intensity fluctuation. In region III, small increases in the stress intensity amplitude, produce relatively large increases in crack growth rate since the material is nearing the point of unstable fracture.

## **Mechanical Properties**

The mechanical properties of a material are those properties that involve a reaction to an applied load. The mechanical properties of metals determine the range of usefulness of a material and establish the service life that can be expected. Mechanical properties are also used to help classify and identify material. The most common properties considered are strength, ductility, hardness, impact resistance, and fracture toughness.

Most structural materials are anisotropic, which means that their material properties vary with orientation. The variation in properties can be due to directionality in the microstructure (texture) from forming or cold working operation, the controlled alignment of fiber reinforcement and a variety of other causes. Mechanical properties are generally specific to product form such as sheet, plate, extrusion, casting, forging, and etc. Additionally, it is common to see mechanical property listed by the directional grain structure of the material. In products such as sheet and plate, the rolling direction is called the longitudinal direction, the width of the product is called the transverse direction, and the thickness is called the short transverse direction. The grain orientations in standard wrought forms of metallic products are shown the image.



The mechanical properties of a material are not constants and often change as a function of temperature, rate of loading, and other conditions. For example, temperatures below room temperature generally cause an increase in strength properties of metallic alloys; while ductility, fracture toughness, and elongation usually decrease. Temperatures above room temperature usually cause a decrease in the strength properties of metallic alloys. Ductility may increase or decrease with increasing temperature depending on the same variables

It should also be noted that there is often significant variability in the values obtained when measuring mechanical properties. Seemingly identical test specimen from the same lot of material will often produce considerable different results. Therefore, multiple tests are commonly conducted to determine mechanical properties and values reported can be an average value or calculated statistical minimum value. Also, a range of values are sometimes reported in order to show variability.