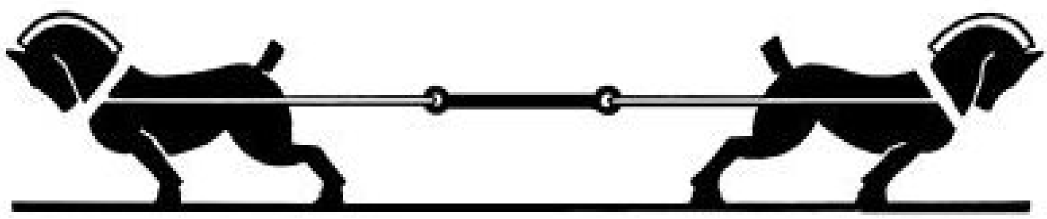
MECHANICAL PROPERTIES OF METALS

The **mechanical properties** of a material are those related to its ability to withstand external mechanical forces such as pulling, pushing, twisting, bending, and sudden impact. In general terms, we think of these properties as various kinds of ”strength”. However, the word ”strength”, used alone, doesn’t tell us very much. Steel, cast iron, rubber, and glass are each ”strong” in different ways.

Tensile Strength, Elasticity, and Ductility

In the field of metals, when the word ”strength” is used alone (as in ”high-strength steels”) it almost always refers to the ability of the metal to resist pulling force; specifically, to what is termed its tensile strength. If we start by considering what happens when a bar of steel is subjected to a steadily-increasing pull, we cannot only define tensile strength, but also yield strength, elasticity, and ductility. It’s obvious that it will take more pull to break a steel bar with a cross-sectional area of 10 square centimeters (10 cm^2) than to break one with a cross-sectional area of 5 cm^2, so we must start with a specimen having a precisely-determined cross-sectional area if the results are to yield useful data. This specimen is secured firmly in a tensile testing machine which is capable of applying all the pulling force needed to break it. The machine is equipped with gauges which will show both the force being applied and the increase in length of the specimen as force is applied. The force can be mathematically converted to stress by applying the known minimum cross- sectional area of the specimen. (Stress equals force divided by area.)



Tensile strength is expressed in terms of the directly-applied pull required to break apart.

As the machine pulls the specimen, it stretches – not a great deal, but enough to register on the strain gauge. If we gradually increase the pulling force, the amount of strain will also increase. A force of 20 kilonewtons (4500 lb.) will cause twice the strain produced by a force of 10 kilonewtons (2250 lb.). The steel is *elastic.* Until the *elastic limit* of the specimen has been reached, the amount of strain will be directly proportional to the amount of pull, and the specimen will always return to its original length if the pulling force is released. If we continue to apply pulling force at a gradually increasing rate, watching both the force and strain gauge hands closely, we reach a point where the strain gauge hand continues to move while the force gauge hand remains stationary, or even drops a bit. We have now reached the elastic limit of the steel. If at this point, the pulling force is released, the specimen will not return to its original length. It has undergone permanent deformation. The force required to produce a slight amount of permanent deformation, expressed as megapascals (MPa) or pounds per square inch (psi) of specimen cross-section, is termed yield point or yield strength. If, instead of releasing the pulling force when the yield point has been reached, we continue to increase that force, the test specimen will stretch at a more rapid rate until the pulling force reaches a maximum point. Then it will begin to ”neck down” or grow visibly narrower at some point; the force gauge hand will start to drop, while the hand on the strain gauge will continue to climb. Then the specimen will break, after ”necking down” substantially. The value established by the highest reading registered on the force gauge is termed the tensile strength or ultimate tensile strength of the steel. To be more specific: The ultimate tensile strength is the maximum force registered on the testing machine divided by the original cross-sectional area of the specimen. The force registered at the instant of breakage, divided by the final cross-section area of the specimen at the point of breakage, is termed the fracture strength. In steel, fracture strength, while of little practical significance, almost always has a higher value than ultimate tensile strength. Permanent deformation of steel increases its unit tensile strength. That’s why steel wire, which is repeatedly deformed as it is drawn, is stronger (in terms of breaking force per unit of cross-section) than a steel bar from the same heat of steel, and why cold-rolled steel is stronger than hot-rolled steel. Let’s now try to define more precisely the several terms just introduced in describing the tensile testing of a steel bar:

Yield Strength. The tensile force required to cause a slight but well-defined permanent deformation.

Yield Point. The force level at which strain (elongation) takes place without any increase in stress (pull).

Elastic Limit. The force required to produce permanent deformation. For all practical purposes, when dealing with ordinary low-carbon structural steels, yield strength, yield point, and elastic limit have the same values.

Ultimate Tensile Strength. The maximum strength of the material in terms of its original cross-sectional area. For engineering purposes, this is the value that can be used to determine the maximum load which a structural member should withstand without breaking. For many purposes, yield strength is the more significant value, since appreciable permanent deformation (stretching) will usually occur before stress has reached ultimate strength value.

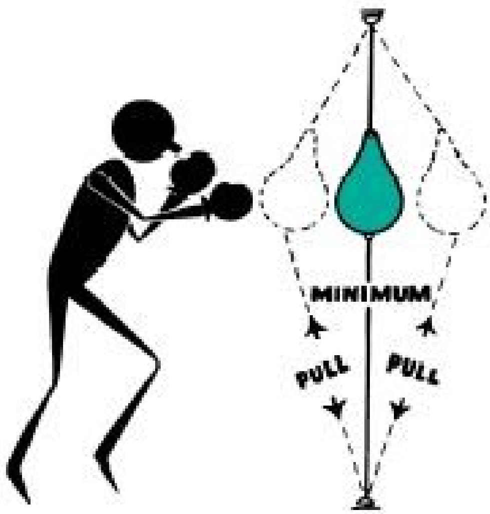
Elasticity. The linear relationship of non-permanent change in length to the force applied (in other words, the relationship of strain to stress). Rubber is extremely elastic; many metals are more elastic than steel in that a given pull will produce a greater increase in length. Cast iron, in this sense, is actually twice as elastic as steel. However, don’t forget that the important value, when dealing with metals, is usually the elastic limit, not the modulus of elasticity (relation of strain to stress below the elastic limit).

Ductility. Elasticity deals with the relationship of non-permanent strain to stress. Ductility is a measure of the ability of a material to undergo permanent deformation without breaking. Copper and aluminum are extremely ductile, generally speaking. Most low-carbon steels are quite ductile. Some cast irons have virtually no ductility; to put it in simple terms, they break before they bend. All types of steel have approximately the same degree of *elasticity;* that is, up to the elastic limit, the stress-strain relationship is the same, regardless of composition. However, ductility varies greatly, depending not only on composition but on several other factors as well. Ordinary low-carbon steels are moderately ductile; high-carbon tool steels have little ductility. Ductility is usually expressed as ”percent elongation in two inches” or as ”percent reduction in cross-section area”. If, before we started the test just described, we had placed two marks on the test specimen, precisely five centimeters (5 cm) apart, we could establish the percent elongation by fitting the pieces of the specimen together, after breaking, and then measuring the new distance between the two marks. In the case of low-carbon steel, we might find that the elongation was 30% (that is, from 5 cm to 6.5 cm). If the original cross-section of the specimen had been two square centimeters (2 cm^2) and the cross-section, remeasured at the point of the break, turned out to be 1 cm^2, we could state that the reduction in area was 50%. To check on the ductility of welds in steel plate, another method of arriving at ”percent elongation” is sometimes used. After the weld has been completed, it is ground flush with the surface of the base metal, and two small punch marks made in the actual weld metal. The specimen is then placed in a vise, and bent until the first crack appears in the surface of the weld metal between the two marks. By using a flexible steel rule, the distance between the punch marks is measured and compared with the original distance between the two punch marks.

While low-carbon steels exhibit relatively high ductility as measured by the methods described above, they are also subject to brittle failure under some conditions. A structural member may break suddenly when subject to stress which is below the expected yield point of the metal – that is, before any measurable permanent deformation has taken place. Such failure (fracture) always starts at a slight crack or notch in the metal. The ability of a steel to resist this type of fracture is termed notch ductility. Notch ductility is somewhat dependent on the composition of the steel. It is always related to temperature, (all steels lose notch ductility rapidly as temperatures drop below the 0-20^0C range) and to the grain structures within the steel, especially the structures which are formed as the result of welding. Stress-relieving – the reheating of the weld zone to a temperature of not more than 600^0C – is widely used to reduce the possibility of brittle fracture in welded structures.

Hardness Where metals are involved, hardness is usually defined as the ability of the metal to resist indentation or penetration by another material. In itself, the exact hardness of a steel is not of great importance in most applications. However, hardness can be measured much more readily than can tensile strength, there is a very close relationship between hardness and tensile strength, and between hardness and ductility. Usually, the harder the steel, the higher its tensile strength, and the lower its ductility. Three methods of hardness testing are widely used: The Brinell method, in which a steel ball is forced against the surface of the specimen by a heavy load, and hardness determined by measuring the diameter of the impression left in the surface; the Rockwell method, in which a diamond cone is pressed into the surface, and hardness determined by a gauge, built into the testing unit, which registers the depth of the impression; and the Scleroscope method, in which a diamond-pointed cylinder of steel is dropped onto the surface of the material from a fixed height, and hardness determined by measuring the height of the rebound.

Other Kinds of "Strength" Compressive Strength. This may be thought of as the opposite of tensile strength: in other words, the ability of a material to resist a gradually applied "push", rather than "pull". Most metals have at least as much strength in compression as in tension, so that exact values for compressive strength are seldom significant. **Fatigue Strength.** Here is a property of great importance in the design of many parts and structures. All metals will fail under repeatedly changing load conditions at a lower stress than they will if the load is applied steadily in one direction. A wire that might support a continuous load of 5000 MPa indefinitely will probably fail in time if a load of 3000 MPa is alternately and repeatedly imposed and then released. The piston rod on a steam locomotive is subjected to tension for a half-cycle, then to compression for a half-cycle, thousands of times every day. Structural members in a bridge are constantly subject to changing load conditions. In all such applications, fatigue strength, which is always lower than tensile strength and sometimes **much** lower, must be considered by a designer. In addition to factors in the internal structure of a metal which cause it to become weaker when subjected to repeated changes in load, metal surface conditions are closely related to fatigue strength. Fatigue failure usually starts with a small crack; any roughness in the surface of a metal which might make it easier for such a crack to start – even slight pitting from a corrosive atmosphere can substantially reduce the fatigue strength. Fatigue strength is usually expressed as **fatigue limit** or **endurance limit***;* both terms mean the same thing: the stress to which the material can be subjected indefinitely, under *varying* load conditions, before failure. If someone says that the fatigue limit of steel from a certain heat is 140 MPa (about 20,000 psi) assume he means that the steel can be subjected to repeated alternation of stress, from 140 MPa tension to 140 MPa compression, for at least 10,000,000 cycles without failure. However, values for fatigue strength are often expressed in more limited terms; for example, that the material will withstand "100,000 cycles of 300 MPa tension to 0 tension”, or ”2,000,000 cycles of 125 MPa, reversed” (meaning that a complete cycle ranges from 125 MPa tension to 125 MPa compression).



The springs or elastic bands which secure this punching bag to floor and ceiling are being subjected to repeated, but not alternating, stress.

The piston rod in this double air pump is being subjected to alternating stress. Each half of the rod is first pulled, then pushed. At some point in each cycle, stress in one half of the rod is zero.

Impact Strength; Fracture Toughness. Both of these terms refer to the ability of a material to withstand shock, or large forces suddenly applied. Neither property can be defined mathematically, for engineering use, in the same sense that tensile strengths can be defined. Impact strength is usually stated in terms of the energy absorbed by a metal when it is broken under carefully-defined and limited conditions. In the Charpy V-notch impact test, a specimen of fixed dimensions, which has been precisely notched, is broken by a blow from a pendulum hammer. The difference between the distance which the hammer travels after breaking the specimen, and the distance it would have traveled had there been no specimen to hit, is a direct measure of the energy absorbed by the specimen before it fractured. This energy, expressed as units of force, is correctly described as impact energy, rather than impact strength. Two steels which have equal tensile strengths at room temperatures may vary widely in their impact energies (strengths) especially when tested at low temperatures.
Fracture toughness refers specifically to the resistance of a material to rapid crack propagation (the brittle fracture mentioned earlier) when a slight crack already exists and a massive load is applied suddenly. For a homely example, think of a loaded grocery bag sitting on the floor. If the bottom of the bag has no holes or tears, you can usually yank it up suddenly without mishap. If there is a

small break in the bottom of the bag, you can often lift the bag slowly and get your arm under it, but if you try to yank it up, you're likely to wind up with groceries scattered on the floor. Similarly, a very small crack in a metal member, which might reduce the strength of that member only slightly were high tensile stress to be created gradually, can sometimes spread with great speed, and destroy the member completely, when an equal load is applied suddenly. Fracture toughness depends on several factors which are not directly involved in the standard Charpy V-notch test, so the results of such tests are often considered only a rough measure of fracture toughness.