ITU
Department of Mechanical Engineering

MANUFACTURING PROPERTIES of ENGINEERING MATERIALS
Lecture Notes

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CONTENTS

1. Engineering Materials and Their Properties

In this Chapter materials are classified and the most important properties of the engineering materials are listed with short explanations. The properties covered here are especially those properties, which are important in manufacturing processes.

1.1. Classification of Engineering Materials

A. Metals and Alloys: Inorganic materials composed of one or more metallic elements.

- They usually have a crystalline structure and are good thermal and electrical conductors.
- Many metals have high strength and high elastic module.
- They maintain their good strength at high and low temperatures.
- They also have sufficient ductility, which is important for many engineering applications.
- They can be strengthened by alloying and heat treatment.
- They are least resistant to corrosion.

B. Ceramics and Glasses: Inorganic materials consisting of both metallic and non-metallic elements bonded together chemically.

- They can be crystalline (ceramics), non-crystalline (glasses) or mixture of both (glass-ceramics).
- Generally they have high melting points and high chemical stabilities.
- They have high hardness, high moduli and high temperature strength.
- But since they are very brittle they cannot be used as good as metals.
- Ceramics are usually poor electrical conductors.
- Ceramics have a high strength on compression

C. Polymers: Organic materials which consist of long molecular chains or networks containing carbon.

- Most polymers are non-crystalline, but some consist of mixtures of both crystalline and non-crystalline regions.
- They generally have low densities and low rigidity.
- Their mechanical properties may vary considerably.
- Most polymers are poor electrical conductors due to the nature of the atomic bonding.
- Most of them are corrosion resistant, but cannot be used at high temperatures.
- They generally have a good strength to weight ratio.

D. Composites: Materials where two or more of the above materials are brought together on macroscopic level.

- Usually they consist of a matrix and a reinforcement.
- They are designed to combine the best properties of each of its components.

1.2. Properties of Engineering Materials

Each material has a property profile. The properties of engineering materials can be classified into the following main groups: physical and chemical. The physical properties can also be further grouped into categories: mechanical, thermal, electrical, magnetic, optical etc. The chemical properties include: environmental and chemical stability.

There are also some general properties which cannot be classified within these groups:

- **Density, ρ** (Units: Mg/m^3, g/cm^3)

The density of a material is defined as its mass (m) per unit volume (V). It is represented in the following equation;

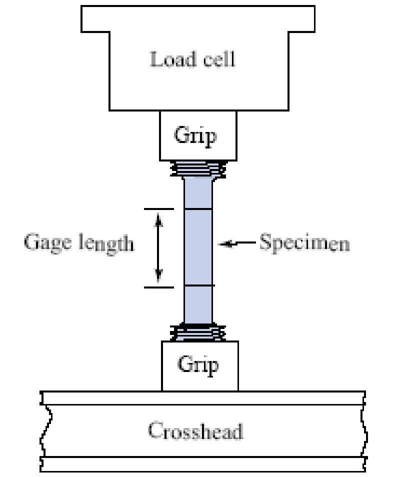
$$\rho = m / V$$

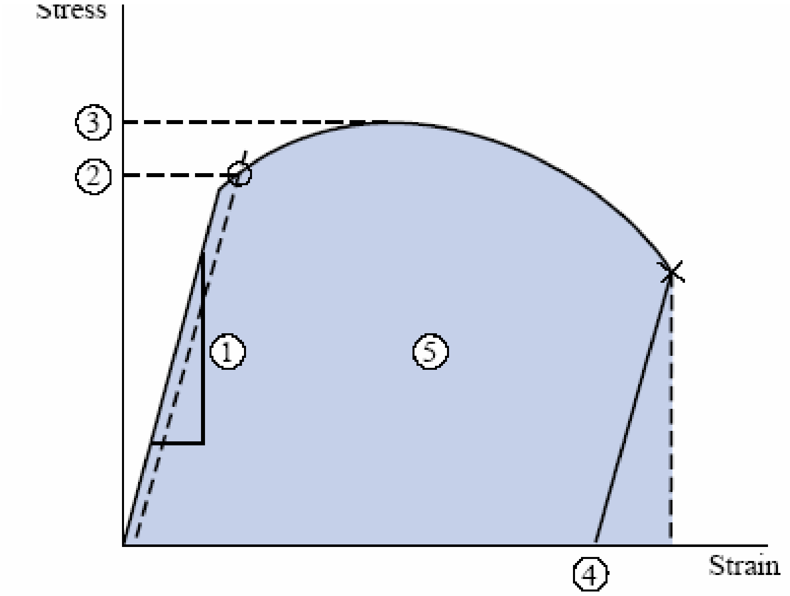
- **Cost** (YTL/kg)

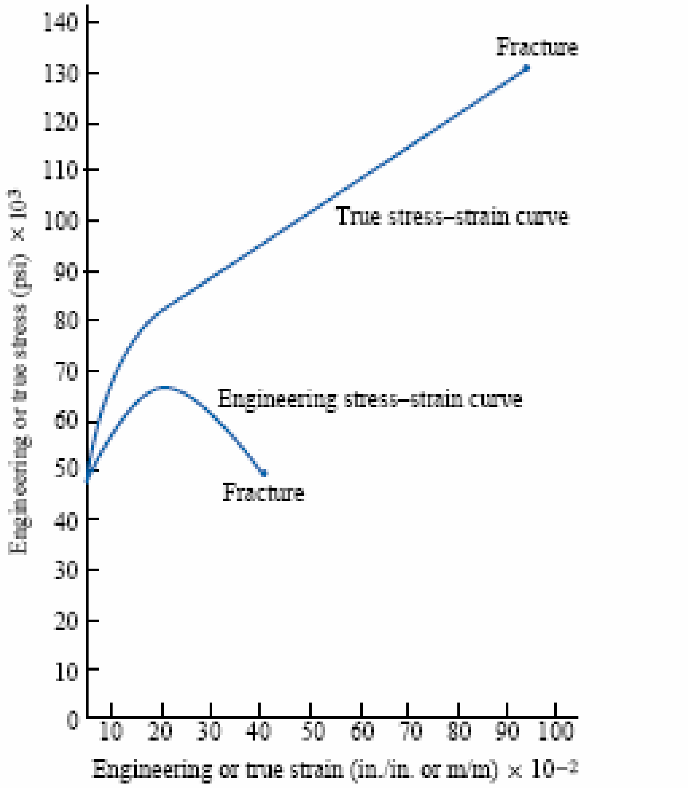
- **Anisotropy**
  <u>Definition:</u> The characteristic of exhibiting different values of a property in different directions.
  Ex: Rubber reinforced with horizontally placed fibers has a high ultimate tensile strength if pulled parallel to the fibers i.e. horizontally, but a relatively low one if pulled vertically.

1.2.1. Mechanical Properties

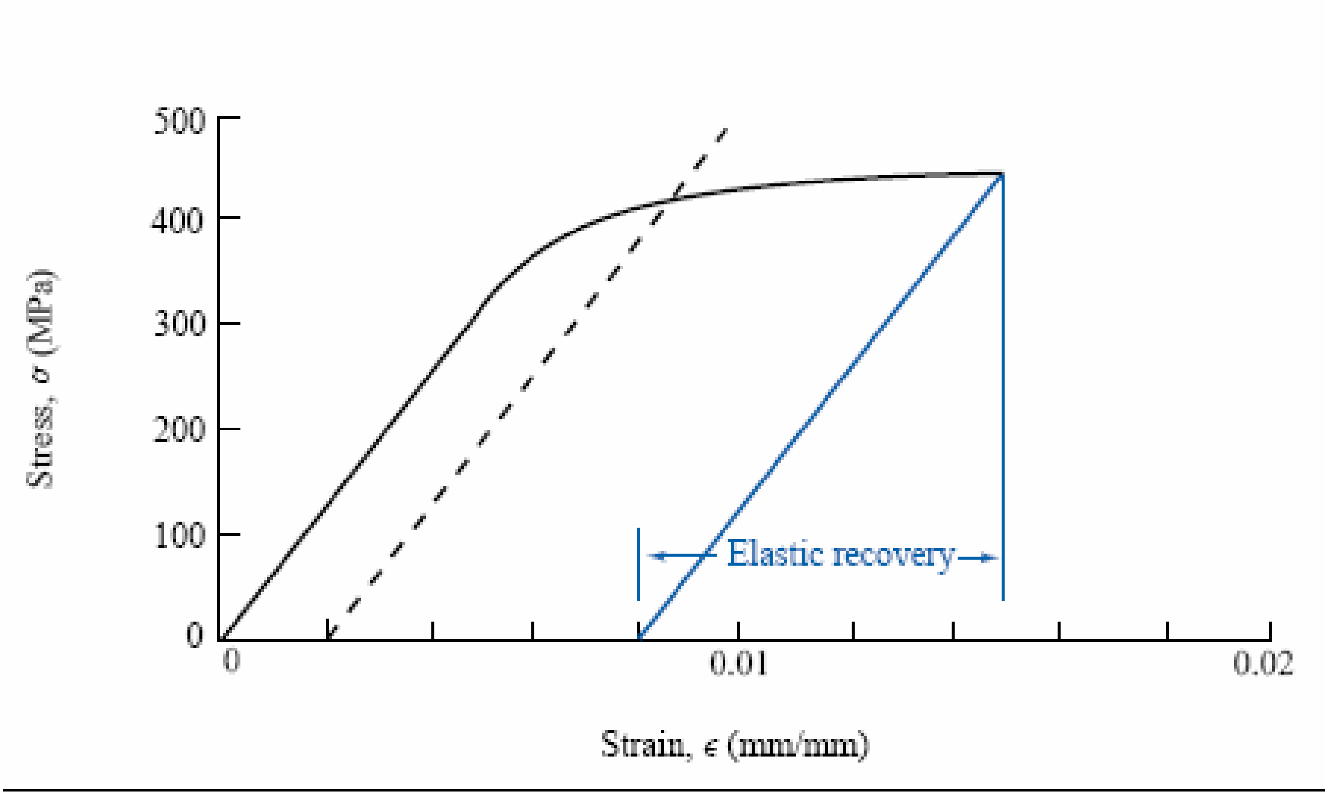
TENSILE TEST







- **Elastic modulus (Young Modulus), E** (Unit: GPa)



Young's modulus, E, is the slope of the initial, linear-elastic part of the stress-strain curve in tension or compression. But accurate moduli are measured dynamically. It is a measure of the rigidity of the material. Young's Modulus (or Elastic Modulus) is the proportionality constant of solids between elastic stress and elastic strain and describes the inherent (natural) stiffness of a material. It can be expressed in the following equation where, E is Young's Modulus;

$$E = \text{Elastic Stress} / \text{Elastic Strain}$$

Tangent modulus: (slope of the stress-strain curve at a certain point)
Secant modulus: (slope of a line from the origin to a specified point)

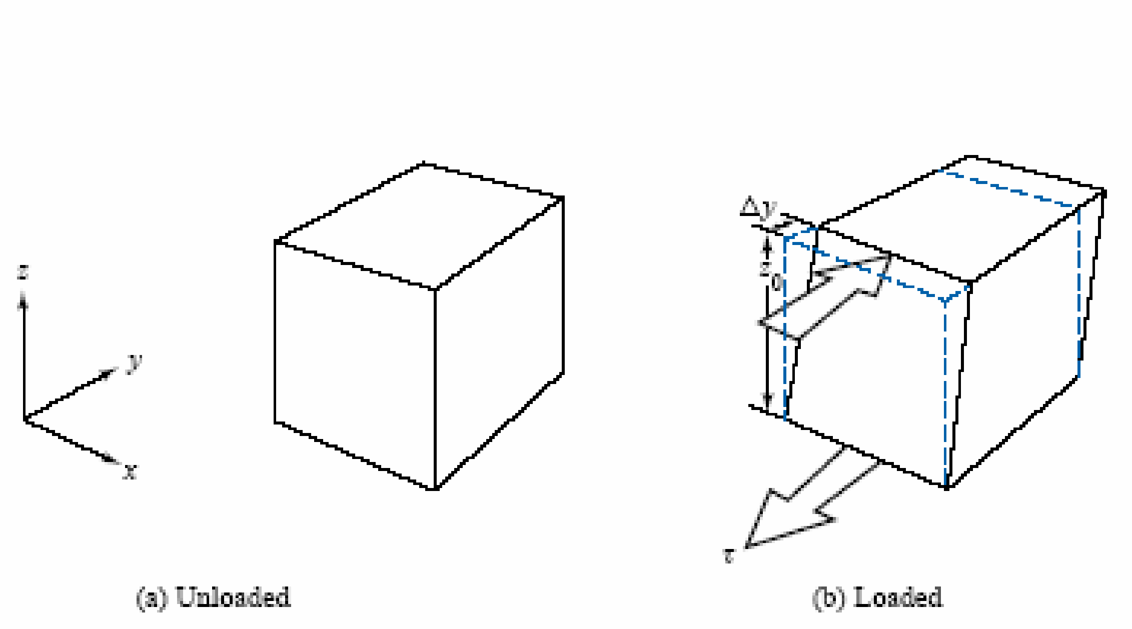
For isotropic materials it is related to the bulk modulus K and to the shear modulus G by

$$E = 3(1 - 2\nu)K$$

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

where ν is Poisson's ratio. Commonly ν = 1/3, and hence E = K, and E = (8/3)G.

• **Shear Modulus, G** (Unit: GPa)



The shear modulus is the initial, linear elastic slope of the stress-strain curve in shear. Shear modulus is the ratio of shear stress divided by the shear strain in the elastic region. It can also be referred to as modulus of rigidity or torsion modulus.
G = Elastic Shear Stress / Elastic Shear Strain

For isotropic materials it is related to Young's modulus E and to the bulk modulus K and Poisson's ratio by

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

$$G = \frac{3(1-2\nu)}{2(1+\nu)}K$$

When v = 1/3, G = (3/8)E, and G = (3/8)K.

- **Bulk Modulus K,** (Unit: GPa)

The bulk modulus, K, measures the elastic response to hydrostatic pressure. Ratio of mean normal stress to the change in volume
Units: SI: GPa; cgs: dyne/cm^2; English: psi

$$K = v\frac{dp}{dv}$$

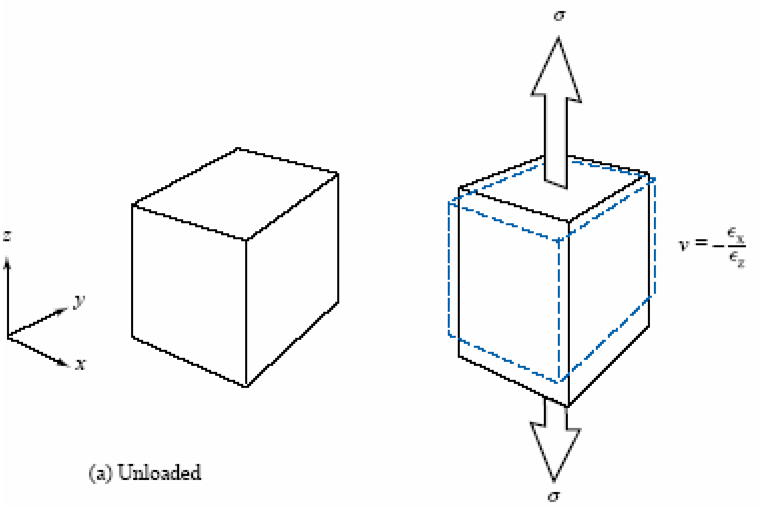
where V is the volume. For isotropic solids it is related to Young's modulus E and to the shear modulus G by

$$K = \frac{E}{3(1 - 2v)}$$

$$K = \frac{2(1 + v)}{3(1 - 2v)} G$$

where v is Poisson's ratio. When v = 1/3, E = K, and K = (8/3)G.

- **Poissons Ratio, v,** (Dimensionless)

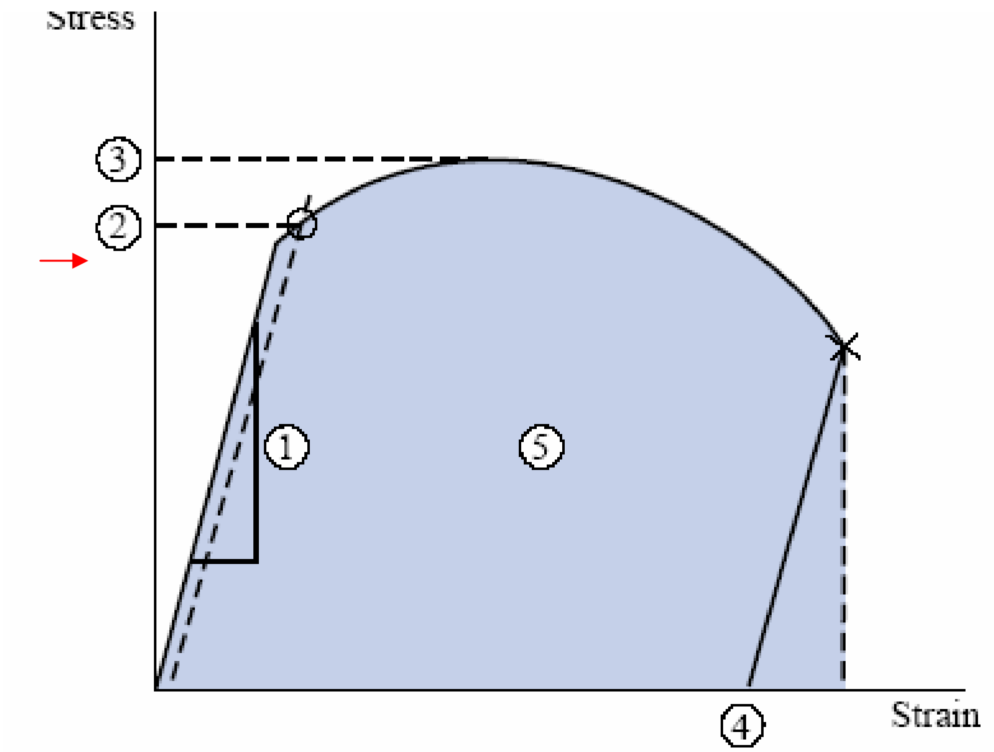


(a) Unloaded

(b) Loaded

Poisson's Ratio is the negative ratio of the thickness decrease divided by the length increase as a result of a tensile stress applied to a material. Its value for many solids is close to 1/3. For elastomers it is just under 0.5

- **Elastic limit, σ_{el}** (Unit: MPa)



The elastic limit (proportionality limit) is the stress beyond which there is permanent deformation. Below the elastic limit all the deformation is recovered when the load is removed. The 'elastic limit' of a solid requires careful definition.
For metals, the elastic limit is defined as the 0.2% offset yield strength. This represents the stress at which the stress-strain curve for uniaxial (=in one direction) tensile loading deviates by a strain of 0.2% from the linear-elastic line. It is the stress at which dislocations move large distances through the crystals of the metal. It is the same in tension and compression as the dislocations' movement is caused by the shear stress, which has its highest value at 45° to the axis of loading.
For polymers, the elastic limit is the stress at which the uniaxial stress-strain curve becomes markedly non-linear: typically, a strain of 1%. This may be caused by 'shear yielding' (irreversible slipping of molecular chains) or by 'crazing' (formation of low density, crack-like volumes which scatter light, making the polymer look white).
For fine ceramics and glasses, the database entry for the elastic limit is an estimate, based on the tensile strength (which is low due to brittle fracture). When based on direct measurements at high pressures, or on hardness measurements, of the stress required to cause plastic flow, it is very high: higher than the compressive strength, which is lowered by crushing.
For composites, the elastic limit is best defined by a set deviation from linear-elastic uniaxial behaviour: 0.5% is taken in the database.

Elastic limit depends on the mode of loading. For modes of loading other than uniaxial tension, such as shear and multiaxial loading, the strength is related to that in simple tension by a yield function. For metals, the Von Mises yield function works well. It specifies the relationship between the principal stresses σ_1, σ_2, σ_3 and the yield strength sy (elastic limit):

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_y^2$$

The Tresca function is sometimes more convenient, because it is less complicated:

$$\sigma_1 - \sigma_3 = \sigma_y \left(1 + \beta \frac{p}{\sigma_y}\right),$$

$$p = -\frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}),$$

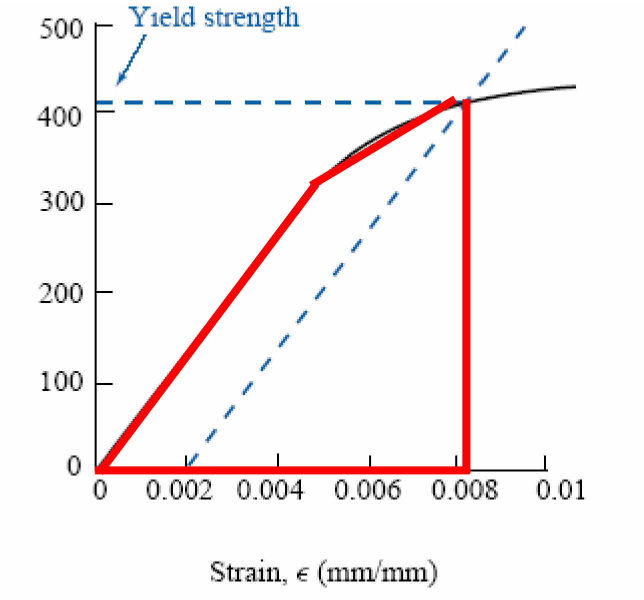
$\sigma_y =$ yield stress in uniaxial tension, $\beta =$ constant

For ceramics, a Coulomb flow law is used:

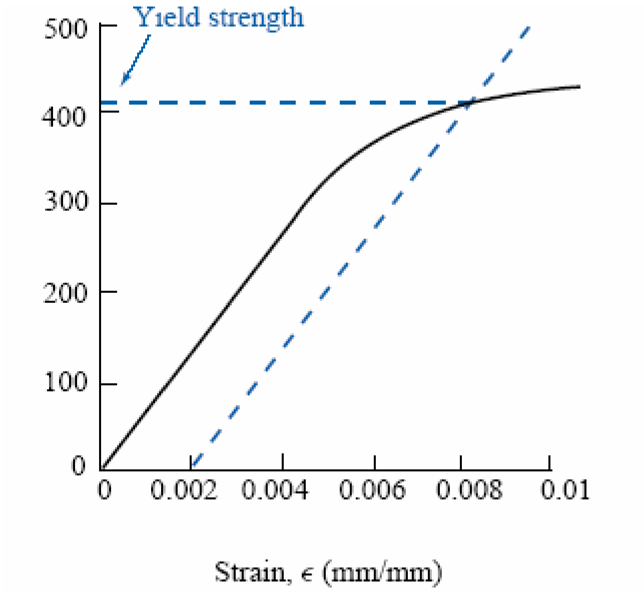
$$\sigma_1 - B\sigma_3 = C$$

- **Resilience**

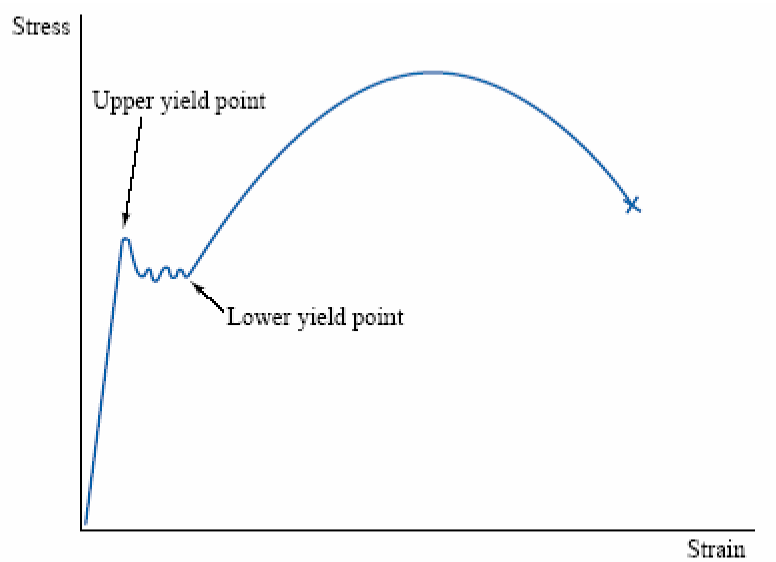
The maximum amount of energy per unit volume which can be stored elastically. This energy is released upon unloading. This value can be calculated as the area under the elastic part of the stres-strain curve.



- **Yield Strength** (Unit: MPa)



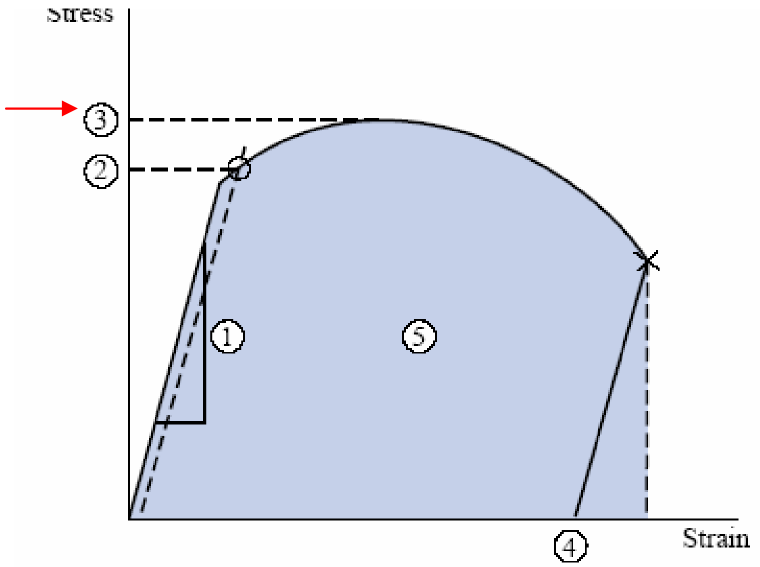
The stress at which a material exhibits a specified deviation from proportionality of stress and strain (Flow stres). An offset of 0.2% is used for many metals.



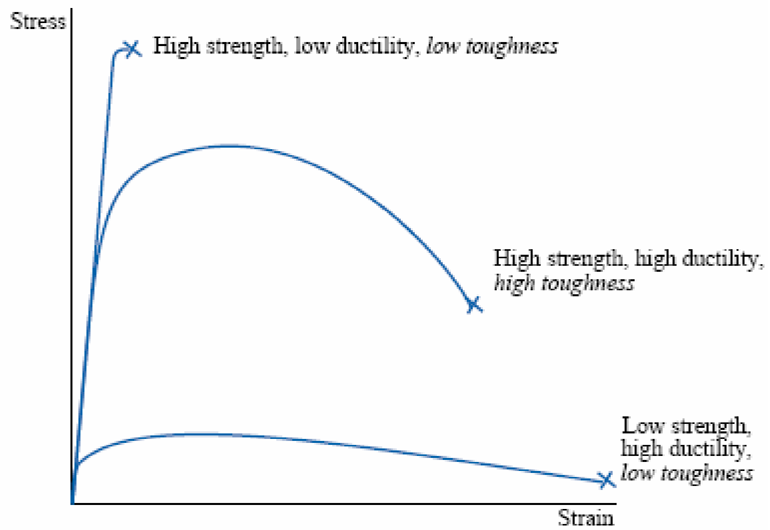
Only certain metals have a yield point (metals with BCC-Body Centered Cubic crystal structure such as iron). If there is a decrease in stress after yielding, a distinction may be made between upper and lower yield points.

- **Tensile Strength** (Unit: MPa)

Tensile Strength is the maximum tensile stress a material can withstand before failure. It is a feature of the engineering stress-strain curve and cannot be found in the true stress-true strain curve.
For brittle solids: ceramics, glasses and brittle polymers - it is much less than the compressive elastic limit. For metals, ductile polymers and most composites - it is larger than the yield strength by a factor ranging from 1.1 to 3.



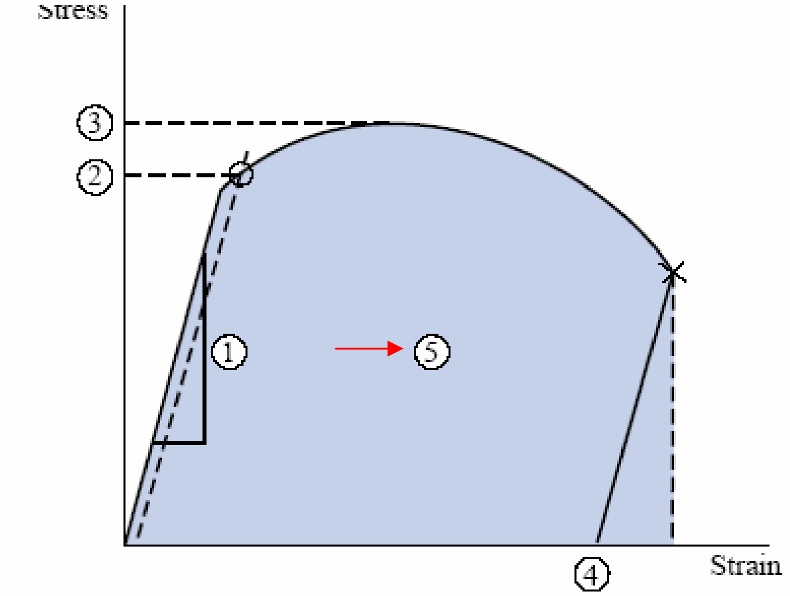
- **Ductility**

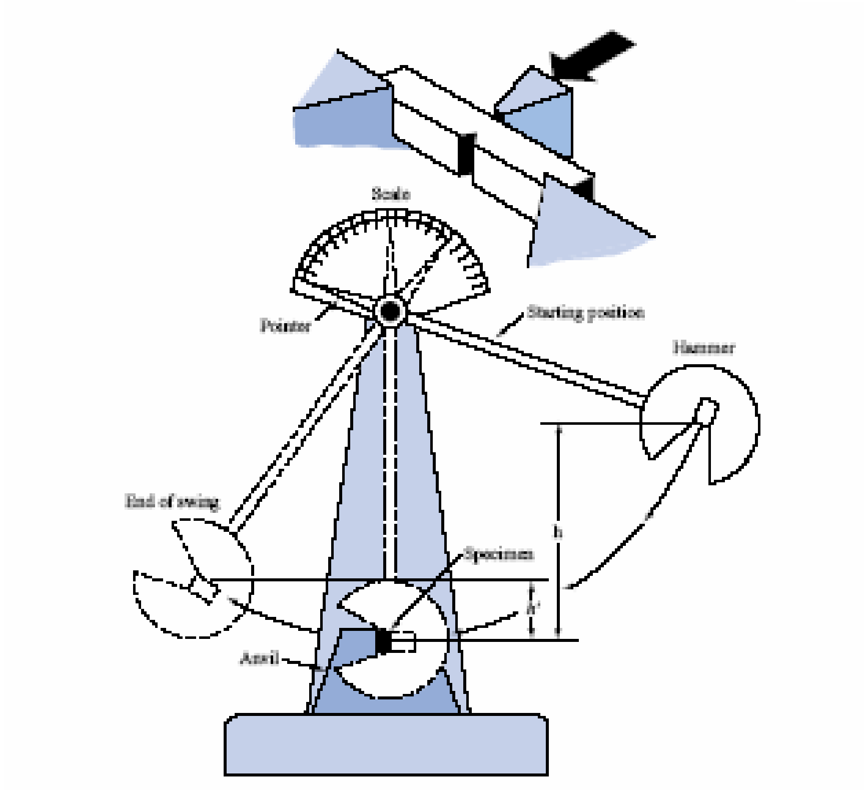


The tensile ductility is the permanent increase in length of a tensile specimen before fracture, expressed as a fraction of the original gauge length. Ductility is the ability of a material to undergo large plastic deformation without fracture or failure. It can also be expressed as the reduction of area of the specimen during the tensile test.
Units: Dimensionless (strain)

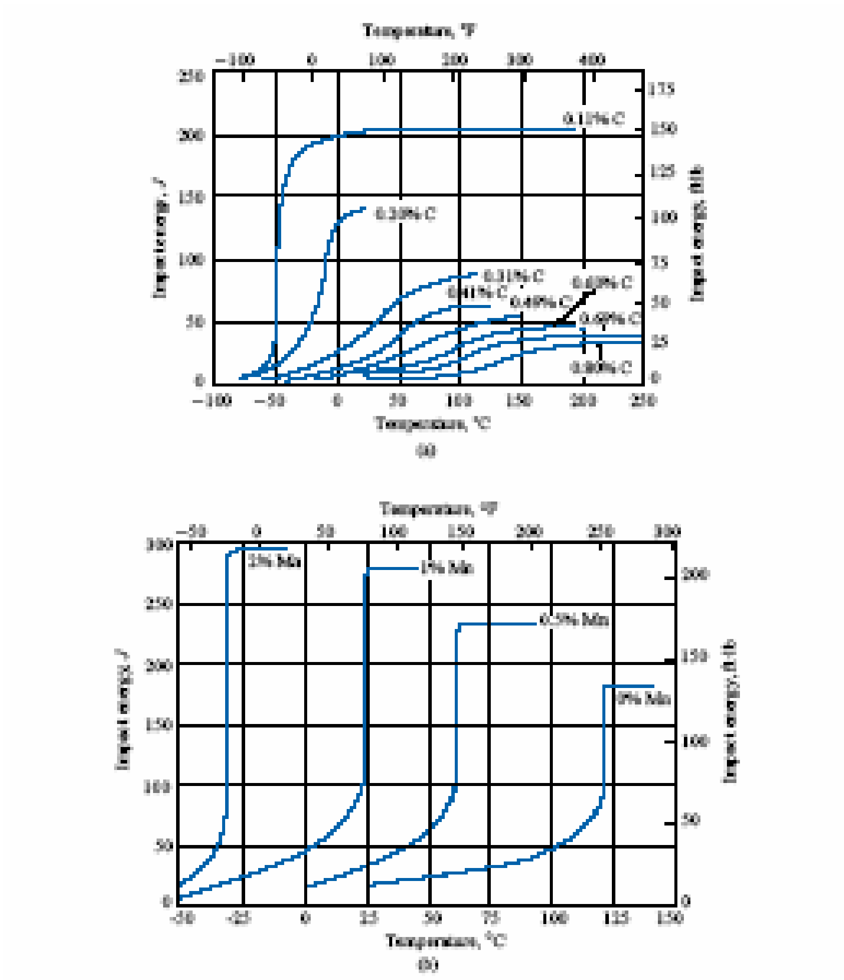
- **Toughness**

Toughness is the ability of a material to absorb energy without rupturing. It is usually measured by the energy absorbed in a notch impact test, but the area under the tensile stress-strain curve is also a measure.



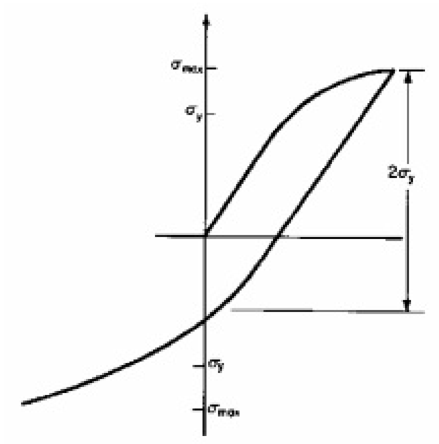


Notch Impact Test



- **Bauschinger Effect:**

The process where the plastic deformation in one direction causes a reduction in the yield strength when stress is applied in the opposite direction.



- **Uniform (necking) strain**

It is the value of strain at which the area of the specimen begins having different values at different points, i.e. necking starts.

- **Strain Hardening Exponent**

An increase in hardness and strength caused by plastic deformation at temperatures below the recrystallisation range. The measure is the exponent n in the equations;

$$\sigma_1 = K\varepsilon_t^n$$

$$or$$

$$\ln\sigma_1 = \ln K + n\ln\varepsilon_t$$

where a logarithmic scale is used and the curve is true stress, true strain.

- **Strain rate sensitivity**

It is the measure for how fast strain hardening occurs when a material is deformed plastically. It is defined as

$$m = \left[\frac{\partial(\ln\sigma)}{\partial(\ln\dot{\varepsilon})}\right]$$

- **Compressive Strength**

For metals, the compressive strength is the same as the tensile yield strength. Polymers are approximately 20% stronger in compression than in tension. In

Ceramics, compressive strength is governed by crushing and is much larger than the tensile strength.

Composites that contain fibers (including natural composites like wood) are a little weaker (up to 30%) in compression than tension as the fibers buckle

- **Shear strength**

The highest value of shear stress a material can withstand before plastic deformation occurs.

- **Impact strength**

Obtained from the notch-impact test. It is expressed in means of energy.

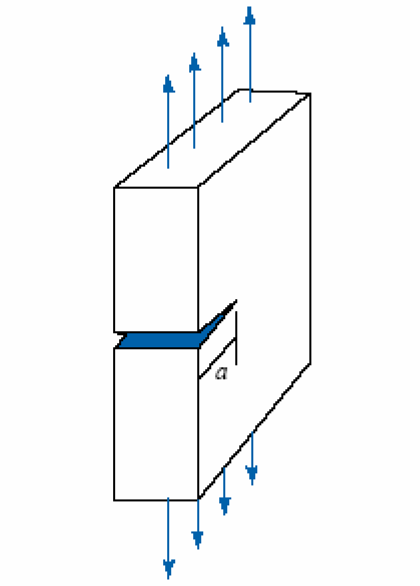
- **Temper Brittleness**

A feature of some materials, which causes the material to become more brittle after tempering. It can be obtained from the notch-impact test.

- **Modulus of Rupture**

When the material is difficult to grip (as is a ceramic), its strength can be measured in bending. The modulus of rupture (MOR) is the maximum surface stress in a bent beam at the instant of failure. One might expect this to be exactly the same as the strength measured in tension, but it is always larger (by a factor of about 1.3) because the volume subjected to this maximum stress is small, and the probability of a large flaw lying in the highly stressed region is also small. (In tension all flaws see the maximum stress.)
The MOR strictly only applies to brittle materials. For ductile materials, the MOR entry in the database is the ultimate tensile strength.
Units: SI: MPa; cgs: 10^7dyne/cm^2; English:10^3psi

- **Fracture Toughness**

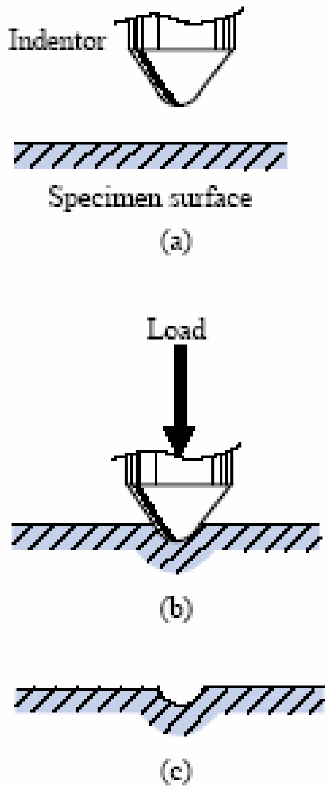


The fracture toughness Kc, is a measure of the resistance of a material to the propagation of a crack. It can be measured by loading a sample containing a deliberately introduced crack of length a=2c and then recording the tensile stress σ at which the crack propagates. Fracture toughness is then calculated from

$$K_c = Y \frac{\sigma}{\sqrt{\pi c}}$$

where Y is a geometric factor, near unity, which depends on details of the sample geometry. Measured in this way, Kc has well defined values for brittle materials (ceramic, glasses, many polymers and low toughness metals like cast iron).
In ductile materials, a plastic zone develops at the crack tip, which introduces new features into the way cracks propagate. This necessitates more complex characterization. Nevertheless, values for Kc are cited and are useful as a way of ranking materials.

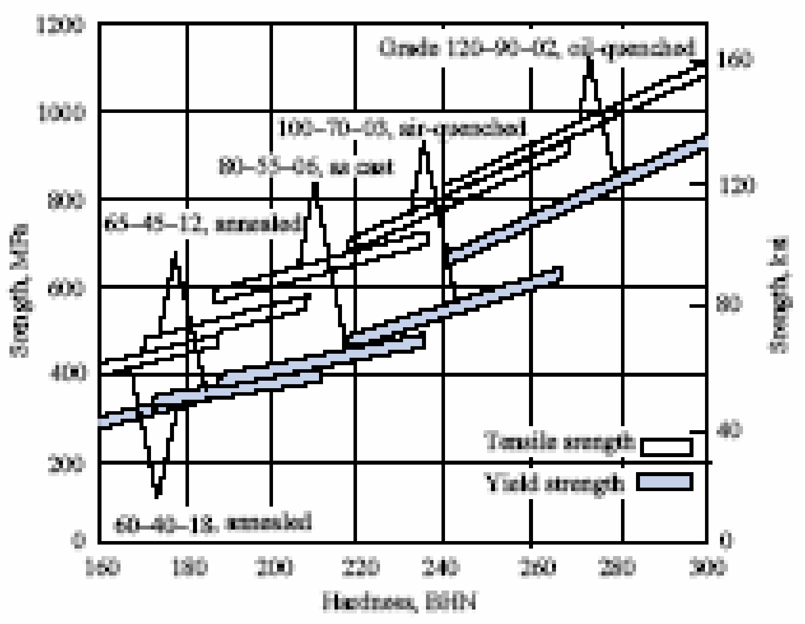
- Hardness Units:(for Brinell, Vickers) SI: MPa; (for Rockwell) Dimensionless



Hardness is the resistance of a materials surface to abrasion, scratching and indentation (local plastic deformation). It is often measured by pressing a pointed diamond or hardened steel ball into the surface of the material. The hardness is generally defined as the indentor force divided by the projected area of the indent. Hardness is measured by different hardness techniques: Brinell, Vickers, Rockwell, Shore etc..

TABLE 7.18 COMMON TYPES OF HARDNESS TEST GEOMETRIES

Test	Indenter	Shape of Indentation: Side view	Shape of Indentation: Top view	Load	Formula for hardness number
Brinell	10 mm sphere of steel or tungsten carbide			P	$\text{BHN} = \frac{2P}{\pi D\left[D - \sqrt{D^2 - d^2}\right]}$
Vickers	Diamond pyramid	136°		P	$\text{VHN} = 1.72P/d_1^2$
Knoop microhardness	Diamond pyramid	$l/b = 7.11$, $b/t = 4.00$		P	$\text{KHN} = 14.2P/l^2$
Rockwell					
A, C, D	Diamond cone	120°		60 kg, 150 kg, 100 kg	$R_A =$, $R_C =$, $R_D =$ } $100 - 500t$
B, F, G	$\frac{1}{16}$ in. diameter steel sphere			100 kg, 60 kg, 150 kg	$R_B =$, $R_F =$, $R_G =$ } $130 - 500t$
E, H	$\frac{1}{8}$ in. diameter steel sphere			100 kg, 60 kg	$R_E =$, $R_H =$ } $130 - 500t$



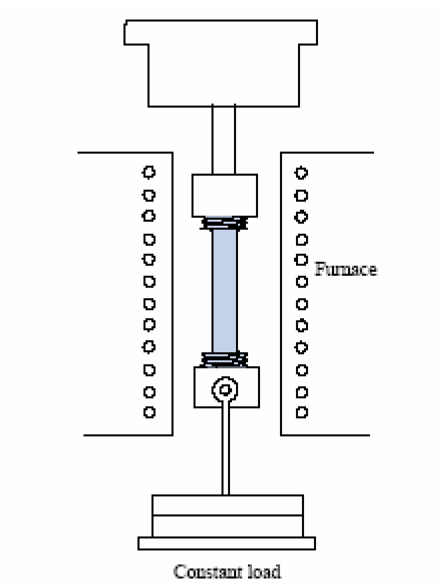
(b) Tensile properties of ductile iron versus hardness

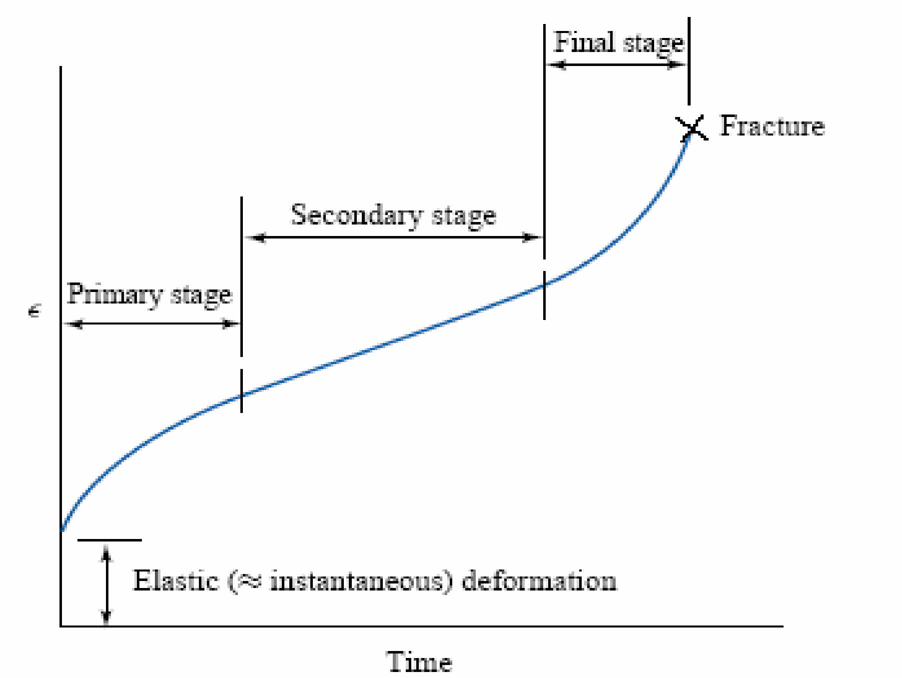
Very rough approximations can be made by relating the Brinell hardness to the yield strength σ_y of ductile materials by $H = 3\sigma_y$. Hardness is a good indicator for controlling or comparison purposes, but has little meaning for scientific purposes or calculations.

- **Creep Strength**

Time-dependent deformation which occurs when materials are loaded above $1/3T_m$.

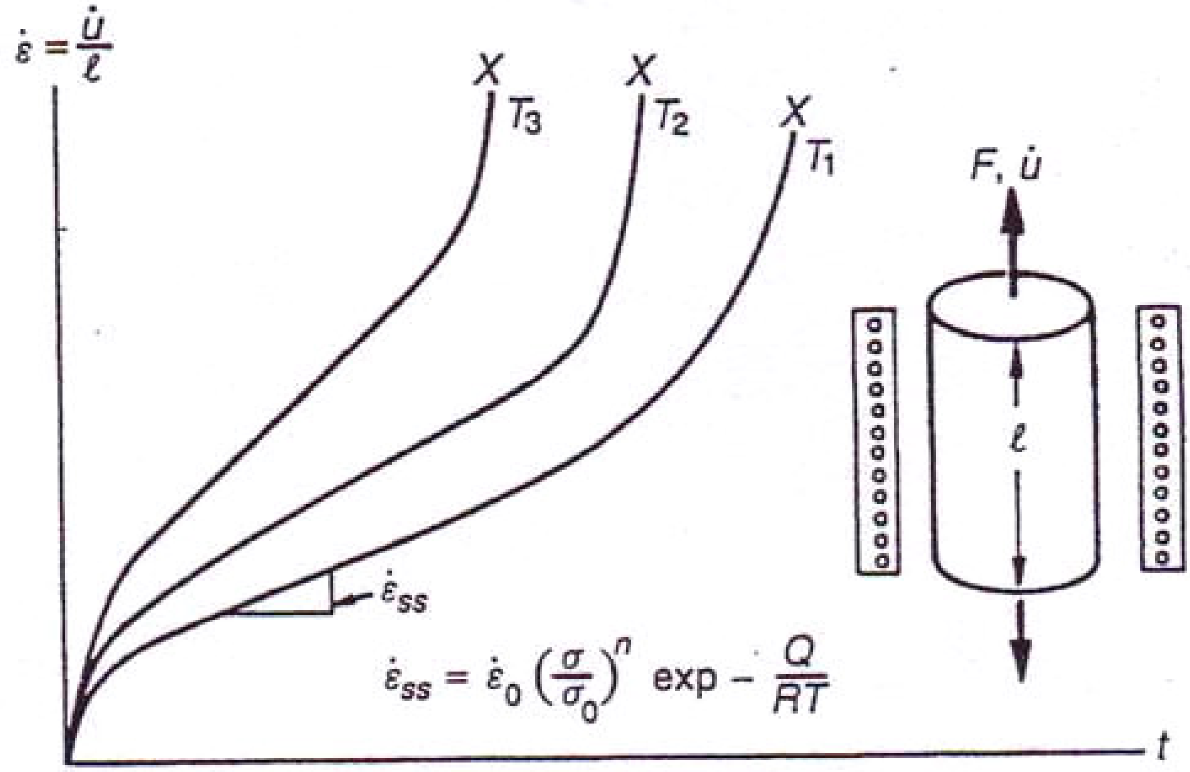
Creep Test





The creep strain rate at a certain temperature can be given by

Creep rate= $\dot{\varepsilon} = \frac{d\varepsilon}{dt}$

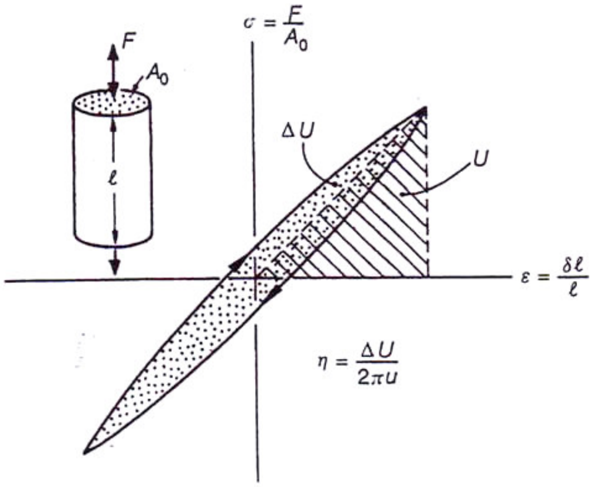


The creep strength of a material can be given as

a. The maximum stress that will cause less than the specified strain in a given time
b. The constant stress that will cause a specified secondary creep strain rate at constant temperature

- **Damping Capacity - Loss-Coefficient, η** (Dimensionless)

The loss-coefficient measures the degree to which a material dissipates vibrational energy.



If a material is loaded elastically to a stress σ_{max}, it stores elastic energy

$$u = \int_0^{\sigma_{max}} d\varepsilon \ \frac{1}{2}\frac{\sigma_{max}^2}{E}$$

per unit volume.
If it is loaded and then unloaded, it dissipates energy equivalent to the area of the stress-strain hysteresis loop:

$$\Delta u = \oint \sigma \, d\varepsilon$$

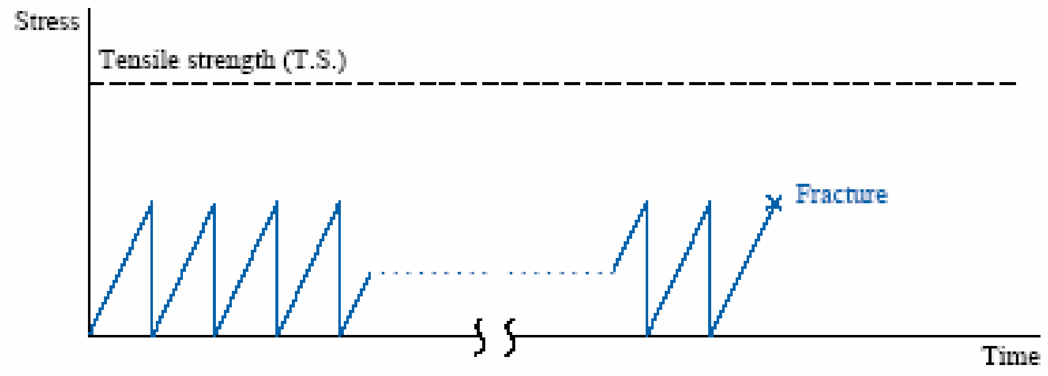
The loss coefficient h is defined as

$$\eta = \frac{\Delta u}{2\pi u}$$

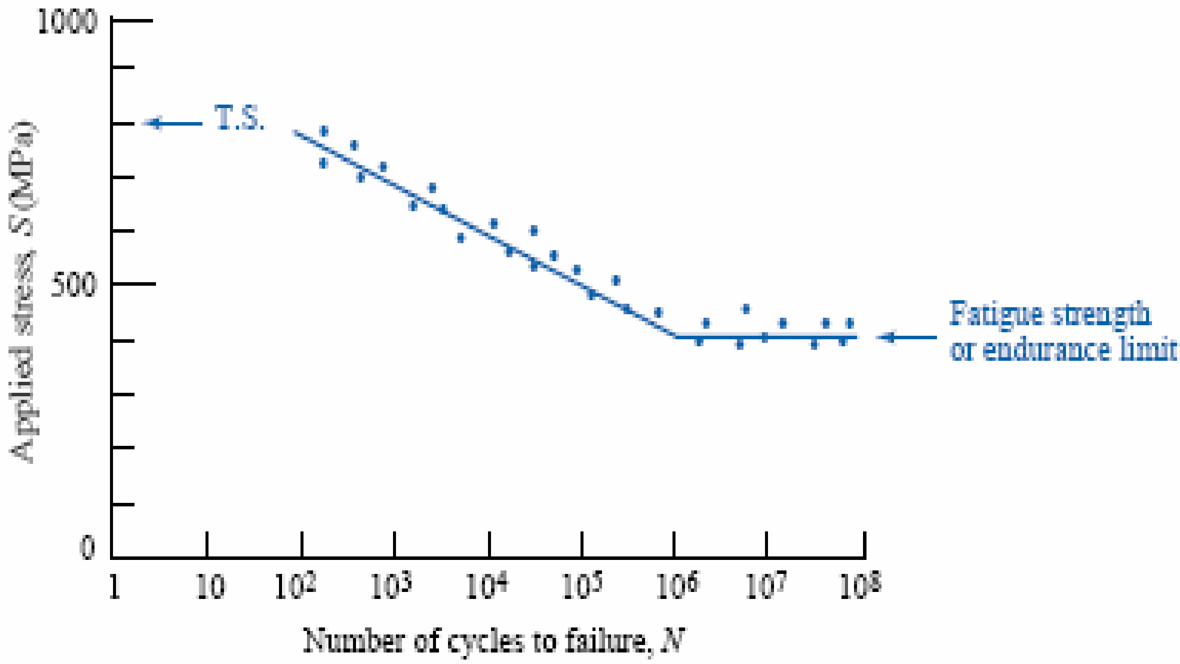
The cycle can be applied in many different ways - some fast, some slow. The value of η usually depends on the time-scale or frequency of cycling.

- **Fatigue strength (Endurance Limit),** Units: MPa

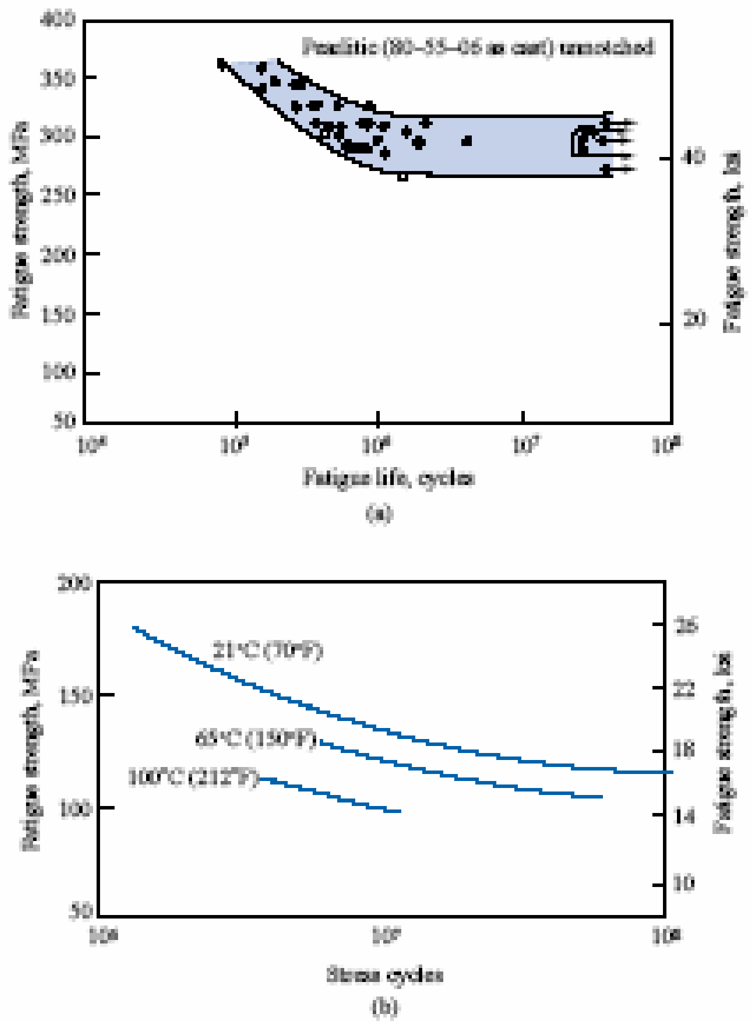
Endurance limit (or sometimes referred to as the fatigue limit) is the maximum stress amplitude in fatigue below which a material can endure an essentially infinite number of stress cycles and not endure failure. Generally 'infinite' life means more than 10^7 cycles to failure. The endurance limit is usually a band of values, which is caused by small differences in the specimens. Fatigue strength is dependent on temperature.



Stress
Tensile strength (T.S.)
Fracture
Time



1000
500
0
Applied stress, S (MPa)
T.S.
Fatigue strength
or endurance limit
1
10
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
Number of cycles to failure, N

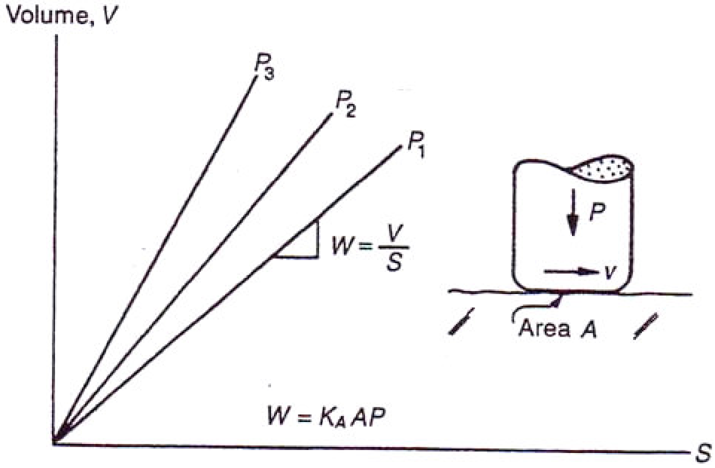


- **Archard wear constant, k_A** (m/MN)

The volume of material lost from one surface, per unit distance slid is called the wear rate. The materials ability to resist wear is given by the Archard wear constant, k_A.

$$W = k_A.A.p$$

Where A is the area of the surface, p is the pressure)



- **Superplasticity**

A feature of materials to withstand plastic deformation over their limits at high temperatures (usually half of the melting temperature). This effect is caused by dynamic recrystallisation during deformation of the material.

- **Thermal fatigue**

When the temperature of a material is repetitively increased and decreased (a cyclic change in temperature) thus generating high temperature gradients continuously, the specimen will fail after a certain number of changes. This is called thermal fatigue and is caused by the inner temperature differences causing stresses inside the material.

1.2.2. Thermal Properties

- **Melting Point, Tm**

The melting point is the temperature at which a material turns from solid to liquid. The melting temperature of an alloy is usually less than the melting temperature of the parent metals.

- **Latent Heat of Fusion Lm**

Latent Heat of Fusion is the heat [energy] required per unit mass to change a materials state to another state i.e. from a solid to liquid or from a liquid to gas, this process is reversible, therefore includes a gas to liquid or from a liquid to solid.
Units: SI: kJ/kg; cgs: cal/g; Imperial: Btu/lb
For pure metals this heat is absorbed at constant temperature (the melting temperature), Tm. Amorphous solids (including many polymers) do not have a sharp

melting point. When the change from a solid state to fluid is over a temperature range, it is not appropriate to define a latent heat of melting.

- **Specific Heat**

C_p is the specific heat capacity at constant pressure. It specifies the amount of heat required to raise the temperature of 1 kg of material by 1°C (K). It is measured by the standard technique of calorimetry.
Units: SI: J/kg.K; cgs: cal/g.K; English: Btu/lb.F

- **Thermal Conductivity** (Unit: W/m.K)

Thermal Conductivity is a measure of heat flow through a material. It relates heat flow (the flow of heat energy per unit area per unit time) to the temperature gradient (which describes a temperature difference per unit distance), causing the heat flow. The rate at which heat is conducted through a solid at 'steady state' (meaning that the temperature profile does not change with time, i.e. the surface of the material is always at the temperature T_1 and the inside of the material at distance X is always at T_2 throughout the experiment) is governed by the thermal conductivity λ. It is measured by recording the heat flux J (W/m^2) flowing from surface at temperature T_1 to one at T_2 in the material, separated by a distance X:

$$J = \lambda \frac{(T_1 - T_2)}{X}$$

Where $\frac{(T_1 - T_2)}{X}$ is the temperature gradient, and λ is to be determined as a material specific constant.
In practice, the measurement is not easy (particularly for materials with low conductivities), but reliable data are generally available.

- **Thermal diffusivity, a** (Unit: m^2/s)

When the heat flow is not steady the flux depends on thermal diffusivity a:
$a = \lambda / (\rho.C_p)$
where ρ is the density and C_p the specific heat at constant pressure. It shows how quick a heat, which is applied to the material, will be distributed among the material. At high λ and low C_p temperature differences will be equalled quickly.

- **Thermal Expansion coefficient, α** (1/K)

Thermal expansion is the term used to describe the change in dimensions that occurs with most materials as the temperature is increased or decreased. Most materials expand when they are heated. The linear thermal expansion coefficient a is the thermal strain per degree K. If the material is thermally isotropic, the volumetric expansion per degree is 3α. If working with a material, which has a high α value, the

cooling differences (ex: the surface cools more quickly) will create high inner stresses, which could for example deform the shape of the material.
Units: SI: 10^{-6}/K; cgs: 10^{-6}/K; English: 10^{-6}/F

- **Thermal shock resistance** (K)

Maximum temperature difference through which a material can be quenched suddenly without damage

- **Maximum Service Temperature** (K)

Maximum service temperature is the highest temperature at which a material can reasonably be used without the effects of oxidation, chemical change or excessive creep.

- **Minimum Service Temperature** (K)

Minimum service temperature is the lowest temperature at which a material can reasonably be used without the loss of its original serviceable properties.

- **Glass Transition Temperature, Tg** (K)

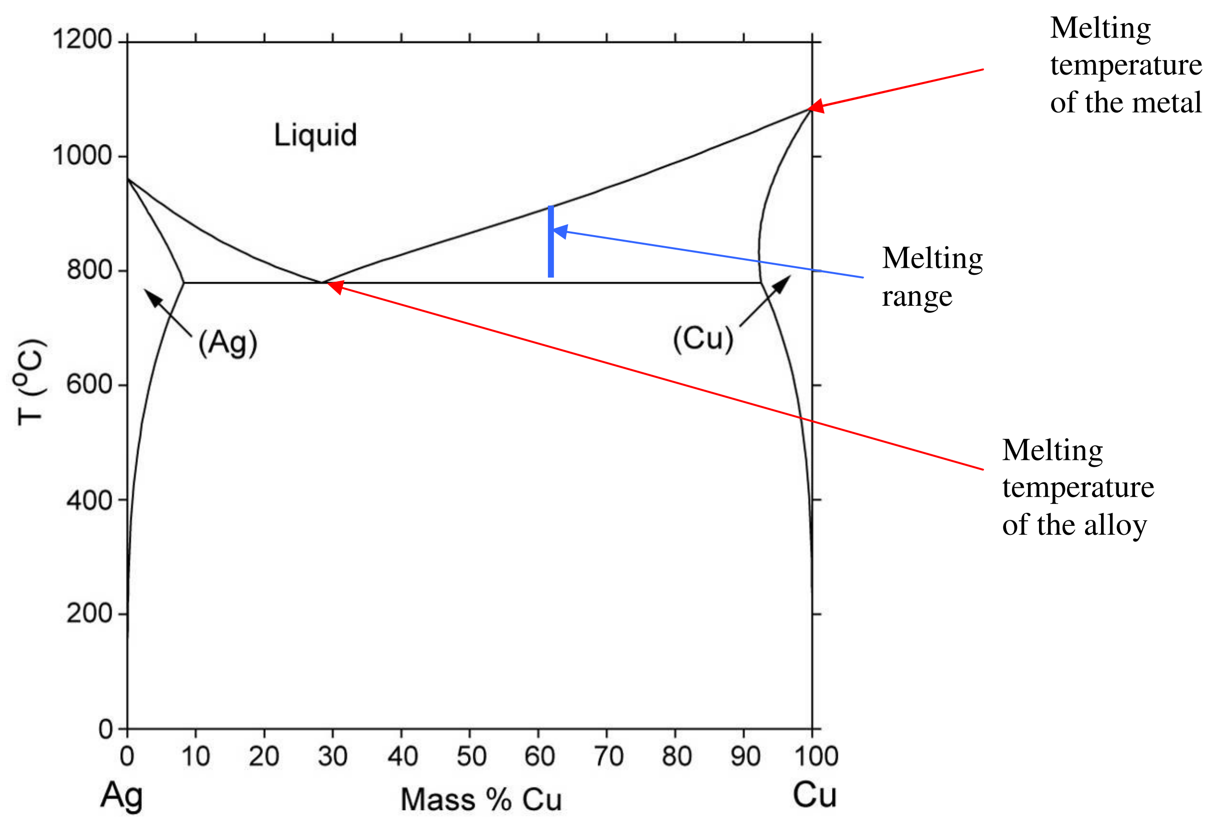
A property of non-crystalline solids which do not have a sharp melting point. It characterises the transition from true solid to viscous liquid in these materials. The Glass Transition Temperature relates to those materials that are non-crystalline solids and is defined by the transition from a true solid to very viscous liquid.
Units: SI: K; cgs: K; English: °R

- **Recrystallisation Temperature**

The approximate minimum temperature at which the deformed crystal structure of a cold worked metal is replaced with a new crystal structure within a specified time.

- **Melting range**

A temperature range where solid and liquid forms of an alloy exist together. For various reasons it is better to have a small melting range.



- **Casting shrinkage**

Casting shrinkage is the sum of

- Liquid shrinkage: The volume of the liquid decreases during cooling.
- Solidification shrinkage: The volume of the material decreases during the transition from liquid to solid state.
- Solid shrinkage: The volume of the solid decreases during cooling.

Casting shrinkage is high for materials with big thermal expansion coefficients. Casting shrinkage should be considered when preparing moulds for casting, i.e. the mould should be prepared using bigger dimensions than the wanted ones, as the product will shrink after casting.

- **Hot shortness**

Hot shortness is a material and structural property, which indicates the tendency of a material to separate the grain boundaries when stressed near the melting temperature. It is usually caused by a phase, which is not dissolved in the main phase, but is located at the grain boundaries.

1.2.4. Environmental Properties

- **Dry Corrosion**

Dry corrosion is the chemical reaction of a solid surface with dry gases. Typically a metal, M reacts with oxygen and forms a surface layer of the oxide.

$$aM + \frac{b}{2}O_2 \rightarrow M_aO_b$$

If the oxide is protective, forming a continuous film without cracks over the surface, the reaction slows down with time, as the oxygen cannot pass through this layer. The oxidation rate mainly depends on the characteristic of this oxide layer, which can be described by the Pilling-Bedworth ratio.

P-B Ratio $= \frac{A_O \rho_M}{a A_M \rho_O}$

A_O ist the molecular weight of the metaloxyde, A_M ist he atomic weight of the metal, ρ_O and ρ_M are the corresponding densities.
If the Pilling-Bedworth ratio is smaller than 1, so the volume of the oxide is smaller than the oxidized metal, than the oxide layer is porous and does not protect the surface. If the P-B Ratio is greater than 1, non-porous and protective oxide layer forms. If this ratio is higher than 2 or 3 the layer breaks and is not protective any more.

- **Flammability**

Flammability is a materials ability to suppress combustion. The number given as flammability corresponds to a relative rating system, thus using it almost only for comparisons is reasonable.

- **Wet corrosion**

(Corrosion caused by a reaction of metal with water, brine, acids and alkalis) is much more complicated and cannot be defined by simple relations. It is more usual to scale the resistance by relative values.

Corrosion is effective in fresh water, organic solvents, sea water, strong acid, strong alkalis, UV, weak acid and weak alkalis.

1.2.4. Electrical Properties

- **Breakdown Potential**

Breakdown Potential is the potential required to apply to a material that is normally an insulator that allows conduction (or partial ionisation) through the material. If the potential gradient becomes too steep, normal conduction is replaced by electrical breakdown: a catastrophic electron-cascade, usually causing permanent damage. Each insulator has a breakdown potential at which the structure of the material is changed and therefore damaged to allow electric flow.
Units: SI: 10^{6} V/m; cgs: V/cm; English: V/mil

- **Dielectric Constant**

When a material (such as that used in a capacitor) is placed in an electric field, it becomes polarised and charges appear at its surfaces which tend to screen (separate) the interior from the external field. The tendency to polarise is measured by the dielectric constant. Dielectric Constant is the degree of polarisation or charge storage capability of a material when subjected to an electric field.
Units: Dimensionless

- **Resistivity**

Resistivity is the materials property that describes the ability of a material to resist, or oppose, the transport of electrical charge in response to an external electric field. It varies over a large range: from 10^{-8}W.m, to more than 10^{16} W.m for the best insulators.
Units: SI: 10^{-8}W.m; cgs: 10^{-6}W.cm; English: 10^{-8}W.m

2. Manufacturing Processes and Manufacturability

Manufacturing processes are technological methods to change the raw material from its raw form to the final product. This chapter summarizes the traditional manufacturing processes. The suitability of materials for a certain process depends usually on a special combination of its properties. There are also special technological tests for certain manufacturing processes to assess the materials suitability for the process.

In this chapter, the traditional manufacturing processes are introduced and the material properties which affect the suitability for these processes are discussed.

The most common manufacturing processes are:

a. Casting
b. Forming (cold, hot, sheet ..)
c. Machining
d. Joining Processes
e. Powder Methods
f. Heat treatment
g. Finishing
e. Special methods

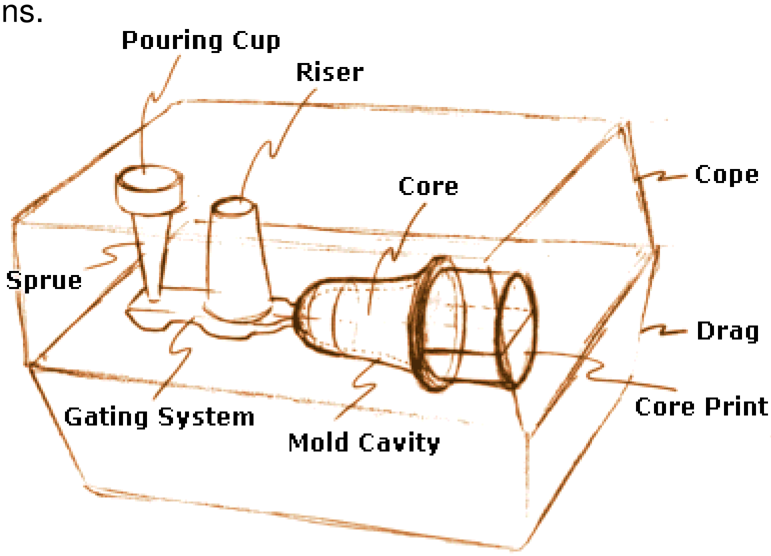
2.1 Casting and Castability

2.1.1. Casting Process:

Casting is usually the first step in manufacturing. In casting, a material in liquid form is poured into a mold where it is allowed to solidify by cooling (metals) or by reaction (plastics). The mold can be filled by gravitational forces or under pressure. The mold cavity is carefully prepared so that it has the desired shape and properties. The cavity is usually made oversize to compansate the metal contraction as it cools down to room temperature. This is achieved by making the pattern oversize. After solidification, the part is removed from the mold. By using casting method, big and complex parts can be produced.

Sand casting is used to make large parts (typically Iron, but also Bronze, Brass, Aluminum). Molten metal is poured into a mold cavity formed out of sand (natural or synthetic). The cavity in the sand is formed by using a pattern (an approximate duplicate of the real part), which are typically made out of wood, sometimes metal. The cavity is contained in an aggregate housed in a box called the flask. Core is a sand shape inserted into the mold to produce the internal features of the part such as holes or internal passages. Cores are placed in the cavity to form holes of the desired shapes. A riser is an extra void created in the mold to contain excessive molten material.

In a two-part mold, which is typical of sand castings, the upper half, including the top half of the pattern, flask, and core is called cope and the lower half is called drag. The parting line or the parting surface is line or surface that separates the cope and drag. Sand castings generally have a rough surface sometimes with surface impurities, and surface variations.

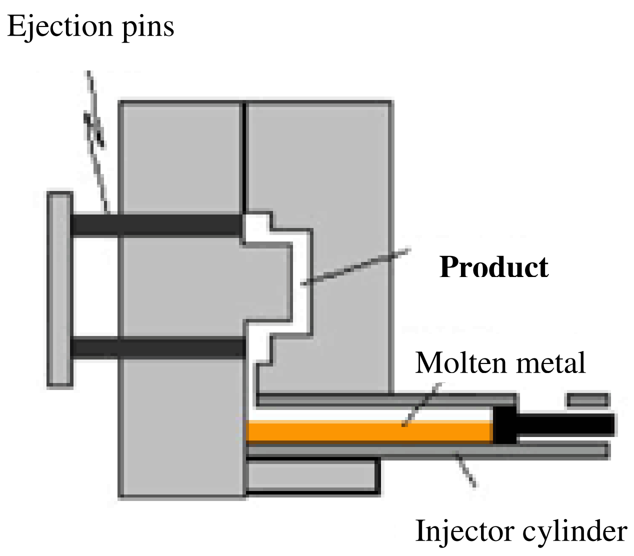


Typical Components of a Two-part Sand Casting Mold.

In **Die-casting** the metal is injected into the mold under *high pressure.* This results in a more uniform part, generally good surface finish and good dimensional accuracy,. For many parts, *post-machining can be totally eliminated,* or very light machining may be required to bring dimensions to size.

Die casting molds (called dies in the industry) tend to be expensive as they are made from hardened steel or other high refractory materials-also the cycle time for building these tend to be long. Therefore die-casting is a good choice for high quantities (mass production), whereas it rises the expenses too much for low quantities.

Furthermore the stronger and harder metals such as iron and steel cannot be die-cast. Materials with relatively low melting points such as *Aluminum*, *Zinc* and *Copper alloys* are the materials predominantly (mainly) used in die-casting. Die casting is limited to smaller parts up to 25 kg.



2.1.2. Castability:

Castability is a term, which reflects the ease with which a metal can be poured into a mold to obtain a casting without defects. Castability depends on part design and material properties. Here we shall only concentrate on material properties, which affect castability.

2.1.3. Material Properties Which Affect Castability:

a) Melting temperature (or temperature range):

Melting temperature is an important material property for castability. In casting, generally low melting points are desired, because low melting points require less energy to melt the material.

Casting temperature has to be higher than the melting temperature. Casting temperature must also be adjusted according to casting technique and the complexity of the casting. Casting temperature also determines the materials fluidity. For a high fluidity, we have to choose a higher casting temperature.

In addition the melting point also influences the selection of the mold material. If the melting temperature is too high, the mold material has to be more refractory and probably expensive. Low melting point is also important for long service life of molds.

Pure metals and eutectic alloys melt and solidify at constant temperature. Alloys mostly have a solidification range and also amorphous solids (including many polymers) do not have a sharp melting point. For good castability of a metallic alloy, the solidification range has to be small. If the temperature range where the liquid and solid phases are both present very high, microsegregation and microporosity will occur. This is the reason why eutectic alloys (solidification at constant temperature) are preferred for casting alloys.

Melting Temperatures of Some Metals and Alloys

Metal and Alloy	Melting Temperature or Range ^{0}C
Iron	1535
Stainless steel	1400-1420
Copper	1083
Red Brass	990 - 1025
Aluminium	660
Nickel	1455
Zamak	380-390
Zinc	419
Lead	327
Tin	232
Magnesium	650

b) Fluidity:
It is a measure of how well the liquid will flow and fill a mold cavity. Complex shaped castings cavities require the best fluidity. The same applies also to the casting process, which uses molds that include rapid cooling rates, like permanent metal mold process. Poor fluidity is less concern when the metal is cast by plaster or investment casting processes (slower cooling!) Fluidity is not only a material property, it is also affected by casting temperature, mold type, mold temperature etc. There are special technological tests to determine the fluidity under certain conditions.

c) Latent Heat of Fusion
Latent Heat of Fusion is the heat required per unit mass to change a materials state to another state i.e. from a solid to liquid. For pure metals this heat is absorbed at constant temperature. When the transition from one state to another happens over a temperature range, it is not appropriate to define a latent heat of fusion.

d) Specific Heat:
Specific heat (c) is the energy amount which is used to rise temperature of 1 kg material by 1 °C (K). In casting process generally low specific heat is desired because low specific heat results in a low energy requirement to reach the melting temperature.

Specific heat also affects the difference between melting temperature and casting temperature. When materials have high specific heat, difference between melting temperature and casting temperature can be less, because materials with high specific heat do not cool very easily as the amount of energy to be removed for cooling is high.

e) Thermal Conductivity:

Thermal conductivity coefficient affects the cooling rate. It also determines the temperature gradient and the internal stresses due to temperature differences. Because during solidification if some parts of the material cool rapidly and other parts of the material stay hot, there will be differences in the shrinkage and as a result internal stresses or some cracks may develop in the material.

The cooling rate may also affect the phase transformation and the microstructure of a material (eg. martensite transformation in steel)

f) Thermal Diffusivity

The heat transfer in a solidified casting is not steady-state. So it is realistic to consider the diffusivity rather than the conductivity. It is a measure of the rate at which a temperature disturbance at one point in a body travels to another point.

g) Coefficient of Expansion:

Metals expand when heated and contract when cooled. As a result of this, the dimensions of the material change during solidification and cooling in the mold cavity. We have to design the mold cavity by considering the expansion coefficient. Generally the cavity has bigger dimensions than the desired part.

h) Resistance to Hot Cracking:

During solidification, the hot metal has a very low strength, but it has to shrink as it cools. Due to temperature differences there will be strain mismatches in the cooling part. The modulus of elasticity determines the stress level of internal stresses which develop during cooling. The ductility determines whether a failure will occur due to these strain mismatches. If stresses are produced because of some factor that restrains the free contraction of the metal, the metal may not be able to resist this stress and cracks, also known as hot tears, will occur. Hot tearing is likely to be more problematic in permanent metal molds than in sand molds which are weak enough so that they can collapse as the casting shrinks.

i) Shrinkage

Most metals expand when heated and contract when cooled. During the solidification the volume of the material will decrease. If no measures are taken this shrinking will result in casting defects like “lunker” and porosity. Shrinkage allowance is therefore one of the basic considerations during the dimensioning of the patterns. The amount of shrinkage is characteristic for each material.

j) Pressure Tightness:

The solidification shrinkage in some alloys creates a significant number of quite small internal voids. In some cases these voids, called porosity, permit gases to pass through the wall of the casting. Pressure Tightness is the ability to hinder gases to pass through.

k) Metallurgical Purity:
Metallurgical purity is important factor for castability. Impurities can also cause local stresses when the material solidifies so as result of this situation hot tearing or hot cracking increase. For example in steels sulfur layers are weak points for hot tearing.

l) Chemical Affinity :
For a good castability, material should not go into reaction with its environment, which is the mold and the atmosphere. If the chemical affinity is high oxidation may occur, in some cases the casting process has to be made under controlled atmosphere. Otherwise the casting quality will be badly affected in terms of dimensional stability and internal integrity.

m) Gas solubility:
The solubility in a material will drop during solidification and cooling. If gases are present in the melt and if they cannot escape, they will cause porosity in the casting.

n) Vapor Pressure:
During melting and pouring of the liquid metal alloy some elements can evaporate from the melt and the alloy's chemical composition can change if their vapor pressure is too low (eg. zinc in brass).

2.1.4. Special Tests for Castability

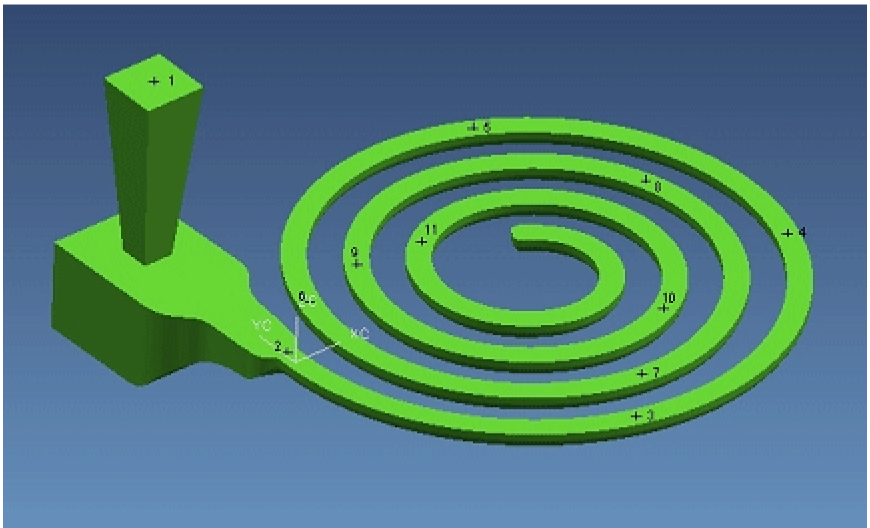


Figure 3.1.1: Fluidity Spiral and Temperature History Locations

2.2 Bulk Forming and Formability

2.2.1. Bulk Forming Processes

Metal forming is a process that changes the shape of metal parts by applying force. The type of deformation that causes permanent change in shape is called plastic deformation. Plastic deformation changes the dimensions of an object without causing failure. Forming processes can be classified grouped in two main groups: bulk deformation and sheet metalworking.

With the help of the forming processes the mechanical properties of the material can be controlled and improved. For example, blowholes and porosity in a cast ingot can be eliminated by forging or hot Rolling, so that toughness and ductility increases. There are very many possibilities to improve the properties with the help of thermo-mechanical processes.

Bulk deformation can be done hot, warm or cold. If forming is done at temperatures more than half of the melting temperature (hot forming) recrystallisation will occur. These temperature ranges can be defined with the help of the homologous temperature:

$$T_h = T_{working} / T_{melting} \quad \text{[in Kelvin]}$$

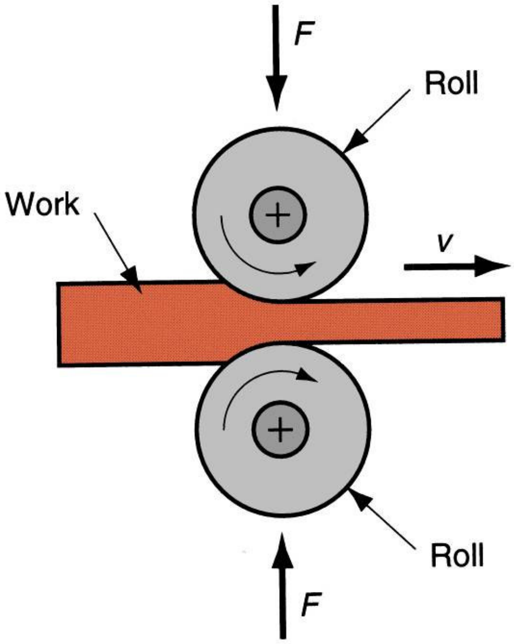
$T_h < 0.2$	Cold working
$0.2 < T_h < 0.5$	Warm working
$0.5 < T_h$	Hot working

Hot working does not always mean working at high temperatures. For a metal with a melting point of 320 degrees (lead) centigrade, room temperature is in the hot working region.

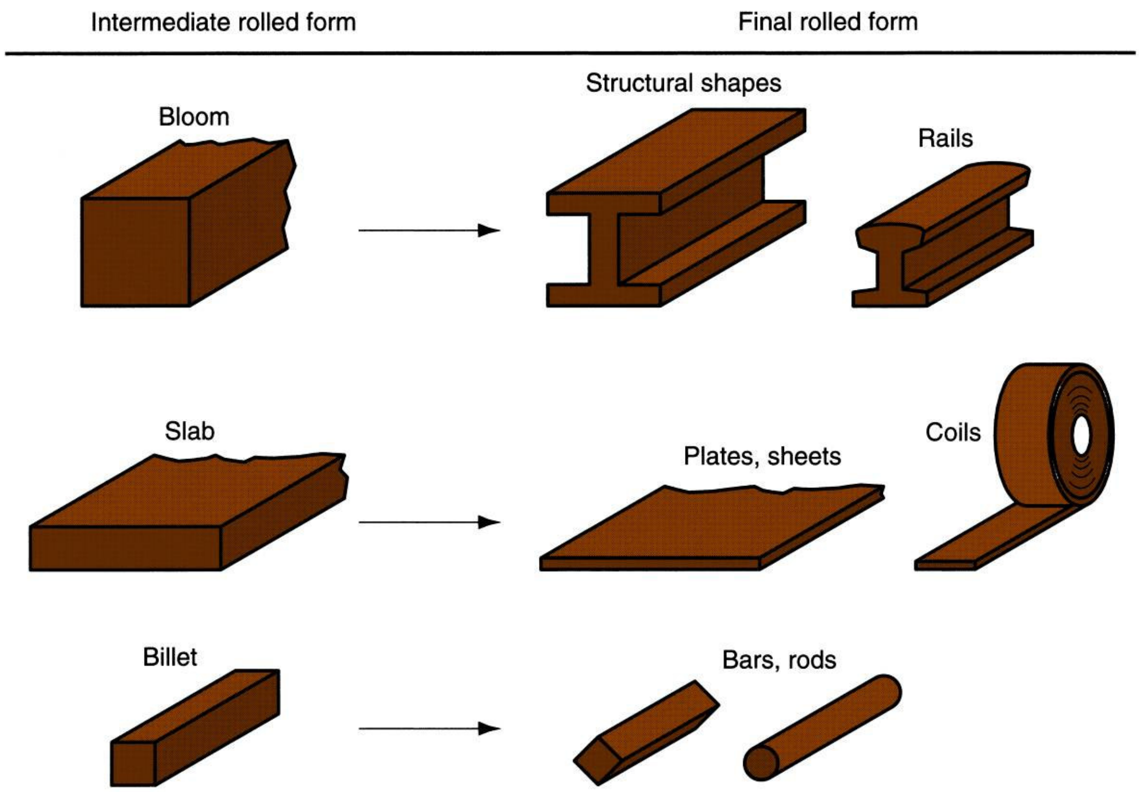
The grain structure can be refined by using suitable thermo-mechanical parameters and the *physical properties* (such as strength, ductility and toughness) *can be improved*. For example applying cold work on a metal increases its yield strength, as strain hardening occurs. With proper design, the grain flow can also be oriented in the direction of principal stresses encountered in actual use.
Considerable force is required in forming; there are three traditional types of bulk forming processes:

1. **Rolling:** In rolling, the material is pushed through a gap between two power-driven rolls. Continuous shapes and sheet metal are commonly produced by rolling.
2. **Forging:** In forging, the material is squeezed between two *dies* (molds) in order to change its shape.
3. **Extrusion:** In extrusion, the material is forced to flow out of an opening of desired form and size.
4. **Drawing:** The material is pulled through a die by means of a tensile force.

2.2.1.1. Rolling:



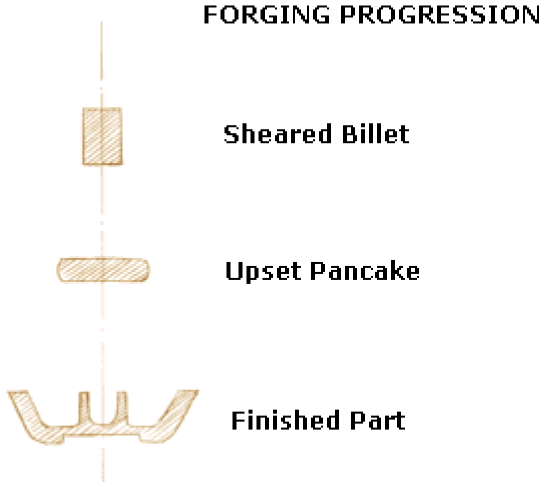
(a)



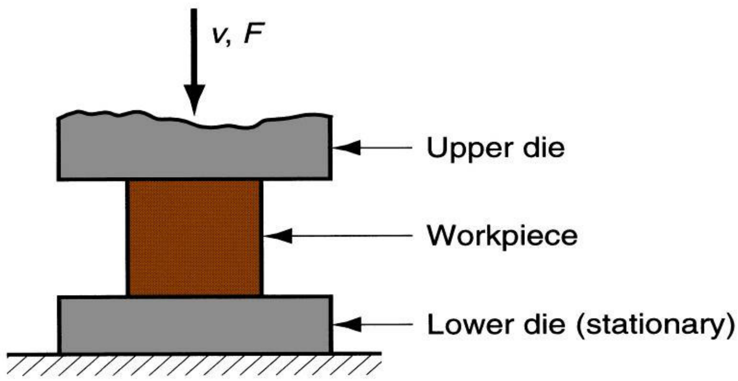
Cold rolling is a process by which the sheet metal or strip stock is introduced between rolls and then compressed and squeezed. The amount of strain introduced determines the hardness and other material properties of the finished product.
Hot Rolling is more suitable for high reductions. At high temperatures the yield stress is lower, the ductility is higher and there is the possibility of improving the physical properties by (dynamic) recrystallisation. But cold rolling is *good* for *dimensional accuracy* and *surface finish.*

2.2.1.2. Forging

Forging is the process where the metal is shaped by suitably applying compressive forces. The compressive force is usually applied by using a power hammer or a press. It is mostly done hot (above *recrystallization temperatures*), but certain metals can also be forged cold. Forgings are reliable from piece to piece, without any of the porosity, voids, inclusions and other defects.

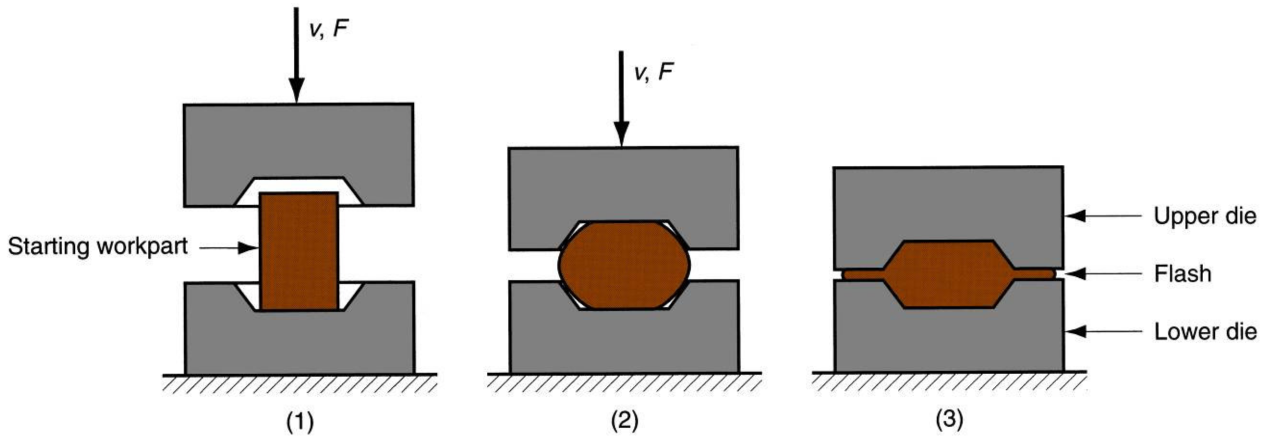


Open Die Forging: Open die forgings or hand forgings are made with repeated blows in an open die (flat dies or dies of very simple shape), where the operator manipulates the workpiece in the die. This is what a traditional blacksmith does, and is an old manufacturing process. Mostly used for large objects and small production numbers.



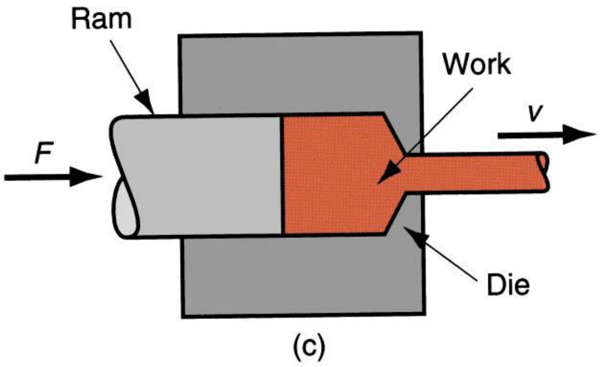
(a)

Closed Die Forgings: Forgings are done in closed dies, which are carefully machined matching blocks to produce forgings to accurate dimensions. The dies are expensive and large production numbers are needed. Generally an empty space is left in the die for the overfilled material. These extra materials, called flashes, are than cut off.



FORGING--EXAMPLE

2.2.1.3. Extrusion:

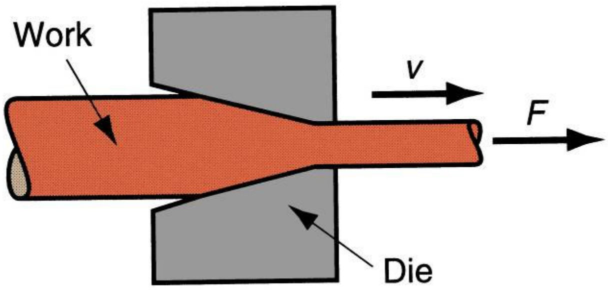


Extrusion is the process by which a block of metal is shaped by forcing it through a die orifice (a narrow opening) using either a mechanical or hydraulic press. By this method long straight parts with constant cross-section can be produced: solid round, rectangular, to L shapes, T shapes, tubes and many other different types. Extrusion produces compressive and shear forces in the stock. No tensile stresses are produced, so high deformation is possible without tearing the material.

Typical parts produced by extrusions are: window frame members, railings, aircraft structural parts, trim parts used in automotive and construction applications.
Hot Extrusion: Hot extrusion is generally done at very high temperatures, approximately 50 to 75 % of the melting point. Due to the high temperatures and pressures and its detrimental (damaging) effect on the die life as well as other components, good lubrication is necessary. Oil and graphite work at lower temperatures, whereas at higher temperatures glass powder is used.

Cold Extrusion: Cold extrusion is the process done at room temperature or slightly elevated temperatures. The required stresses in cold extrusion are high, but the advantages of this process are:
- No oxidation takes place
- Good mechanical properties due to strain hardening
- Good surface finish with the use of proper lubricants.

2.2.1.4. Drawing:



(d)

Drawing is a process in which the material is pulled through a die by means of a tensile force. Usually the constant cross section is circular (bar, rod, wire, tube).

2.2.2. Bulk Formability

Formability is a measure to which extend a material can be deformed in specific process without formation of cracks (surface or internal). In some processes the limit is necking rather then fracture. Formability is not only a material property; it also depends on process parameters (reduction, friction, temperature, strain rate etc)

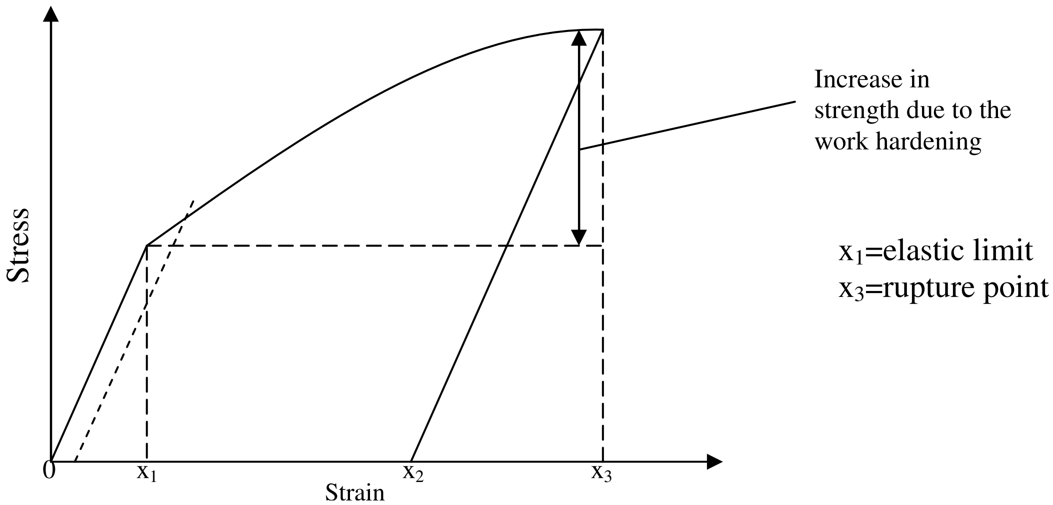
2.2.2.1. Cold Formability

Cold formability is a measure of the ability of a metal to endure deformation for $T_h < 0.2$. The greater the cold formability of a material, the higher deformation and/or the more complex shapes can be produced. Some factors that effect cold formability are:

- Material properties
- Die properties
- Shape of the part etc.

2.2.2.2. Material properties that affect cold formability:

Cold formability is related with a lot of factors like material property, die property etc. and main material properties that effect cold formability are strength properties, elastic modulus, ductility, cleanliness, microstructure and chemical composition.



Stress- Strain diagram

a) Yield point:
No deformation of a metal can occur until this limit is exceeded. So the yield point determines the force required to start permanent deformation.

b) Strain Hardening:
Once deformation is initiated, the moving dislocations interact with each other and with the grain boundaries; therefore continuing yielding becomes more difficult. This mechanism is called strain (or work) hardening. In the cold forming temperature range the relation between flow stress and plastic strain is given by:

$\sigma_0 = K\varepsilon^n$

where σ_0 is the flow stress, K is the strength coefficient, ε is the plastic strain and n is the work hardening exponent.

Work hardening has positive and negative effects on cold formability:

- Negative: Higher work hardening means higher load and energy need, high tool wear and higher cost.

- Positive: If there is no work hardening local necking will occur during the stretching of the materials. There will be no uniform plastic deformation.

c) Elastic modulus: Elastic modulus is important because it determines elastic springback. In bulk deformation, part of the total deformation is elastic, and if the load is removed, this elastic part will be recovered (elastic springback). Elastic springback is important in cold working because the deformation must always be carried beyond the desired point by an amount equal to the springback. In Figure 1, the length between x_2 and x_3 is elastic springback.

d) Ductility: Ductility indicates the amount of plastic deformation before fracture (the length between 0 and x_3 in Figure). Higher ductility means higher plastic deformation, thus higher cold formability.

e) Grain size: The attainable strength level is also dependent on the grain size of the steel. Depending on the material group, the optimal microstructural condition must be chosen to ensure optimal cold formability.

Cold working results in deformed **grain** structure with the grains being elongated in the direction of metal flow. At cold working temperatures, the grain boundaries are more resistant to deformation, so work pieces with fine grains and therefore a large amount of grain boundary area are stronger than coarse grained material of the same alloy. Also strain hardening in fine-grained pieces is higher, as there are more grain boundaries, which interact the moving of dislocations.
If coarse-grained material is stretched, its surface becomes like the surface of an orange "orange peel" , because the orientation and elongation in each grain is different. In a coarse grained material these differences are visible and the surface finish is of poor quality.

f) Metallurgical Cleanliness: High demands on the cleanliness of the metal are also essential; slag or other inclusions on the surface will result in cracking or splitting during the forming process. To ensure optimal cold formability of the metals, it is also important to limit the levels of trace elements.

2.2.2.1. Hot Formability

Hot formability is a measure of the ability of a metal to endure deformation without failure for $T_h > 0.5$. During hot working, the metal is dynamically recrystallized. The materials properties in this region are temperature and rate dependent.

2.2.2.2. Material properties that affect hot formability:

a) Yield Strength: If the yield strength of the material is low plastic deformation can be realized with less force and energy need.

b) Ductility: The metal must have a good ductility to avoid failure during the shaping process.

c) Modulus of Elasticity: In hot forming, a small part of the total deformation is elastic, and there will be some elastic springback. It is not as high as in the cold deformation, but has to be considered for precise dimensions.

d) Strain Rate Sensitivity: The mechanical properties at high temperatures are rate dependent.

$$m = \left[\frac{\partial(\ln\sigma)}{\partial(\ln\dot{\varepsilon})}\right]$$

High values of m correspond to better formability.

e) Thermal Expansion Coefficient: After hot working, the material will cool down and shrink. We must consider the thermal expansion coefficient of the material in order to achieve the desired dimension within desired tolerances.

f) Thermal Conductivity: The forming rolls or dies, which are normally at a lower temperature than the materials, are in contact with the shaped part. Therefore there will be a heat flow out of the shaped part and the surface will cool more rapidly than the center of the part. Therefore, the final microstructure within the part will not be homogeneous. For example the recrystallisation will be different and the surface may have a finer grain size than the center.
If the thermal conductivity is high

a) the part will cool more rapidly
b) temperature differences between the surface and center will be lower

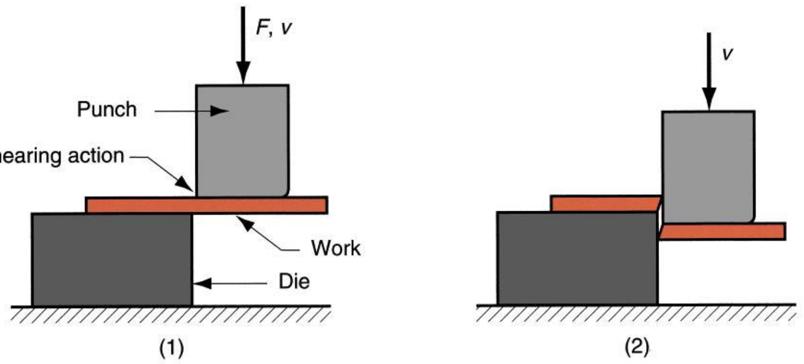
g) Chemical Composition: The plasticity decreases when the elements are not completely dissolved in the solid solution, but form excess phases, which occur in the metal as inclusions.

2.3 Sheet Metal Forming and Formability

2.3.1. Sheet Metal Forming Processes

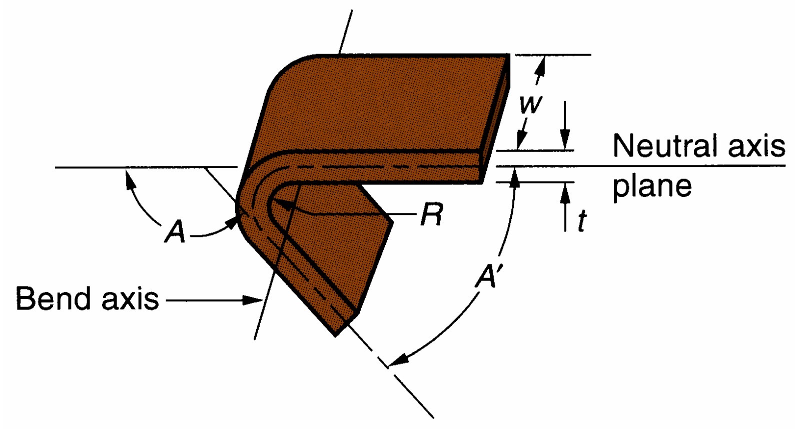
Forming of flat sheets by stretching and shrinking. Sheet metal forming is an important manufacturing process for metals because half of total metal production is ended in sheet form. Sheet metal forming methods are:

- Shearing and Blanking (Separation of the materials by two cutting edges)



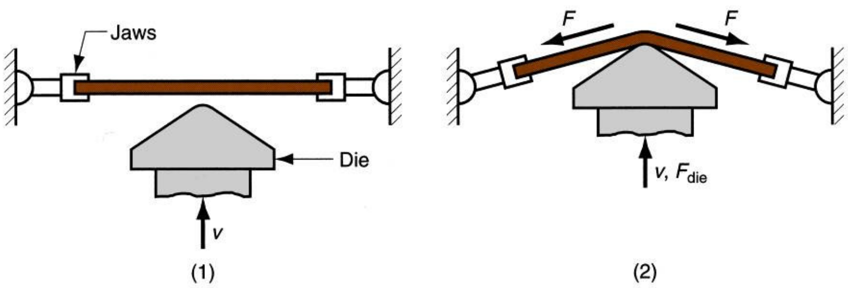
(c)

- Bending (Transforming a straight length into a curved length)

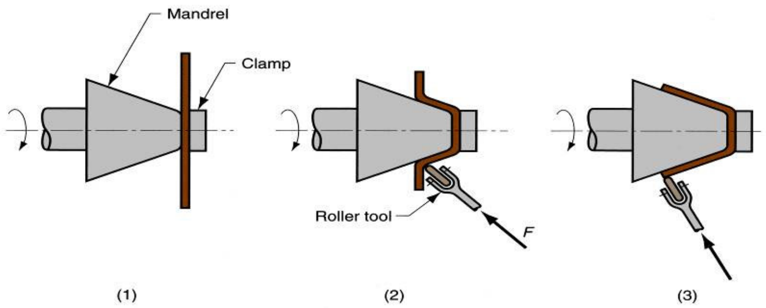


(a)

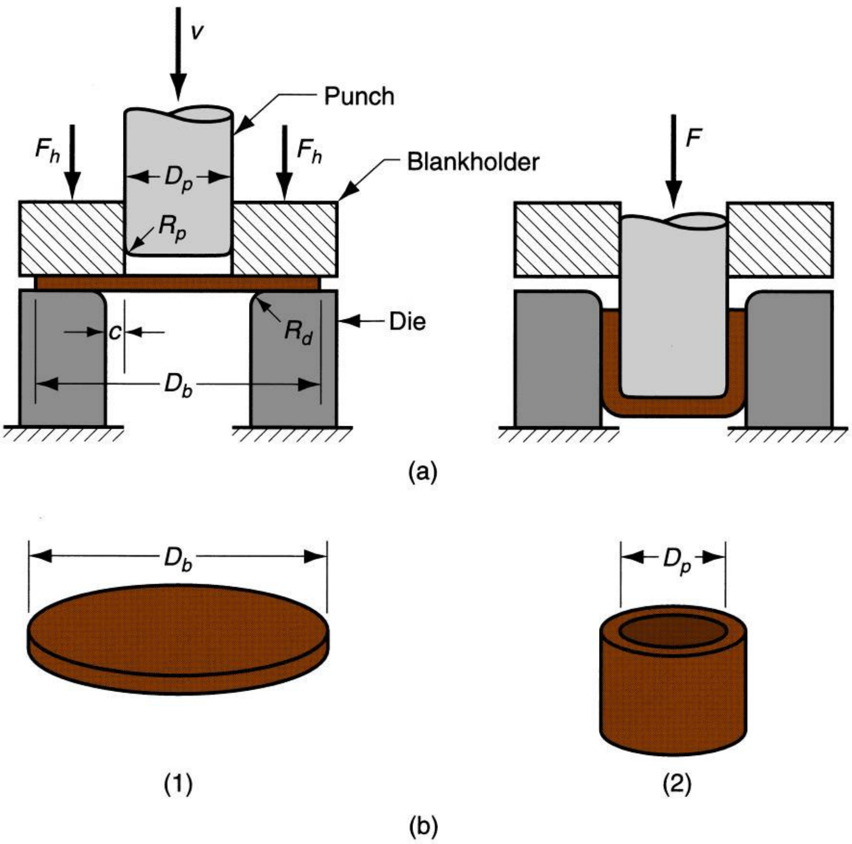
- Stretching (Forming by tensile stresses over a tool)



- Spinning (Forming against a rotating form block with a tool)



- Deep Drawing (Shaping flat sheets into cup-shaped articles)



2.3.2. Sheet Metal Formability

Formability is the term used to evaluate the capacity of a material to withstand the stretch/draw stresses of forming before splitting (failure) occurs

2.3.3. Material Properties that affect Sheet Metal Formability

a) Ductility: Metal used in the sheet metal work must be ductile. If we use a brittle metal it can easily undergo failure during forming. That's why metal's ductility is very important in sheet metal working.

b) Yield Strength: Yield strength of a material used in sheet metal forming must be low. High strength metals have reduced stretch distribution characteristics, making them less stretchable and drawable than lower strength metals. Stretch distribution characteristics determine the steel's ability to distribute stretch over a large surface area. The better the stretch distribution, the more the steel can stretch over the draw punch to create the final geometry.

d) Elastic Modulus: Stretch distribution affects not only stretchability, but also elastic recovery, or springback, and the metal's total elongation.

e) Discontinuous Yielding: Low carbon steels show a discontinuous yielding accompanied with the formation of Lüder bands, which reduces the surface quality of the end product. In order to remove the discontinuous yield point a temper rolling (rolling where a few percent of reduction is applied) can be applied.

f) Work Hardening Rate (n): Work hardening rate is a very important sheet metal forming parameter. When n increases material's resistance to necking also increases. The work hardening is the mechanism, which prevents local yielding and increases the uniform elongation "elongation in a tensile test up to necking". This is why a reasonable work hardening is desired in sheet metal forming, if the principal stresses are in the tensile mode (stretching).
But as the work hardening rate increases, the applied force must also be increased.

g) Anisotropy (Directionality): Anisotropy is another factor that affects formability. One consequence of directionality is a change in mechanical properties with direction. When forming sheet metal, practical consequences of directionality include such phenomena as excess wrinkling, puckering, ear-formation, local thinning, or actual rupture.

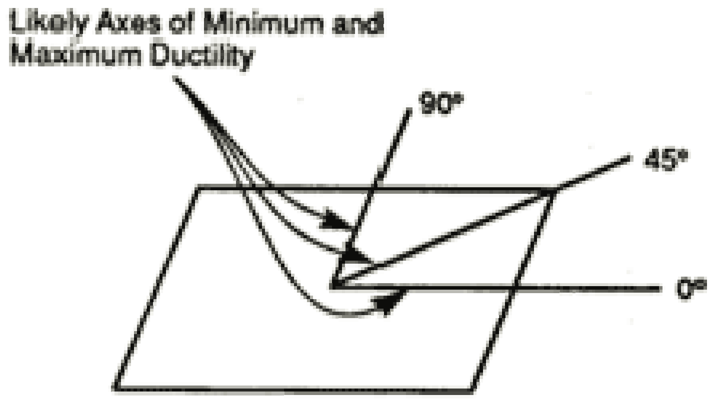
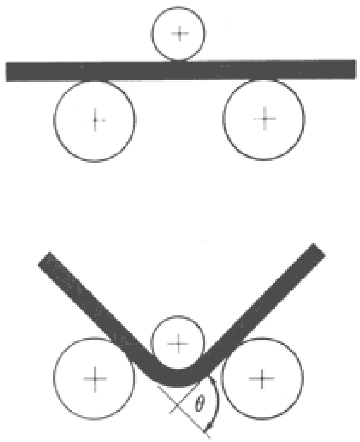


Figure 1
Directionality in Properties of a Rolled Sheet

h) Grain Size: In general, a fine- grained metal is preferred in the fabricating of sheet metals. The individual crystal grains of the metal flow differently and in most cases the grain boundaries are visible on the surface. The surface consequently becomes rough and uneven. If the grain size exceeds a certain limit the roughness becomes noticeable and a condition termed "orange peel" should be assumed. Depending on the surface requirements the grain size of the sheet is limited to a maximum value. On the other hand it is undesirable to use a material with extremely small grains as the yield stress increases with decreasing grain size.

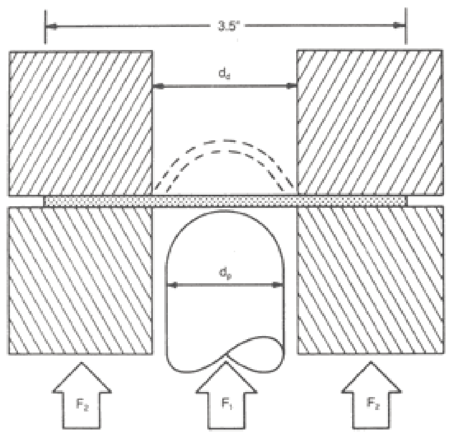
i) Surface Finish: The sheet metal must have good surface properties to provide minimum friction during forming. If the metal is very rough, mold life becomes shorter.

2.3.4. Special Tests for Sheet Formability



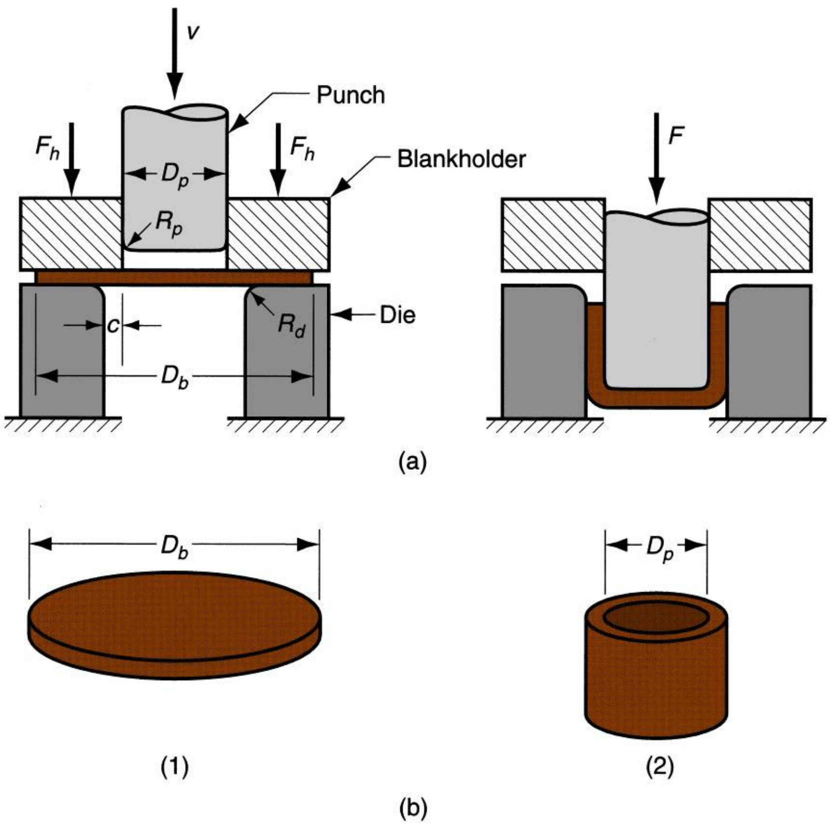
Simple Bend Test

Bending Test:
The bending test is performed to determine the ductility of steel. In the test, the specimen is bent to a specified angle on a mandrel or a specified radius until fracture. The ductility of the sheet is judged by the cracks on the outside of the bent specimen. The interpretation of results is a matter of the material specification. The metallurgical and mechanical factors important in all bending operations are the strength and ductility of the steel, the degree of inclusion shape control, and the condition of the edge of the test blank. Bendability is described by the radius to thickness ratio (in multiples of thicknesses) that the steel can be bent without developing cracks over a specified length.



	d_p	d_d
OLSEN < 0.061" 0.061–0.080"	0.875" 0.875"	1.00" 1.125"
ERICHSEN 0.01 to 0.8	20 mm	27 mm

Erichsen / Olsen Test:
The specimen is clamped and a punch is pressed against the sheet. The deformation is mainly streching. If fracture occurs the test is stopped the depth is measured as Erichsen Number (mm). The Olsen test is more popular in the USA and is similar.



Cupping Tests

The specimen is a circular blank. A hole is present. The sheet is bulged with a flat bottom punch. The drawability is measured by the ratio of the initial blank diameter to the diameter of the cup drawn from the blank:

LDR - Limiting Drawing Ratio = D_b/D

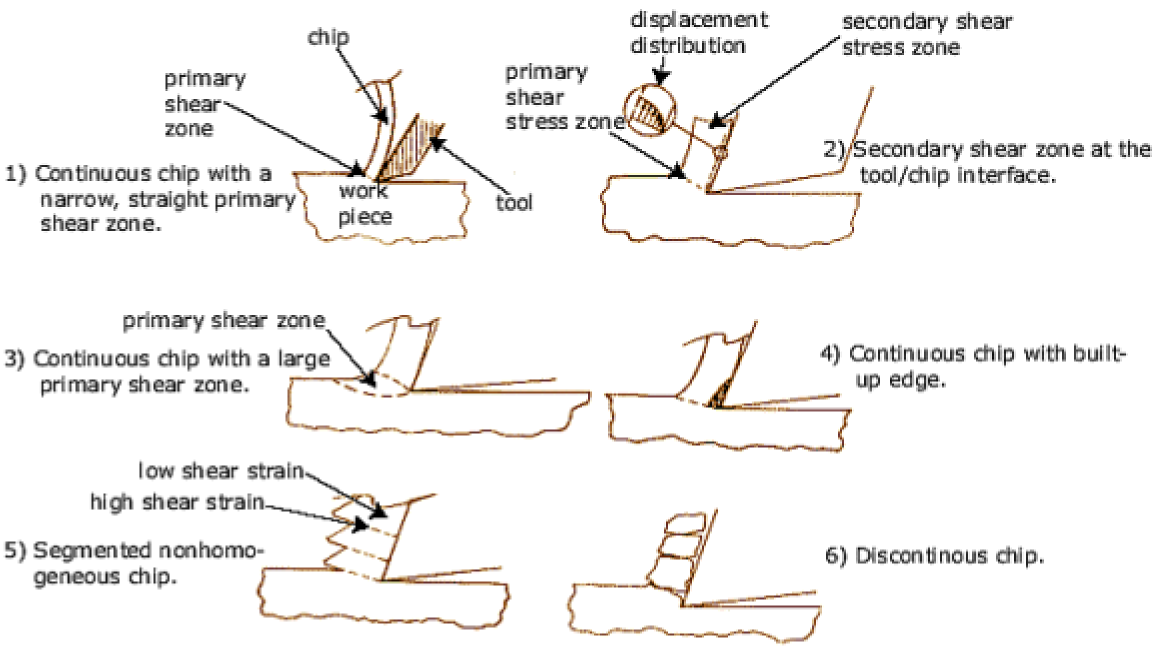
2.4. Machining and Machinability

2.4.1.Machining Processes

Machining is the most important one among manufacturing processes. *Machining* can be defined as the process of removing material from a workpiece in the form of chips. Machining is necessary where tight tolerances on dimensions and finishes are required.

Any machining process requires a cutting tool to remove material. The cutting tool is stronger than the material being machined, and causes fracture of the material: *chips.* For all types of machining, including grinding, honing, lapping, planing, turning, or milling, the chip formation process is similar.

Categories of chip types are illustrated below:



The fracture process usually causes heat, and a *cooling fluid* has to be continuously poured into the cutting area. The first processes in the production of a part remove a large volume of material but usually produce a rough surface. Such processes are called *rough* machining processes. Usually rough machining processes are followed by finishing processes to improve the surface quality.

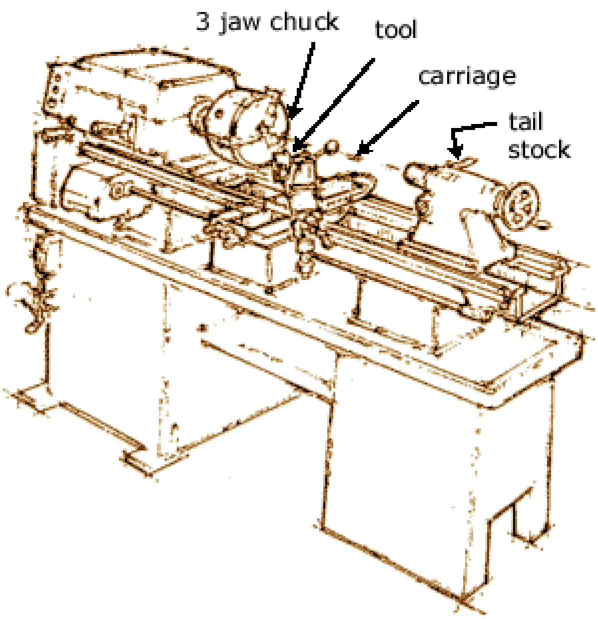
With CNC machine tools producing parts at ever-faster rates, it has become important to provide automatic algorithms for determining speeds and feeds. The information presented in this section are some of the more important aspects of chip formation.

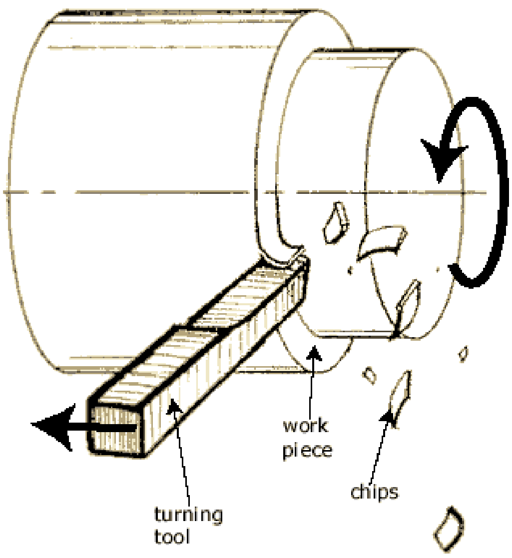
The most important machining processes are:

1. Turning
2. Milling
3. Drilling
4. Shaping / Planing.

2.4.1.1. Turning

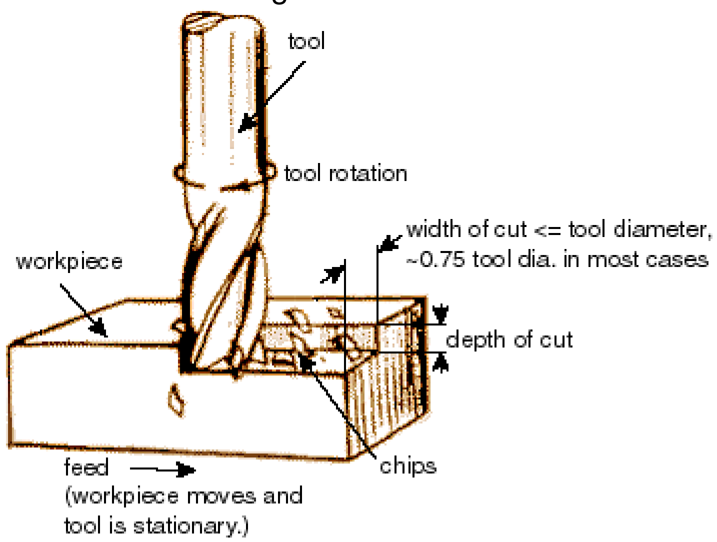
Turning is one of the basic machining processes. Turning is performed on a machine called a lathe in which the work piece is mounted on the chuck, which rotates relative to the stationary cutting tool. Turning is generally used to produce cylinderical parts.



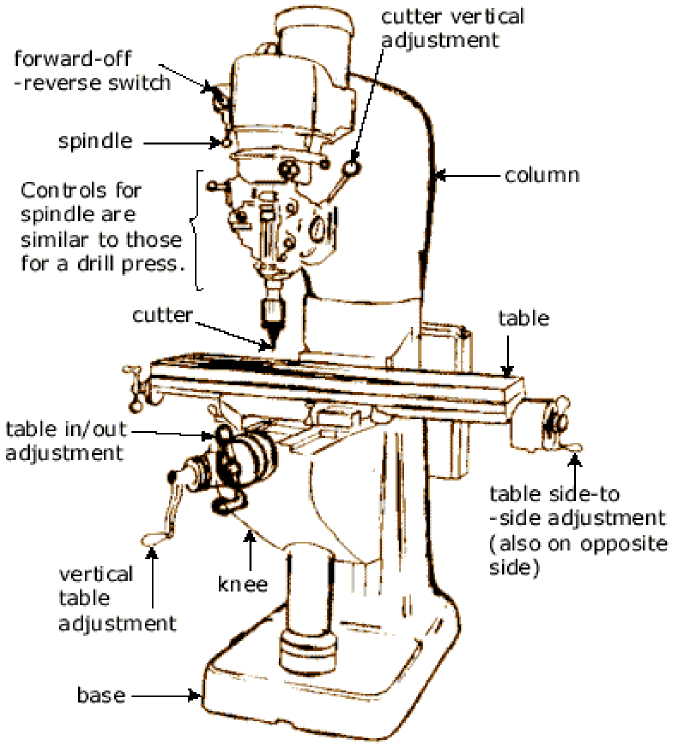


2.4.1.2. Milling

Milling is a widely-used machining operation for producing slots (openings) of various shapes and sizes at surfaces. The tool is called a milling cutter. It has a large number of cutting edges.
For manual machining, milling is essential to fabricate any object that is not axially symmetric. There is a wide range of different milling machines, ranging from manual light-duty to huge CNC machines for milling parts hundreds of feet long. Below the process at the cutting area is illustrated.

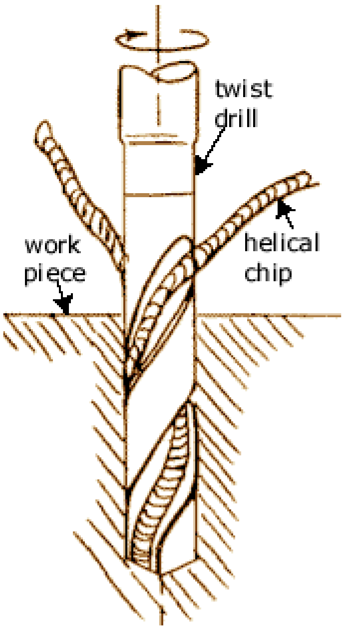


Below a typical column-and-knee type manual mill is illustrated.

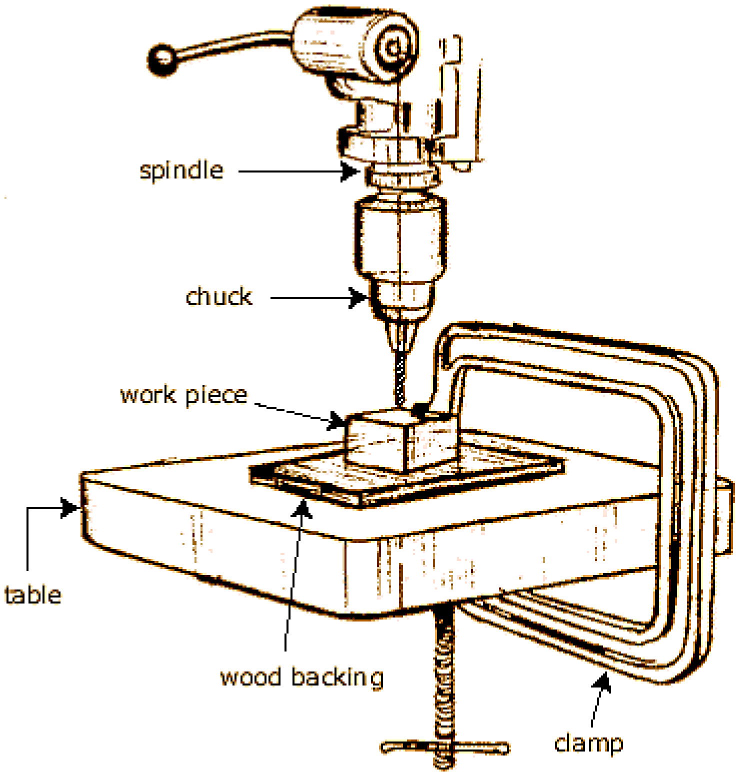


2.4.1.3. Drilling

Drilling is a process used to produce holes inside solid parts. The tool is rotated and also moved in the axial direction. The tool has cutting edges on its surface.

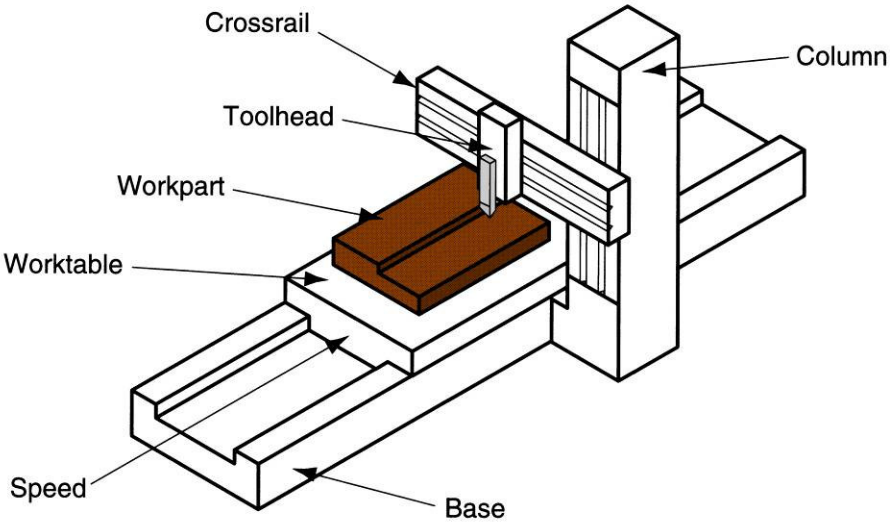


The chips must exit through the flutes to the outside of the tool. As can be seen in the figure, the cutting front is embedded within the workpiece, making cooling difficult. The cutting area can be flooded, coolant spray mist can be applied, or coolant can be delivered through the drill bit shaft.

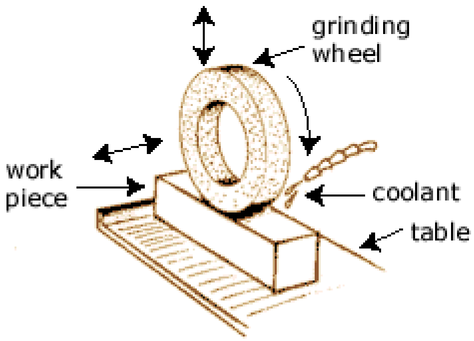


2.4.1.4. Planing Shaping

Shaping is used to produce surfaces. The tool is given reciprocating (moving backwards and forwards) motion. When the tool completes one stroke, the job is moved in a direction perpendecular to the motion of the tool by a small distance so that uncut material is provided to the tool to perform one more stroke. In a planar, the job moves in a reciprocating style and tool moves a small distance after one stroke.



2.4.1.5. Grinding



Grinding is a finishing process used to improve surface finish, abrade hard materials, and tighten the tolerance on flat and cylindrical surfaces by removing a small amount of material. In grinding, an abrasive material rubs against the metal part and removes tiny pieces of material. The abrasive material is typically on the surface of a wheel or belt and abrades material in a way similar to sanding. On a microscopic scale, the chip formation in grinding is the same as that found in other machining processes. The abrasive action of grinding generates excessive heat so that flooding of the cutting area with fluid is necessary.

Grinding is applied if:

a) The material is too hard to be machined economically.
b) Close tolerances are required.

2.4.2. Machinability

Machinability is a broad term covering the relative ease of machining or the satisfaction with which a material is cut by sharp tools in various operations. In general, this implies the speed with which metal can be cut, but it also includes such factors as good finish and long tool life.

The most machinable metal is the one which will permit the fastest removal of the greatest amount of material per grind (without reshapening the tool) with a satisfactory finish.

Machinability involves tool life, tool performance, machine speeds, feed and depth of cut, character and design of cutting tools, cutting fluid, and also the quality, composition, hardness, and microstructure of the metal being cut. The various factors affecting machinability may be classified as follows:

- **Material cut**
- **Cutting tool used**
- **Cutting fluid**
- **Operating machine**

2.4.3. Material Properties Which Affect Machinability:

The best machinability is achieved in materials if:

a) no too high ductility
b) no high strain hardening
c) not too abrasive

It is not easy to define the materials machinability with the help of ordinary mechanical properties. But certain trends can be found for certain materials.

a) Chemical Composition: Chemical composition of a metal is a major factor in determining its machinability. The effects of composition though, are not always clear, because the elements that make up an alloy metal, work both separately and collectively. Certain generalizations about chemical composition of steels in relation to machinability can be made, but non-ferrous alloys are too numerous and varied to permit such generalizations. There are certain steel types (free-cutting steels), which are specially alloyed for good machinability.

b) Microstructure: Metals whose microstructures are similar have similar machining properties. But even small variations in the microstructure can affect machinability. The grain size plays an important role; it determines the yield strength, the ductility and the surface quality. Heat treatments can be used to optimize the microstructure for the best machinability.

c) Fabrication: Whether a metal has been hot rolled, cold rolled, cold drawn, cast, or forged will affect its grain size, ductility, strength, hardness, structure - and therefore – its machinability.

d) Hardness: In general, materials hardness and yield strength are related. If hardness and yield strength are high, the machinability is low, because of the decrease in the tool life. But this is not always true; for steels if the carbon content is reduced, the material becomes more ductile and the machinability is reduced, as the chip makes the tool blunt (less sharp), so that the tool life reduces. On the other hand if the carbon content is too high, the material becomes too hard and it also lowers the tool life. As a conclusion we must say that we must look for optimized values of ductility and hardness for a good machinability.

For cast irons hardness is a reasonable indication for machinability. They have very good machinability, because they contain graphite which reduces friction. Very short chips are produced. If there are hard carbides in the microstructure wear problems can occur.

Yield and Tensile Strength: A material with a high strength requires a high level of force to initiate chip formation in a machining operation. Materials with relatively high strengths will be more difficult to machine and will reduce tool life.

Modulus of Elasticity: In machining high modulus of elasticity values are preferred. If the material is rigid, the elastic deformation during cutting will be small and high dimensional accuracy is achieved.

Thermal Conductivity: Metals which exhibit low thermal conductivities will not dissipate heat freely and therefore, during the machining of these materials, the cutting tool and workpiece become extremely hot. This excess heat accelerates wear at the cutting edge and reduces tool life, thus machinability. Materials with a high thermal conductivity have a better machinability.

Thermal Expansion: In terms of general machining practice, materials with large thermal expansion coefficients will make precise machining with close dimensional tolerances extremely difficult, since a small rise in the workpiece temperature will result in dimensional changes. Materials with a low thermal expansion have a better machinability.

2.4.4. Special Tests for Machinability

Machinability is actually a relative measure of how easily a material can be machined when compared to 160 Brinell AISI B1112 free machining low carbon steel. B1112 represents a 100% rating; materials with a rating less than this level would be more difficult to machine, those that exceed 100% would be easier to machine.
The machinability rating of a metal takes the **cutting speed**, **surface finish** and **tool life attained** into consideration. These factors are weighted and combined to get a

final machinability rating. The following chart shows some materials and their specific machinability ratings:

Material	Hardness	Machinability Rating
B1112 Steel	160 BHN	100%
6061-T 7075-T Aluminum Alloys	-	190%
Aluminum	-	120%
416 Stainless Steel	200 BHN	90%
1120 Steel	160 BHN	80%
1020 Steel	148 BHN	65%
8620 Steel	194 BHN	60%
304 Stainless Steel	160 BHN	40%

There are also other machinability ratings based on the type of chip that is formed during the machining operation. A material that produces long stringy (thin and tough) chips would receive a low rating, as would one, which produces fine chips (small, grainlike). Materials, which form nicely broken chips, a half or full turn of the normal chip helix, would receive top rating.

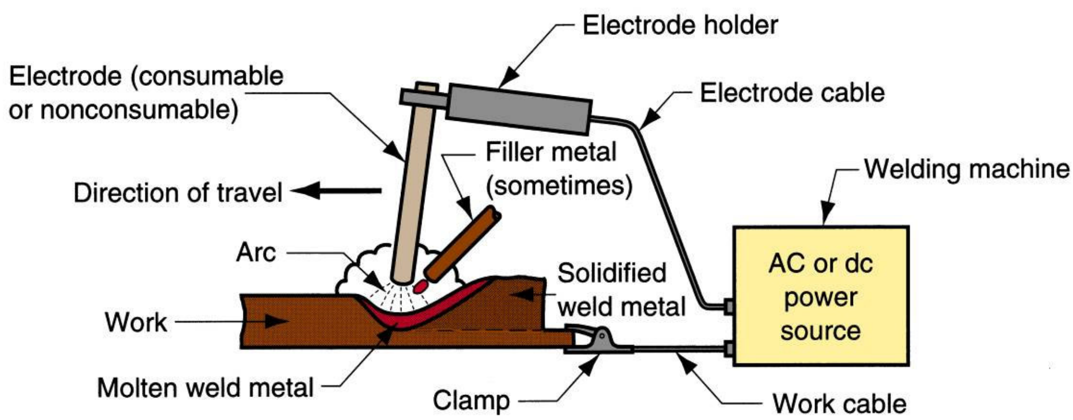
2.5. Welding

Welding is the most common way of permanently joining metal parts. In this process, heat is applied to metal pieces, melting and fusing them to form a permanent bond. Welding is done by local melting in the welding area and can be considered as a local casting. A good weld should have good mechanical properties, be crackless, and have a good fusion so that the part can serve without losing its good properties. Because of its strength, welding is used in shipbuilding, automobile manufacturing and repair, aerospace applications, and thousands of other manufacturing activities.

2.5.1. Welding Processes

The parts, which are to be welded can be melted either using chemical energy (gas welding) or electrical energy (electric arc welding).

Arc Welding

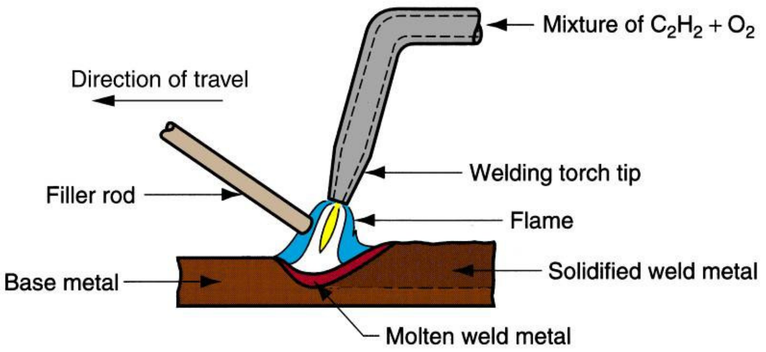


Arc welding is the most common type of welding. Standard arc welding involves two large metal clamps that carry a strong electrical current. One clamp is attached to any part of the workpiece being welded. The second clamp is connected to a thin welding rod. When the rod touches the workpiece, a powerful electrical circuit is created. The massive heat created by the electrical current causes both the workpiece and the steel core of the rod to melt together, cooling quickly to form a solid bond. During welding, the flux that surrounds the rod's core vaporizes, forming an inert gas that serves to protect the weld from atmospheric elements that might weaken it.

The need to weld nonferrous metals, particularly magnesium and aluminum, challenged the industry. A solution was found called **gas tungsten arc welding** (GTAW) and was defined as "an arc welding process which produces coalescence (joining together) of metals by heating them with an arc between a tungsten (non-consumable) electrode and the work piece. Shielding is obtained from a gas or gas mixture." Another welding process also related to gas tungsten arc welding is known as **gas metal arc welding** (GMAW). It was developed in the late 1940s for welding aluminum and has become extremely popular. It is defined as "an arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work piece. Shielding is obtained entirely from an externally supplied gas or gas mixture." The electrode wire for GMAW is continuously fed into the arc and deposited as weld metal.

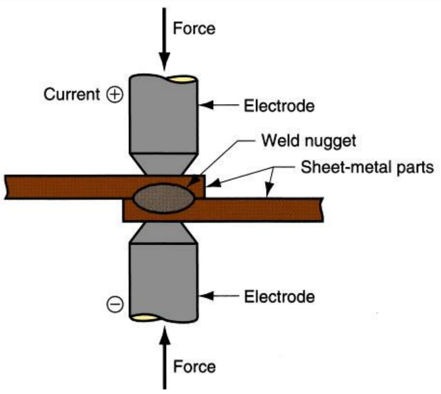
Oxy Fuel Gas Welding

Oxy fuel gas welding is "a group of welding processes which produces coalescence by heating materials with an oxy fuel gas flame or flames with or without the application of pressure and with or without the use of filler metal." The heat of the flame is created by the chemical reaction or the burning of the gases. The most commonly used fuel gas is Acetylene. Thus the process is called as "oxy-acetylene welding".



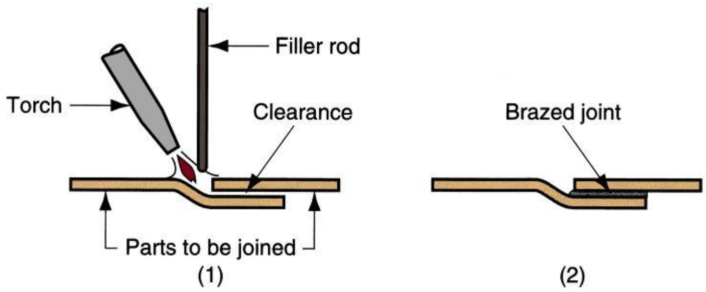
Resistance Welding

Resistance welding is "a group of welding processes which produces coalescence of metals with the heat obtained from resistance of the work to electric current in a circuit of which the work is a part, and by the application of pressure". In general, the difference among the resistance welding processes has to do with the design of the weld and the type of machine necessary to produce the weld. In almost all cases the processes are applied automatically since the welding machines incorporate both electrical and mechanical functions.



Brazing and Soldering

Brazing is "a group of welding processes which produces coalescence of materials by heating them to a suitable temperature and by using a filler metal, having a liquidus (temperature above which a material is completely in a stable liquid phase) above 450°C and below the solidus (temperature below which a material is completely in a stable solid phase) of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction." A braze is a very special form of weld, the base metal is theoretically not melted. Soldering is "a group of joining processes which produces coalescence of materials by heating them to a suitable temperature and by using filler metal with a liquidus not exceeding 450 °C and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction."



(a)

Other Welding Processes

This group of processes includes those, which are not best defined under the other groupings. It consists of the following processes: **electron beam welding, laser beam welding, thermit welding, and other miscellaneous welding** processes in addition to **electroslag welding** which was mentioned previously. Solid state welding is "a group of welding processes which produce coalescence at temperatures essentially below the melting point of the base materials being joined without the addition of a brazing filler metal. Pressure may or may not be used." The oldest of all welding processes **forge welding** belongs to this group. Others include **cold welding, diffusion welding, explosion welding, friction welding, hot pressure welding,** and **ultrasonic welding**. These processes are all different and utilize different forms of energy for making welds.

2.5.2. Weldability

Weldability is the capacity of a material to be welded under the imposed fabrication conditions into specific suitably designed structure and to perform satisfactorily in the intended service. Weldability depends on some factors including material properties. Weldability can be considered from different points:

- Melting and cooling of the material
- Metallurgical and thermal changes
- Cracking and brittleness

2.5.3. Material Properties Which Affect Weldability:

a) <u>Melting Point and Vapour Pressure</u>

Though welding involves local melting, the melting point of the material is very important. Material with low melting point can be melted easier; on the other hand some materials even can not be melted. Sometimes control of the temperature level is not possible, so a material can be vaporized during the welding process.

b) <u>Thermal Conductivity</u>

To melt the weld metal locally in the welding area, we expect the heat that we apply not to diffuse away. Otherwise the melting point of the material cannot be reached easily. So the thermal conductivity of the material should be low in order to keep the heat in the welding area.

c) <u>Specific Heat</u>

Specific heat is the amount of heat, which is necessary to increase the temperature of a material with a unit mass by 1°C. Therefore heating and welding of a material with a high specific heat is difficult, as it requires a high amount of energy delivered.

d) <u>Thermal Diffusivity</u>

It is a measure of the rate at which a temperature disturbance at one point in a body travels to another point. It is expressed by the relationship $K/\rho C_p$, where K is the coefficient of thermal conductivity, ρ is the density, and C_p is the specific heat at constant pressure. This should be very low.

e) <u>Electrical Conductivity</u>

In electric arc welding, the source of the heat is the heat produced by the resistance of the electricity, so the material’s electrical conductivity is desired to be low. Otherwise the electricity flows easily without heating the part.

f) <u>Coefficient of thermal expansion</u>

Welding involves high temperatures and a material with high thermal expansion coefficients will expand a lot. Welding is sometimes done by fixing the parts and on fixed parts expansion may cause stresses. Similar problems arise also during cooling. In order to obtain a good weld the coefficient of thermal expansion is desired to be low.

g) Modulus of Elasticity

The level of stresses due to strain mismatches depends on the modulus of elasticity. Higher stiffness causes higher stresses.

h) Ductility

High ductility materials can withstand higher strains without failure.

i) Chemical Composition and Phase transformations

In metallic alloys where phase transformations occur during the temperature changes, the cooling rate after welding may influence the resulting microstructure. Steels have a tendency to form martensite from austenite. If the carbon content is high, then the amount of martensite formed will be high and the welding area will be brittle. High sulphur contents also cause the weld area to be brittle. The presence of sulphur and high amounts of carbon are undesired for steels.

j) Gas Solubility and Affinity Towards Gases

If a material "likes" gases, it attracts gases from the medium at high temperatures like the temperature levels of welding and this result in a porous weld. These pores act like cracks and affect the mechanical properties of the welded part negatively (reduces toughness).

k) Wetting

Wetting refers to the contact between a fluid and a surface, when the two are brought into contact. High wetting (sometimes also called wetting action) means, that the liquid will spread on the surface more easily. Wetting characteristics are very important for the welding process. Addition may be used to increase wetting by lowering the surface tension of the liquid. Wetting is also the basis of the capillary forces, which are crucial for brazing and soldering.

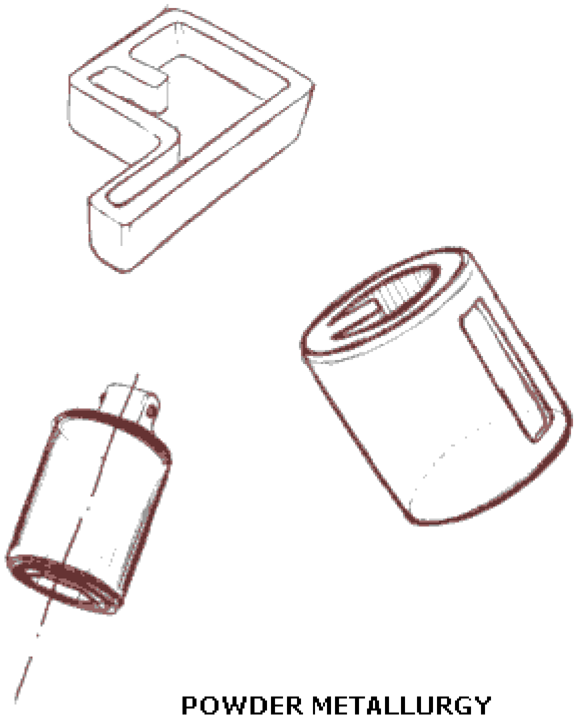
l) Surface Properties

The welding area should be cleaned from any kind of surface films and dirtiness. Their presence will decrease the quality of the weld.

2.5. Other Methods

2.5.1. Powder Metallurgy

Powder metallurgy uses sintering process for making various parts out of metal powder. The metal powder is compacted by placing in a closed metal cavity (the die) under pressure. This compacted material is placed in an oven and sintered in a controlled atmosphere at high temperatures and the metal powders coalesce and form a solid. A second pressing operation, repressing, can be done prior to sintering to improve the compaction and the material properties.



POWDER METALLURGY
(EXAMPLES)

The properties of this solid are similar to cast or wrought materials of similar composition. Porosity can be adjusted by the amount of compaction. Usually single pressed products have high tensile strength but low elongation. These properties can be improved by repressing as in the following table.