

# Unit-1- Materials

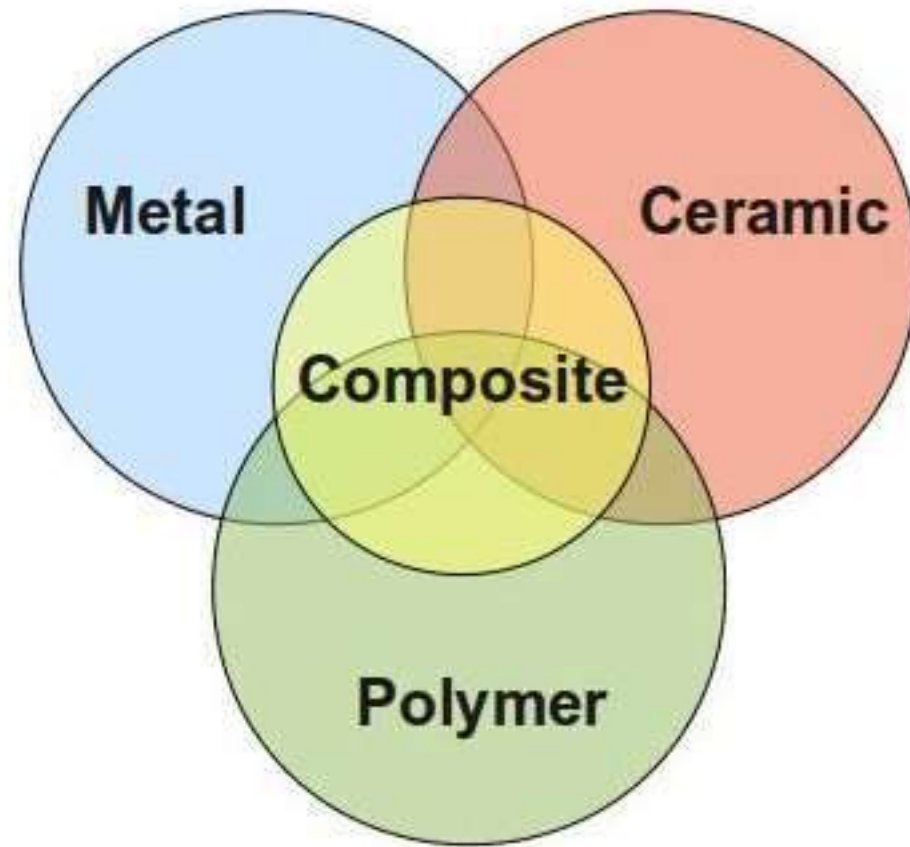
**Materials :** Classification of engineering material, Composition of Cast iron and Carbon steels, Iron Carbon diagram. Alloy steels their applications. Mechanical properties like strength, hardness, toughness , ductility, brittleness , malleability etc. of materials , Tensile test- Stress-strain diagram of ductile and brittle materials , Hooks law and modulus of elasticity, Hardness and Impact testing of materials, BHN etc

# Engineering Materials

*Engineering materials* refers to the group of materials that are used in the construction of manmade structures and components. The primary function of an engineering material is to withstand applied loading without breaking and without exhibiting excessive deflection. The major classifications of engineering materials include metals, polymers, ceramics, and composites. The important characteristics of the materials within each of these classes are discussed on this page, and tables of material properties are also provided.



# Different Types of Material





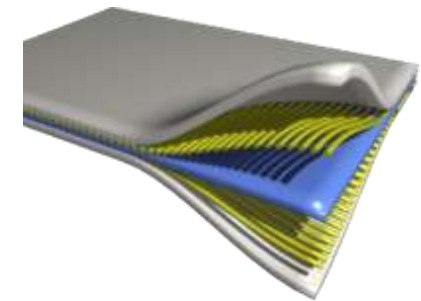
**Metal**, any of a class of substances characterized by high electrical and thermal conductivity as well as by malleability, ductility, and high reflectivity of light.



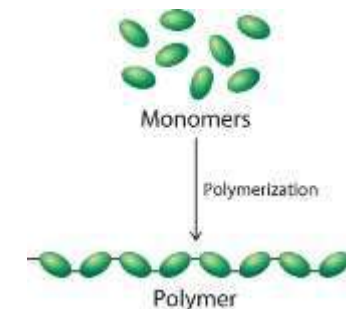
A **ceramic** is any of the various hard, brittle, heat-resistant and corrosion-resistant materials made by shaping and then firing a nonmetallic mineral, such as clay, at a high temperature. Common examples are earthenware, porcelain, and brick.

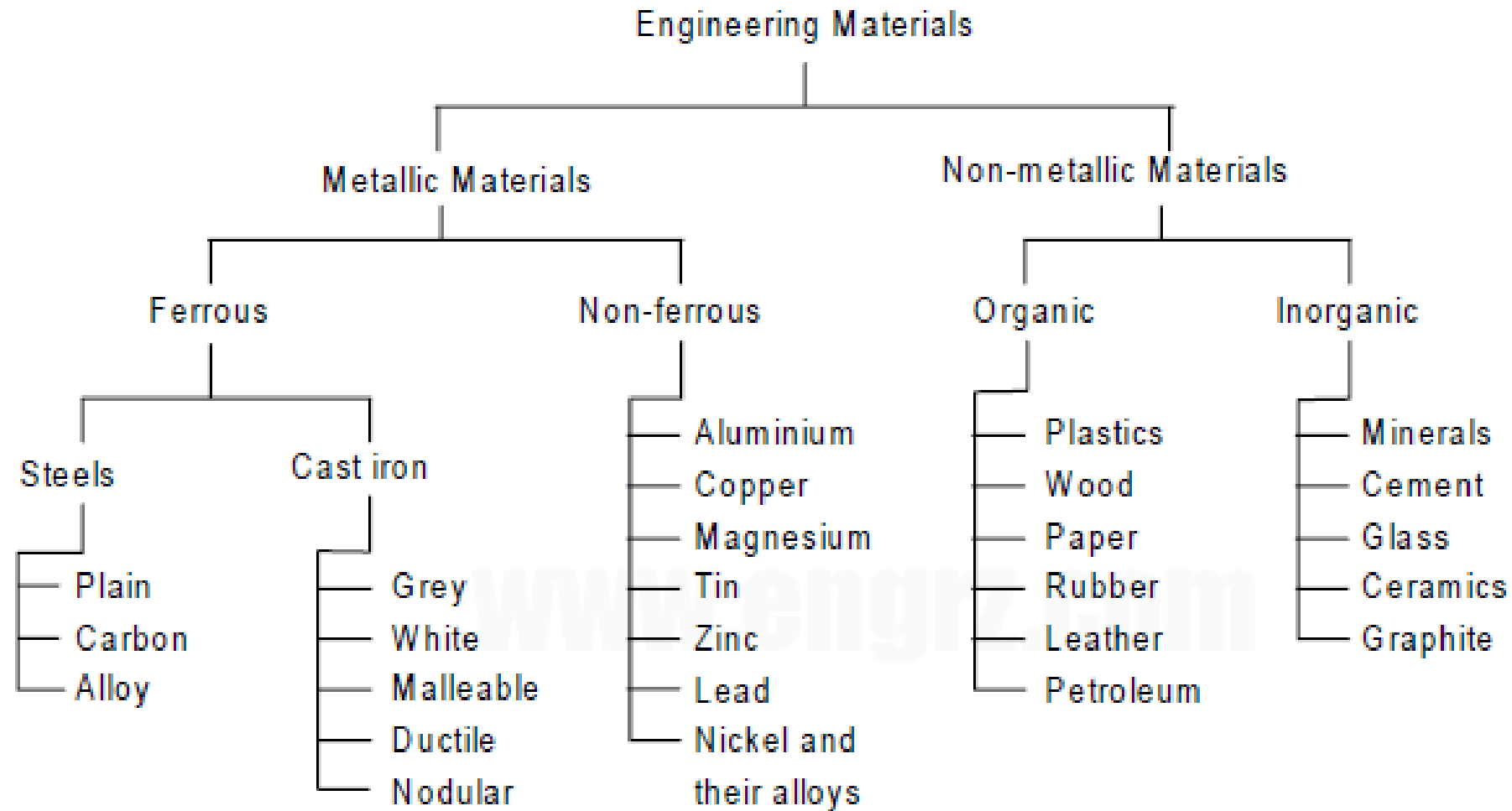


A **composite material** is a combination of two **materials** with different physical and chemical properties. When they are combined they create a **material** which is specialised to do a certain job, for instance to become stronger, lighter or resistant to electricity. They can also improve strength and stiffness



**Polymers** are materials made of long, repeating chains of molecules. The materials have unique properties, depending on the type of molecules being bonded and how they are bonded. Some **polymers** bend and stretch, like rubber and polyester.





# Properties of Material

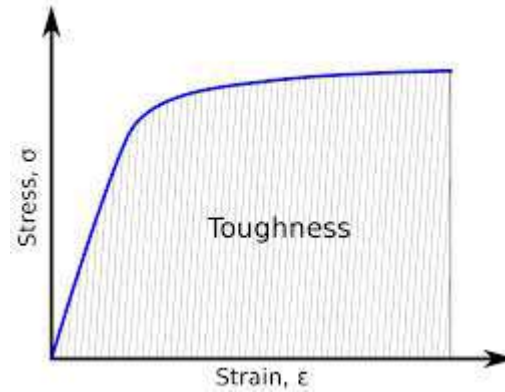
- Physical Properties of Materials
- Chemical Properties of Materials
- Thermal Properties of Materials
- Electrical Properties of Materials
- Magnetic Properties of Materials
- Optical Properties of Materials
- Mechanical Properties of Materials

# Physical Properties of Material

- Strength
- Toughness
- Hardness
- Hardenability
- Brittleness
- Malleability
- Ductility
- Creep
- Resilience
- Fatigue



- **Strength:** It is the property of a material which opposes the deformation or breakdown of material in presence of external forces or load. Materials which we finalize for our engineering products, must have suitable mechanical strength to be capable to work under different mechanical forces or load



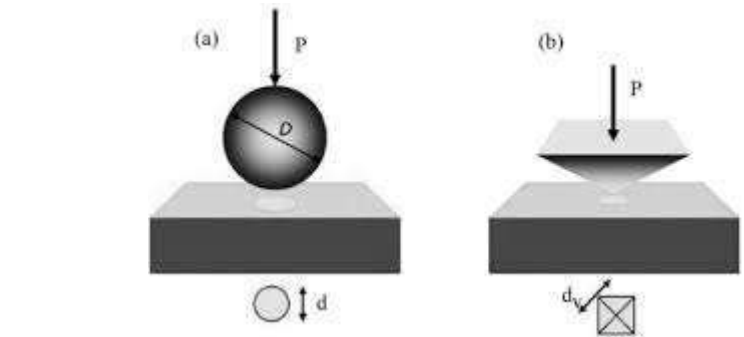
- **Toughness:** It is the ability of a material to absorb the energy and gets plastically deformed without fracturing. Its numerical value is determined by the amount of energy per unit volume. Its unit is Joule/ m<sup>3</sup>. Value of toughness of a material can be determined by stress-strain characteristics of a material. For good toughness, materials should have good strength as well as ductility

- **Hardness:** It is the ability of a material to resist to permanent shape change due to external stress. There are various measure of hardness – Scratch Hardness, Indentation Hardness and Rebound Hardness.

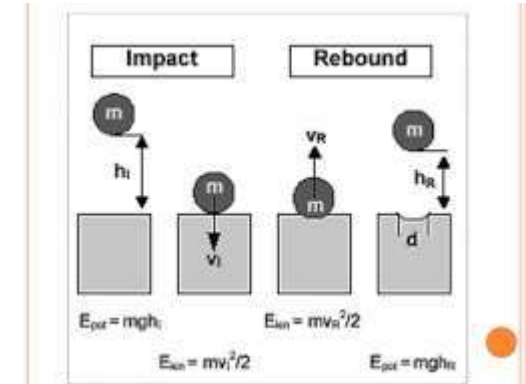
**1. Scratch Hardness**  
 Scratch Hardness is the ability of materials to the oppose the scratches to outer surface layer due to external force.



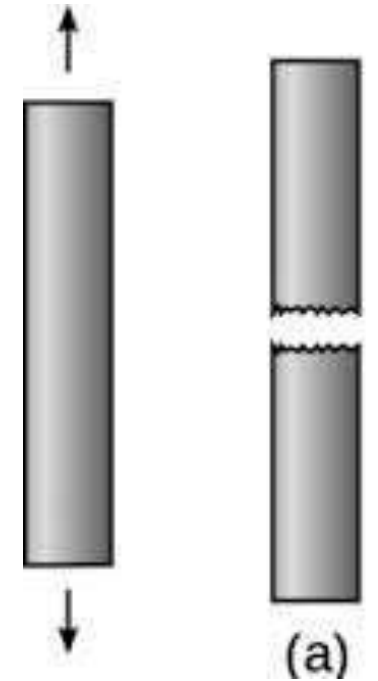
**2. Indentation Hardness**  
 It is the ability of materials to oppose the dent due to punch of external hard and sharp objects.



**3. Rebound Hardness**  
 Rebound hardness is also called as dynamic hardness. It is determined by the height of “bounce” of a diamond tipped hammer dropped from a fixed height on the material.



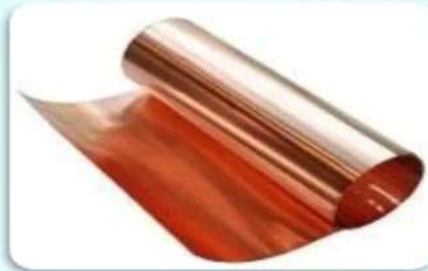
- **Hardenability:** It is the ability of a material to attain the hardness by heat treatment processing. It is determined by the depth up to which the material becomes hard. The [SI unit](#) of hardenability is meter (similar to length). Hardenability of material is inversely proportional to the weld-ability of material.
- **Brittleness:** Brittleness of a material indicates that how easily it gets fractured when it is subjected to a force or load. When a brittle material is subjected to a stress it observes very less energy and gets fractures without significant strain. Brittleness is converse to ductility of material. Brittleness of material is temperature dependent. Some metals which are ductile at normal temperature become brittle at low temperature



- **Malleability:** Malleability is a property of solid materials which indicates that how easily a material gets deformed under compressive stress. Malleability is often categorized by the ability of material to be formed in the form of a thin sheet by hammering or rolling. This mechanical property is an aspect of plasticity of material. Malleability of material is temperature dependent. With rise in temperature, the malleability of material increases.

## **MALLEABILITY**

The property of a substance that describes its ability be **bent** or **hammered** into a **thin sheet** without **breaking**.



**Aluminum** is very malleable and that is why we use it to make foil to wrap our food. Other substances, like glass, are **not** malleable because it would break instead of change shape. Wood is **not malleable**, while copper is **malleable**.

- **Ductility:** Ductility is a property of a solid material which indicates that how easily a material gets deformed under tensile stress. Ductility is often categorized by the ability of material to get stretched into a wire by pulling or drawing. This mechanical property is also an aspect of plasticity of material and is temperature dependent. With rise in temperature, the ductility of material increases.

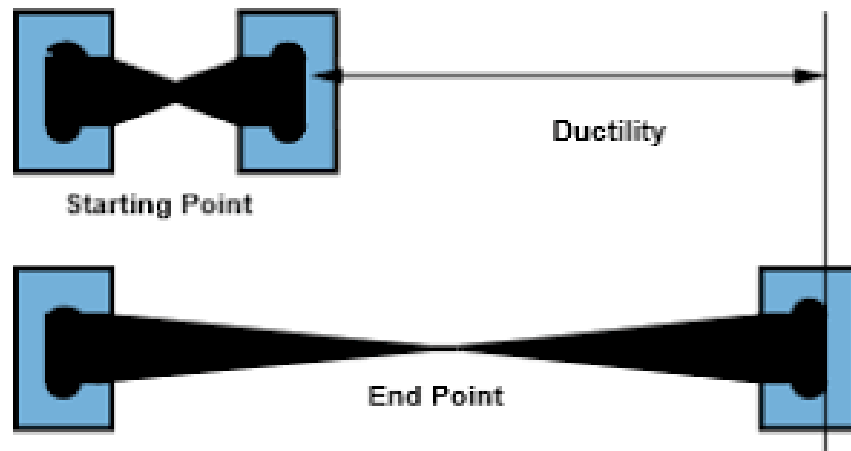
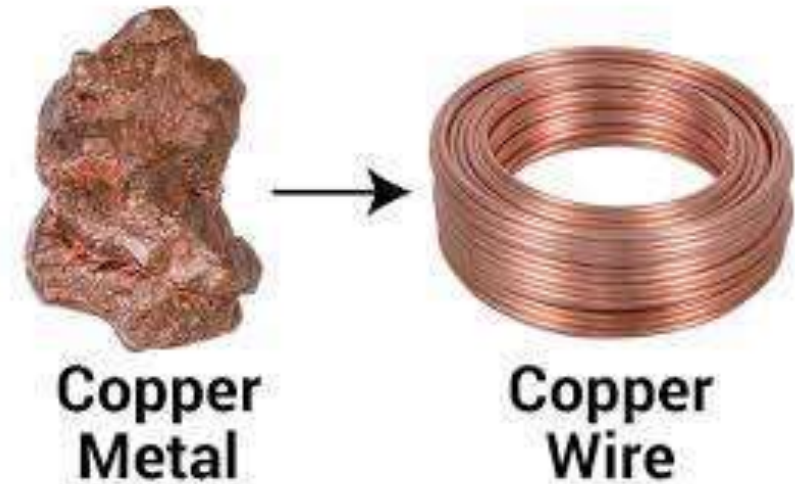


Figure 23:2: Ductility Test



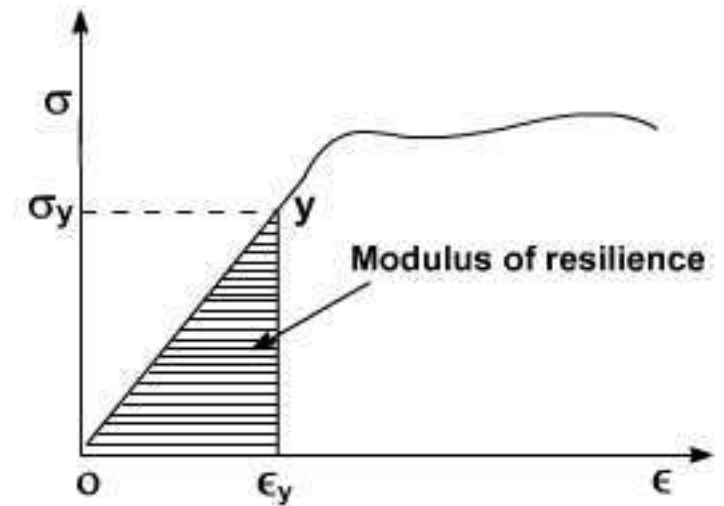


- Creep: Creep is the property of a material which indicates the tendency of material to move slowly and deform permanently under the influence of external mechanical stress. It results due to long time exposure to large external mechanical stress within limit of yielding. Creep is more severe in material that are subjected to heat for long time.
- Or
- Creep may be defined as a time-dependent deformation at elevated temperature and constant stress. It follows, then, that a failure from such a condition is referred to as a creep failure or, occasionally, a stress rupture

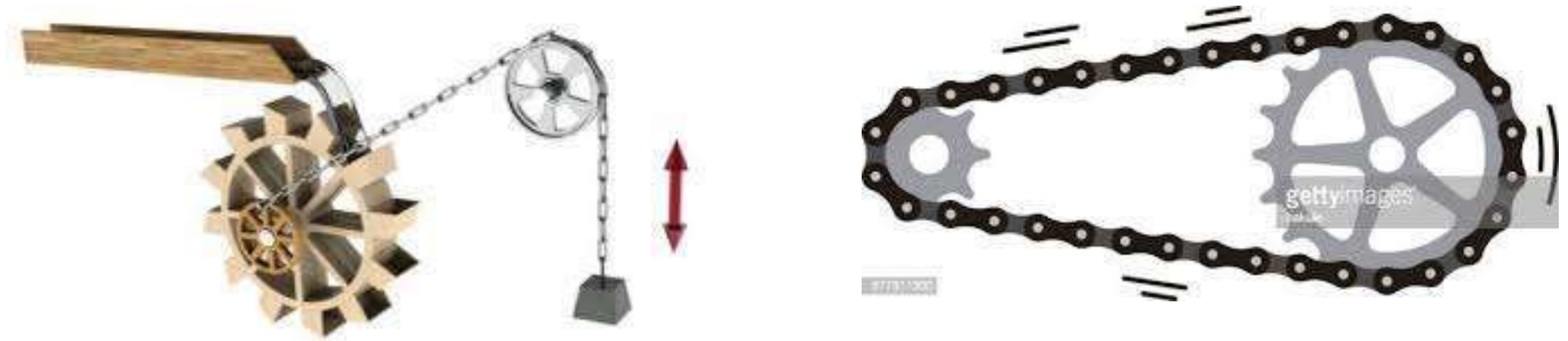




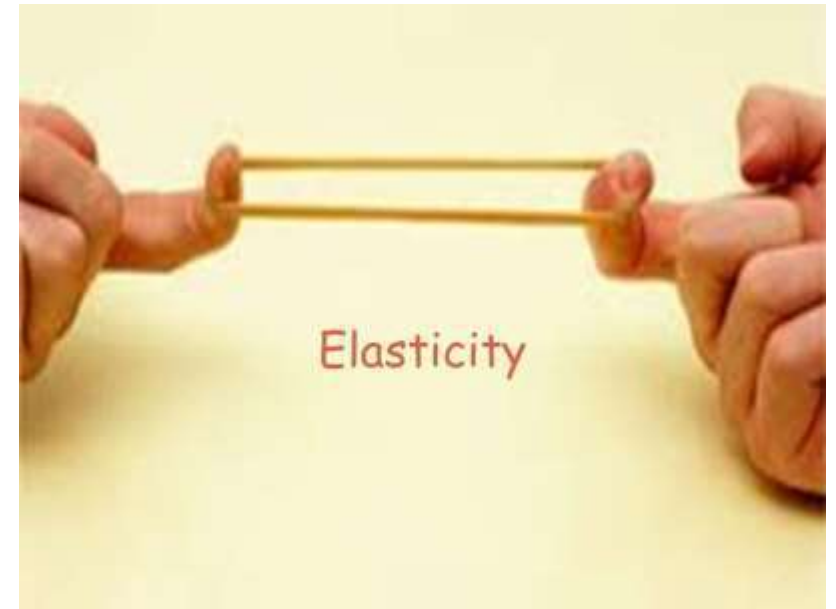
•**Resilience:** is the ability of material to absorb the energy when it is deformed elastically by applying stress and release the energy when stress is removed. Proof resilience is defined as the maximum energy that can be absorbed without permanent deformation. The modulus of resilience is defined as the maximum energy that can be absorbed per unit volume without permanent deformation. It can be determined by integrating the stress-strain curve from zero to elastic limit. Its unit is joule/m<sup>3</sup>



- **Fatigue:** Fatigue is the weakening of material caused by the repeated loading of the material. When a material is subjected to cyclic loading, and loading greater than certain threshold value but much below the strength of material (ultimate tensile strength limit or yield stress limit), microscopic cracks begin to form at grain boundaries and interfaces. Eventually the crack reaches to a critical size. This crack propagates suddenly and the structure gets fractured. The shape of structure affects the fatigue very much. Square holes and sharp corners lead to elevated stresses where the fatigue crack initiates



- **Elasticity:** In the science of physics, **elasticity** is the ability of a deformable body (e.g., steel, aluminum, rubber, wood, crystals, etc.) to resist a distorting effect and to return to its original size and shape when that influence or force is removed



**Plasticity:** is the non-reversible deformation of a material due to applied forces. While that sounds very scientific, simply picture a piece of strong **steel** that has been bent at a 90 degree angle



# Difference Between Metals and Non Metals

Properties	Metals	Non-Metals
Appearance	Lustrous	Dull
Hardness	Hard	Soft
Malleability	Can be beaten into thin sheets	Cannot be beaten into thin sheets
Ductility	Can be drawn into wires	Can Not Be drawn into wires
Heat Conduction	Good Conductor of Heats	Poor Conductors of Heat
Conduction of Electricity	Good Conductors of Electricity	Poor Conductors of Electricity

# Stress-Strain in Material

## Stress

In mechanics and materials science, stress (represented by a lowercase Greek letter sigma –  $\sigma$ ) is a physical quantity that expresses the internal forces that neighboring particles of a continuous material exert on each other, while strain is the measure of the deformation of the material which is not a physical quantity.

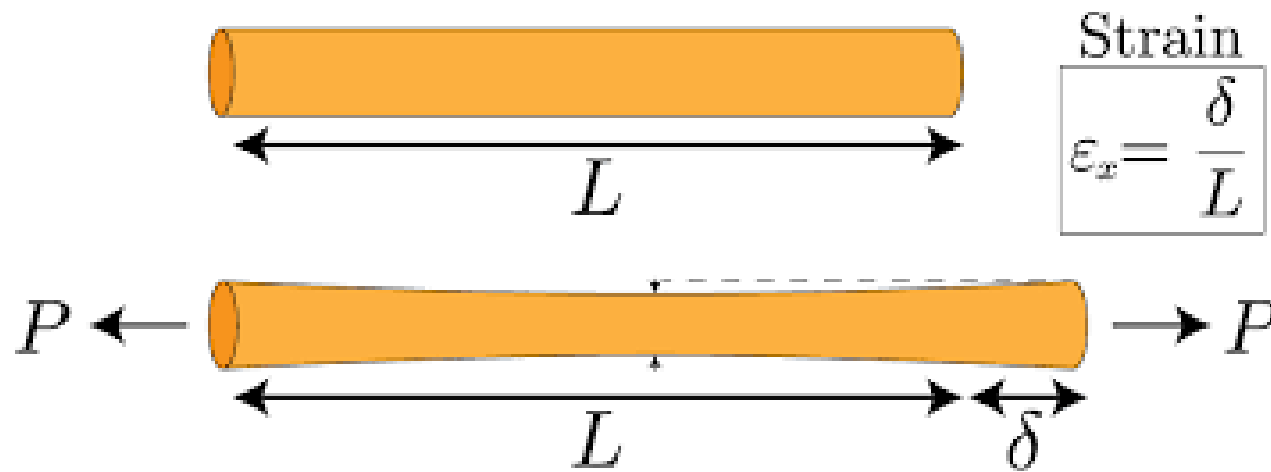
Although it is impossible to measure the intensity of this stress, the external load and the area to which it is applied can be measured. Stress ( $\sigma$ ) can be equated to the load per unit area or the force ( $F$ ) applied per cross-sectional area ( $A$ ) perpendicular to the force as:

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

where

- $\sigma$  stress [Pa]
- $F$  applied force [N]
- $A$  cross-sectional area [ $\text{m}^2$ ]

**Strain.** Strain is the response of a system to an applied stress. When a material is loaded with a force, it produces a stress, which then causes a material to deform. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material.





# Types of Stresses

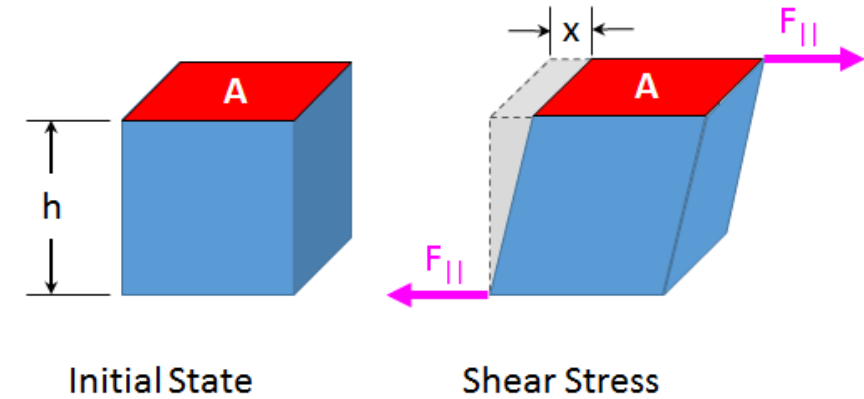
**1.Compression stress** is the result of axially-loaded forces pointing towards the center of an object. There are two major issues with compression stress: Compression forces can cause an object to shorten, or they can cause an object to buckle. When an object buckles, it bends in such a way that it can no longer hold the load, even though structurally speaking, the object can hold more stress than is applied to it.



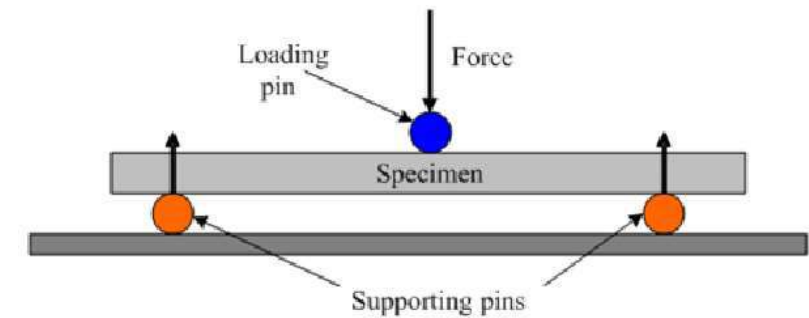
**2.Tension Stress** is caused when axially-loaded forces are pulling away from an object's center, and perpendicular to the object's surface. Tension stress can cause lengthening of an object. There are several materials, concrete for example, where the object can only withstand a fraction of the stress when the object is in compression.



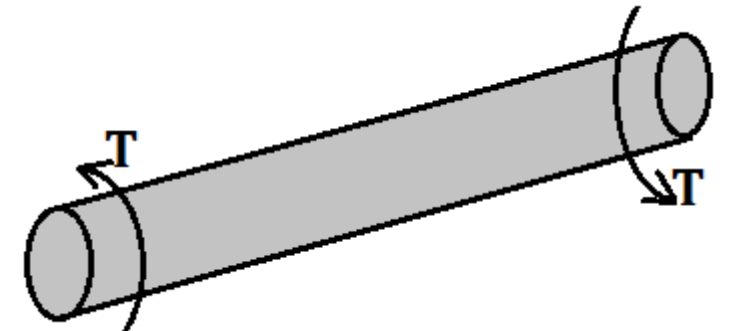
**3. Shear stress** is caused when the forces applied to an object are parallel to the object's cross-section. This stress can cause the object to deform and, in some cases, pull apart. As the object deforms, it changes. The shape of the object can change, which can affect how the object withstands other forces.

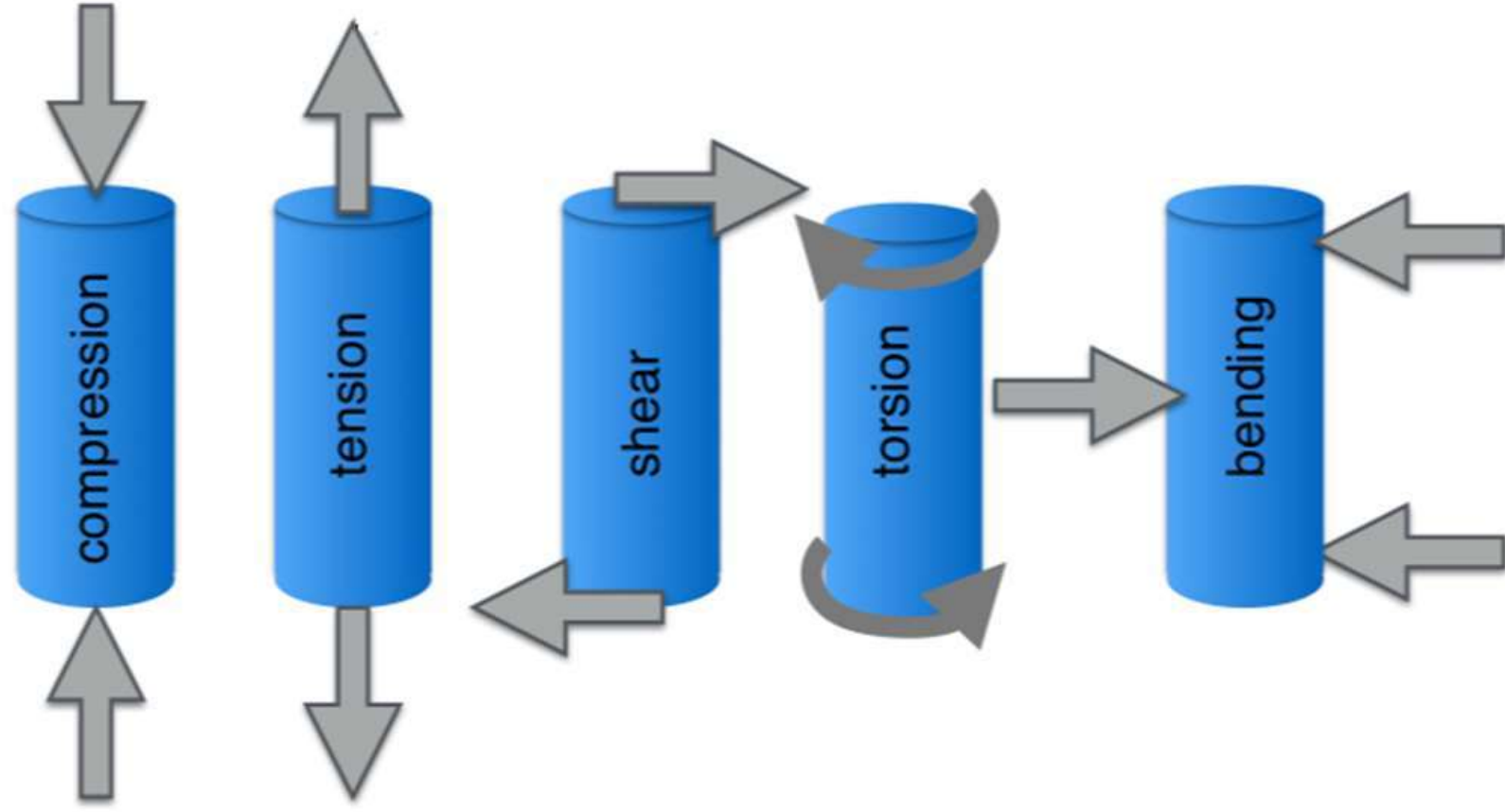


**4. Bending stress** is seen in longitudinally-loaded objects. The forces cause the object to bend, usually in a downward direction. The farther away from the object's fixed supports, the greater the bending stress as is seen in the diagram here:



**5. Torsional shear stress** or **Torsional stress** is the shear stress produced in the shaft due to the twisting. This twisting in the shaft is caused by the couple acting on it.





# Stress –Strain Curve for Ductile Material

**(O-A)-** The proportional limit is the point on a stress-strain curve where the linear, elastic deformation region transitions into a non-linear, plastic deformation region. In other words, the proportional limit determines the greatest stress that is directly proportional to strain.

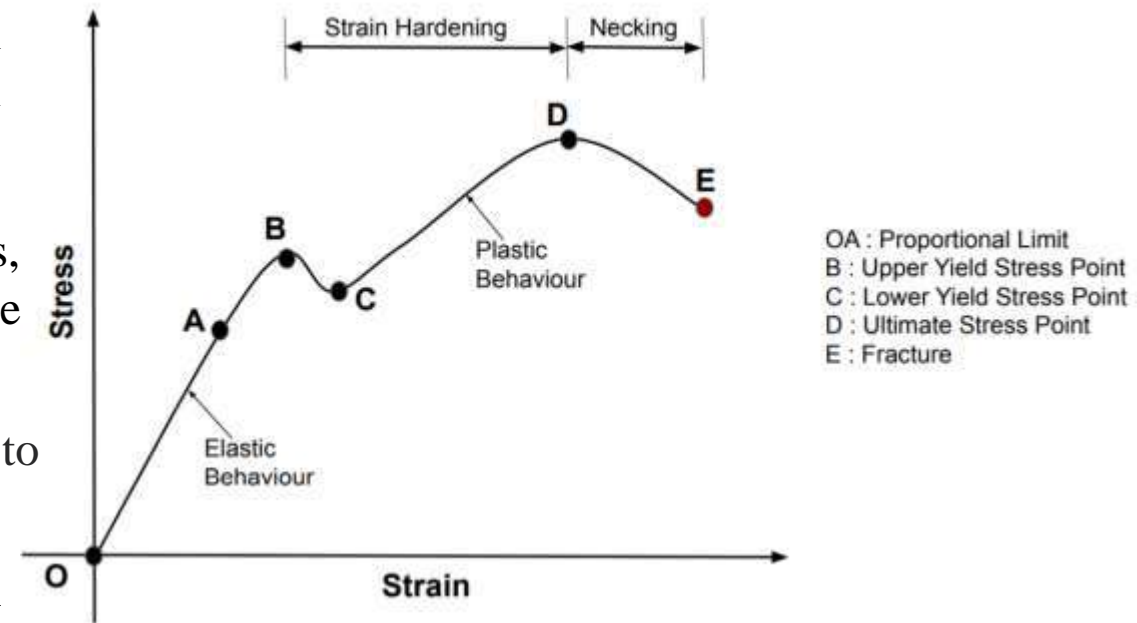
**(O-B)** A material's **elastic limit** is the greatest **stress** that can be applied to it without causing plastic (permanent) **deformation**. When a material is stressed to a point below its **elastic limit**, it will return to its original length once the **stress** is removed

**Point B** Upper yield point is the max load at which deformation starts, starting of deformation means dislocations are started moving in the material.

**Point C** lower yield point stress) which is the minimum stress required to maintain the deformation in the material.

**Point D** The material is handling the highest amount of load it can handle safely. Ultimate strength is, therefore, a crucial point to be considered on the stress-strain curve. It shows the maximum amount of stress a material can bear before failure.

**Point E** is the rupture or fracture point at where material fracture or break.

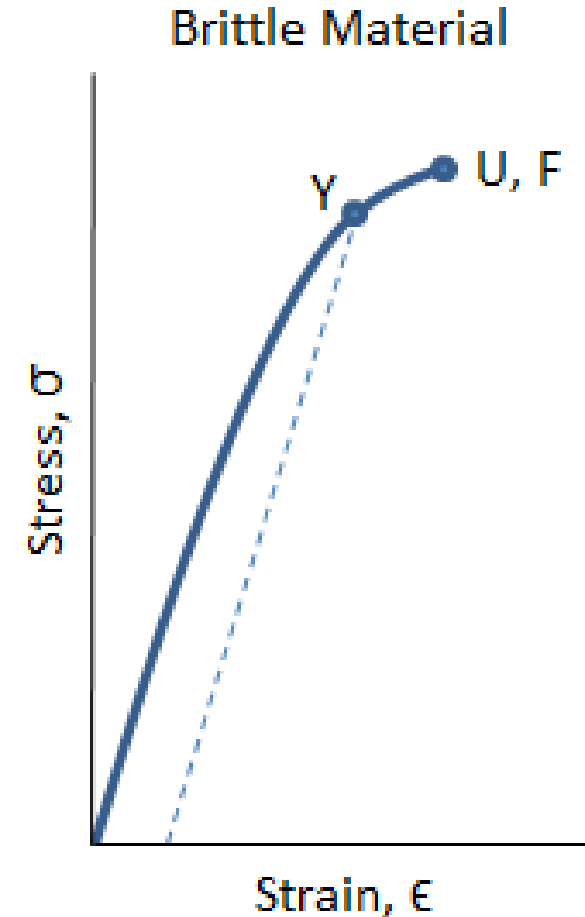


# Stress-Strain Curve for Brittle Material

OY is non-linear elastic YU is the Strain Hardening.

- Brittle material never yields, a point similar to yield point is first cracking point, where simple cracks develop; which may expand further leading to failure.

- A point is the first cracking point. After first cracks develop, the material undergoes an increase in strain by widening the crack and fails almost at the same stress. Therefore for all calculation in brittle material design stress is **ultimate or breaking stress**



**Hooke's law** states that the strain of the material is proportional to the applied stress within the elastic limit of that material. When the elastic materials are stretched, the atoms and molecules deform until stress is been applied and when the stress is removed they return to their initial state.

$$\sigma = E \cdot \varepsilon$$

where

- $\sigma$  is stress [Pa]
- $\varepsilon$  is strain  $= \frac{\Delta L}{L_0}$
- $E$  is the modulus of elasticity [Pa]

**Modulus of Elasticity**, also known as Elastic Modulus or simply Modulus, is the measurement of a material's elasticity. Elastic modulus quantifies a material's resistance to non-permanent, or elastic, deformation. When under stress, materials will first exhibit elastic properties: the stress causes them to deform, but the material will return to its previous state after the stress is removed. After passing through the elastic region and through their yield point, materials enter a plastic region, where they exhibit permanent deformation even after the tensile stress is removed



Q.1 How much force is needed to pull a spring with a spring constant of 20 N/m a distance of 25 cm?

Q.2 A spring is pulled to 10 cm and held in place with a force of 500 N. What is the spring constant of the spring?

$$\delta = \frac{P\ell}{AE}$$

Where:

P = force producing extension of bar (lbf)

$\ell$  = length of bar (in.)

A = cross-sectional area of bar (in.<sup>2</sup>)

d = total elongation of bar (in.)

E = elastic constant of the material, called the Modulus of Elasticity, or Young's Modulus (lbf/in.<sup>2</sup>)

# Brinell Hardness Test

Brinell hardness tester is mainly used for hardness determination of cast iron, steel, nonferrous metals and soft [alloy](#) materials. Brinell hardness test is the biggest indentation test of all test method. It is a high accuracy hardness test method, as it can reflect the comprehensive performance of the material without effected by the microscopic segregation of the specimen and the uneven composition. It is widely used in metallurgy, forging, hardened steel and nonferrous metals and other industrial fields, laboratories, universities and scientific research units.

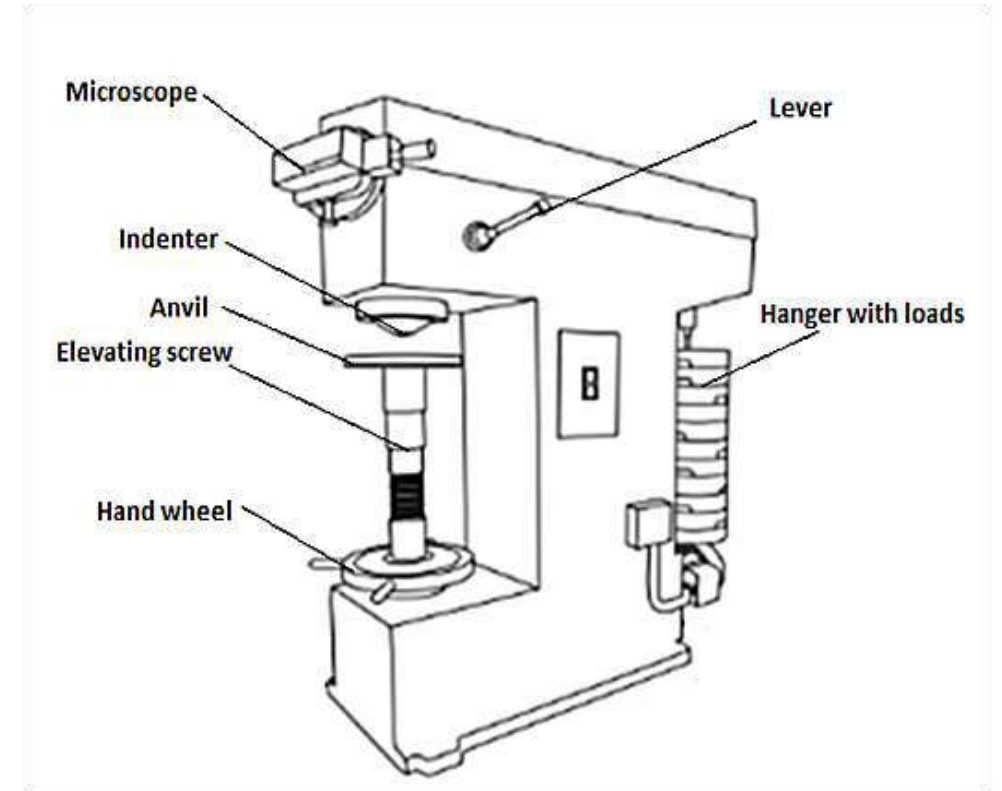
Brinell hardness tester can be used to test castings, forgings, supplied steel, nonferrous metals and semi-finished steel parts after heat treatment. This is a portable instrument that can be used in the workshop. It is easy to operate and carry. It can test large parts without any sampling on site. It can realize the detection of large parts by piece.

# Brinell Hardness Test

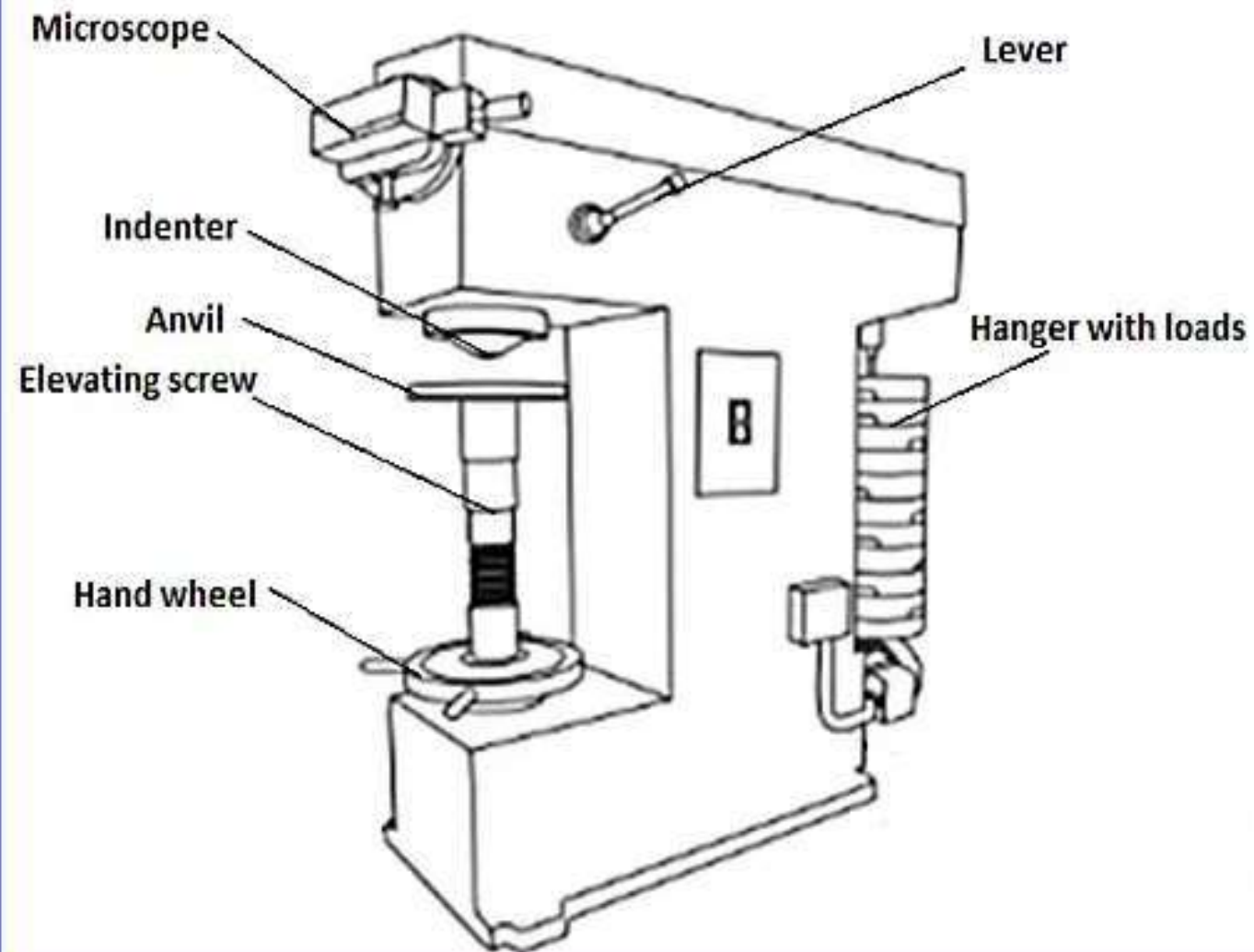
The working principle of [\*Brinell hardness tester\*](#) is to press the ball of certain diameter into the sample [surface](#) under a certain test force and a certain rate, remove the test force after the specified test force maintain time. The Brinell hardness value of the metal is expressed by the average pressure on the spherical [surface](#) area of the sample indentation

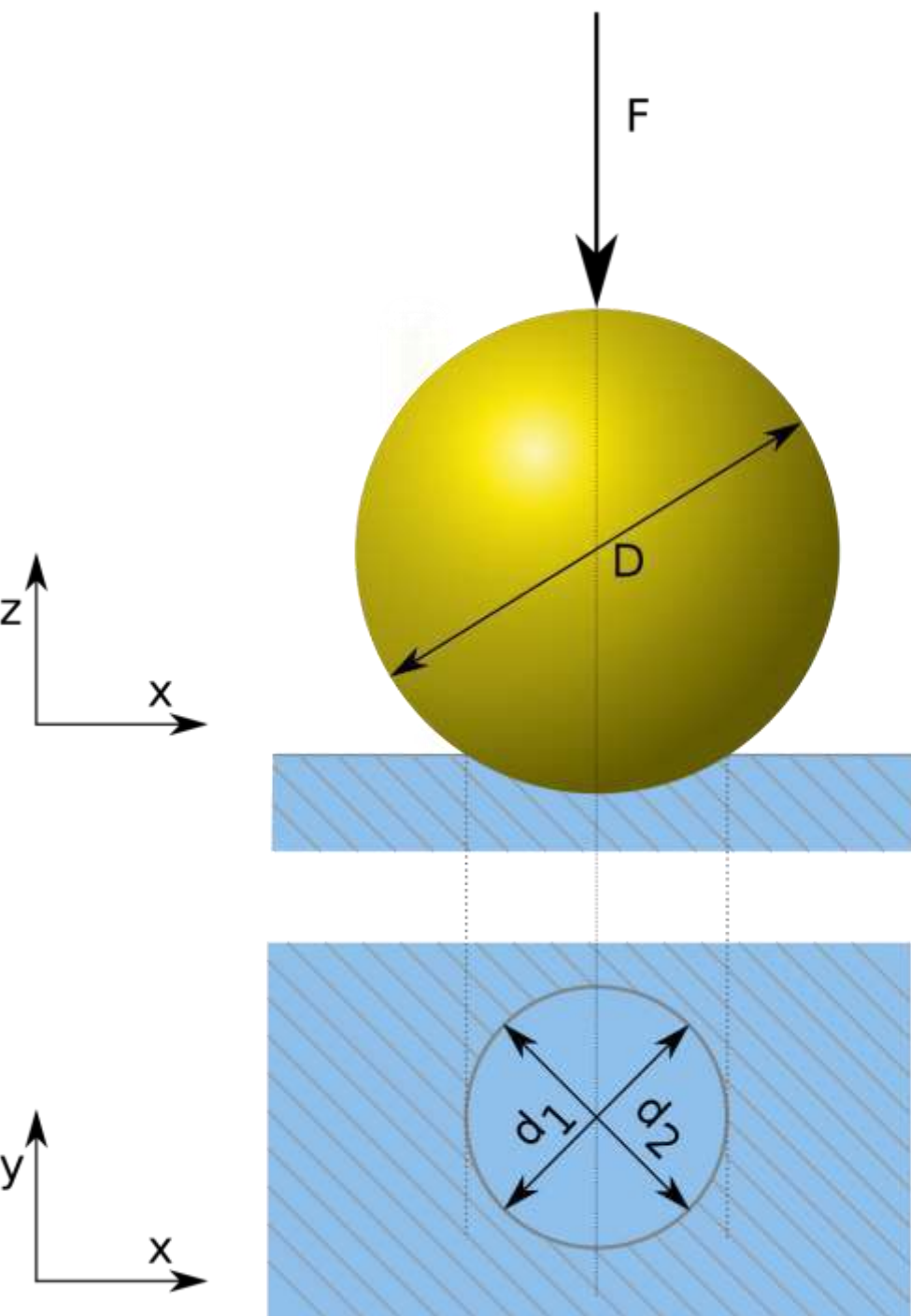
The Brinell test involves applying a constant load (usually 500 to 3000 kg) through a spherical hardened steel penetrator (5 or 10 mm in diameter) until plastic deformation ceases (10 to 30 seconds). The test should be performed on a flat surface. The diameter of the permanent indentation is then measured and the hardness number (HB - Hardness Brinell) determined from the equation:

where P is the load (in kilograms), D is the penetrator diameter in mm, and d is the indentation diameter in mm. Calculation of hardness number is usually avoided by referring to a [chart](#), supplied by the testing machine manufacture, relating indentation diameter (d) to hardness number (HB) for a given load and penetrator diameter.



$$HB = \frac{2P}{\pi D \left[ D - \sqrt{D^2 - d^2} \right]}$$





# Brinell Hardness Test

- Steel or tungsten carbide ball indenter

$$\text{BHN} = \frac{2P}{\pi D \left( D - \sqrt{D^2 - d^2} \right)}$$

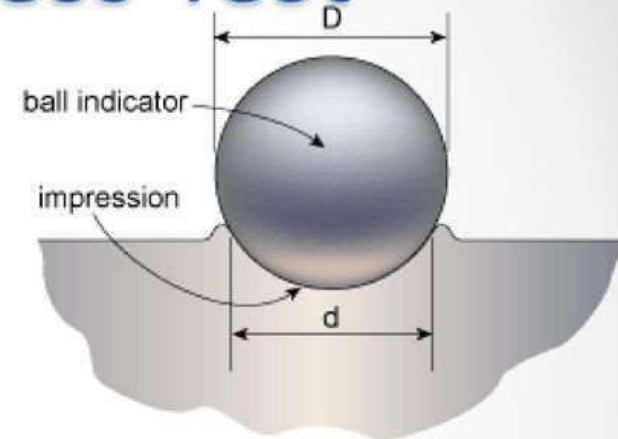
where:

BHN = Brinell Hardness Number ( $\text{kgf/mm}^2$ )

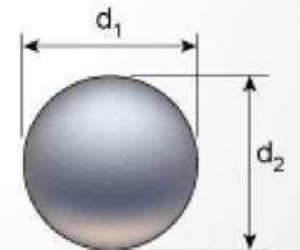
$P$  = applied load in kilogram-force (kgf)

$D$  = diameter of indenter (mm)

$d$  = diameter of indentation (mm)



(a) Brinell indentation

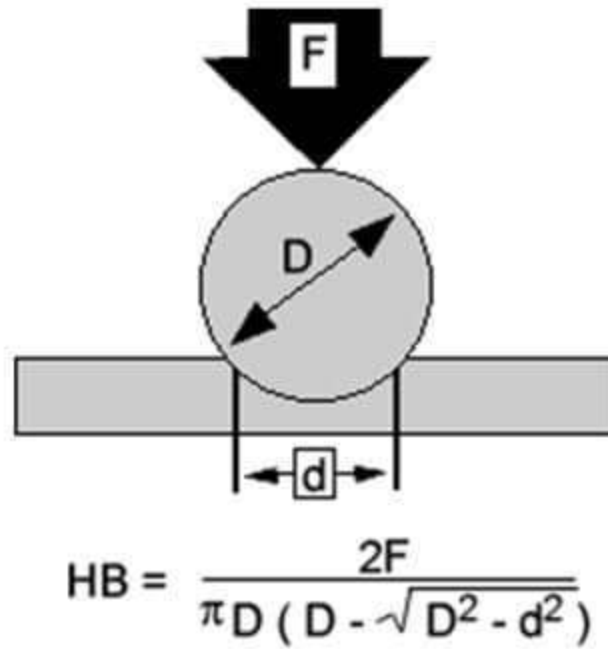
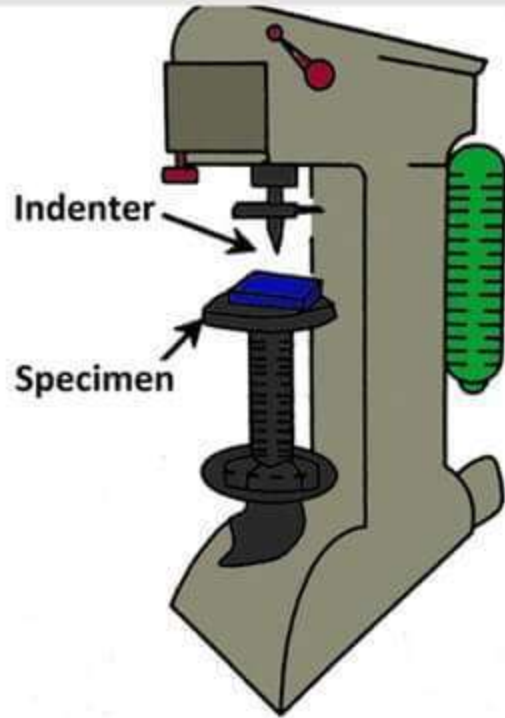


(b) measurement of impression diameter

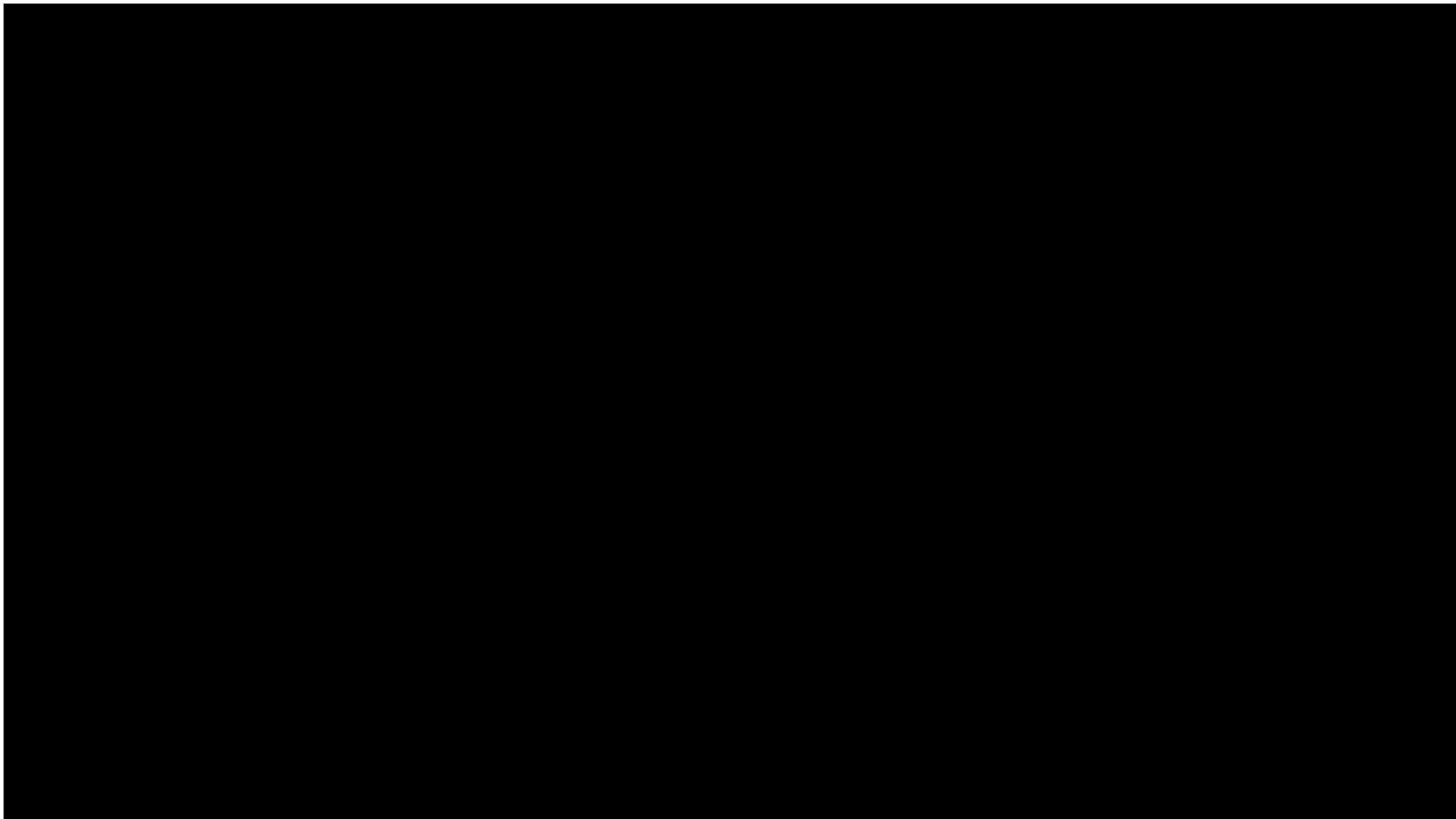
- Calculate or use chart to get hardness value. Value is denoted as HBS or HBW.
- Large indentation. For example – GCI  $\sim 4.2$  mm with 10 mm and 3000 kgf
- Can be compared to UTS (based on material, Meyer's Law)
- [ASTM E10-15](#)



## Brinell Hardness Test: For Rough and Coarse Micro-structured Materials







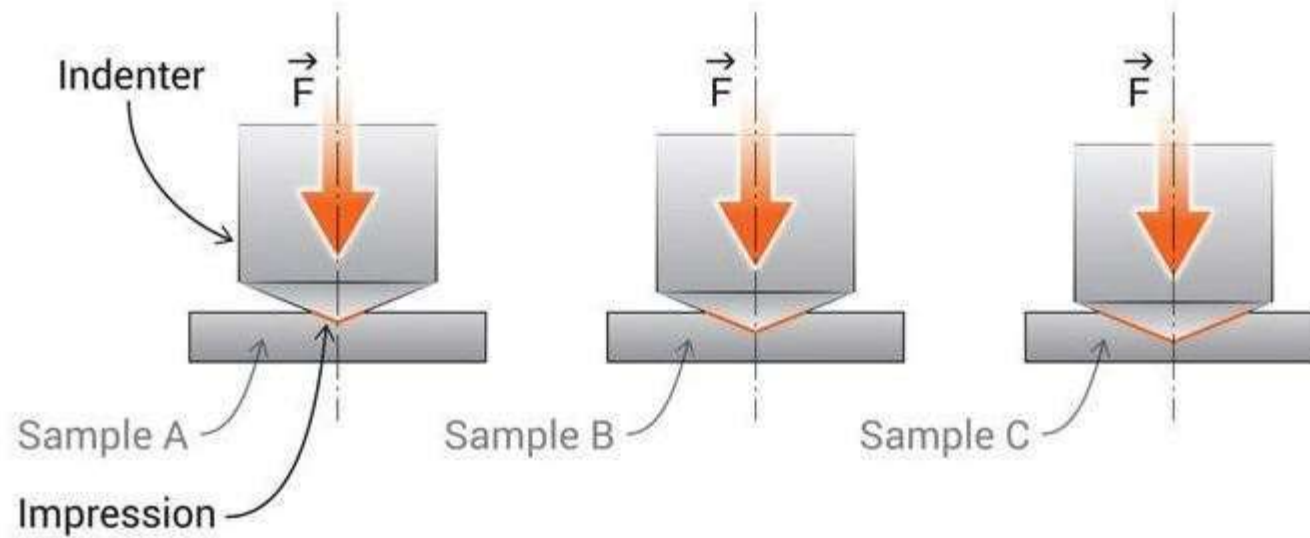
# Vickers Hardness Test Method

- The **Vickers hardness test method**, also referred to as a microhardness test method, is mostly used for small parts thin sections , or case depth work.
- The Vickers method is based on an optical measurement system.
- The Microhardness test procedure, ASTM E-384, specifies a range of light loads using a [diamond indenter](#) to make an indentation which is measured and converted to a hardness value.
- It is very useful for testing on a wide type of materials, but test samples must be highly polished to enable measuring the size of the impressions.
- A square base pyramid shaped diamond is used for testing in the Vickers scale. Typically loads are very light, ranging from 10gm to 1kgf, although "Macro" Vickers loads can range up to 30 kg or more.
- The Microhardness methods are used to test on metals, ceramics, composites - almost any type of material.
- Since the test indentation is very small in a Vickers test, it is useful for a variety of applications: testing very thin materials like foils or measuring the surface of a part, small parts or small areas, measuring individual microstructures, or measuring the depth of case hardening by sectioning a part and making a series of indentations to describe a profile of the change in hardness.

The indenter is made of diamond and is in the form of a square-based pyramid with an angle of 136° between faces. The faces of diamond indenter are highly polished, and the point is sharp. The loads applied vary from 1 to 120 kg; the standard loads are 5, 10, 20, 30, 50, 100, and 120 kg. For most hardness testing, 50 kg is maximum.

The Vickers test can be used for all metals and is one of the widely used test among hardness tests. The unit of hardness is known as the VICKERS PYRAMID NUMBER (HV) or DIAMOND PYRAMID HARDNESS (DPH). The hardness number can be calculated by the load over the surface area of the indentation.

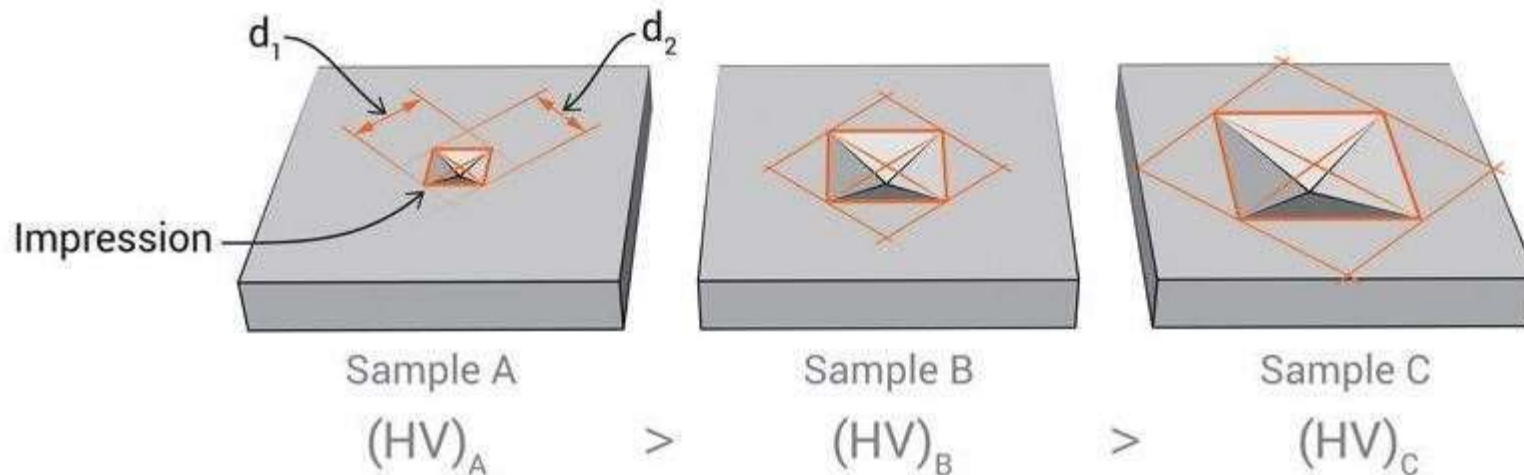




The angle between the two faces of diamond indenter used in Vickers hardness test is  $136^\circ$  and the faces makes an angle  $22^\circ$  with the horizontal. The HV number is then determined by the ratio  $F/A$ , where  $F$  is the force applied to the diamond in kilograms-force and  $A$  is the surface area of the indentation in square millimeters.  $A$  can be determined by the formula

Measurement of impression diagonals

$$A = d^2 / 2 \sin(136^\circ / 2)$$



by eliminating the sine term we get,

$$A = d^2 / 1.8544$$

Where  $d$  is the average length of the diagonal in millimeters.

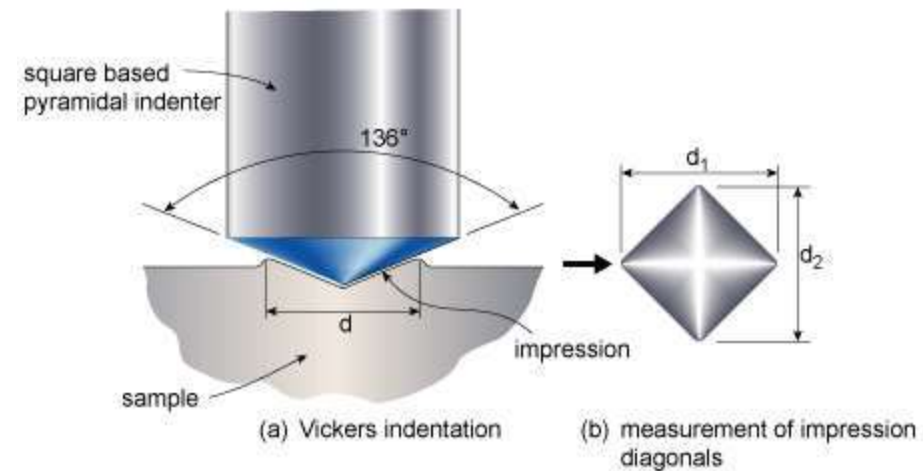
The corresponding units of HV are then kilograms-force per square millimeter (kgf/mm). To calculate Vickers hardness number using SI units we must convert the force applied from kilogram-force to Newtons by multiplying by 9.80665 (standard gravity) and then dividing by 1000 to get the answer in GPa. This will leads to the following equation that can be used to do any calculation directly.

$$HV=0.1891(F/d^2)GPa$$

Where F is in N and d is in millimeters.

$$HV=F/A=(1.8544F/d^2)kgf/mm^2$$

Where F is in kgf and d is in millimeters.



Vickers hardness numbers are expressed as xxxHVyy, e.g.440HV30, or xxxHVyy/zz if duration of force differs from 10 s to 15 s, e.g.440HV30/20,Where

440 is the hardness number,

HV gives the hardness scale (Vickers),

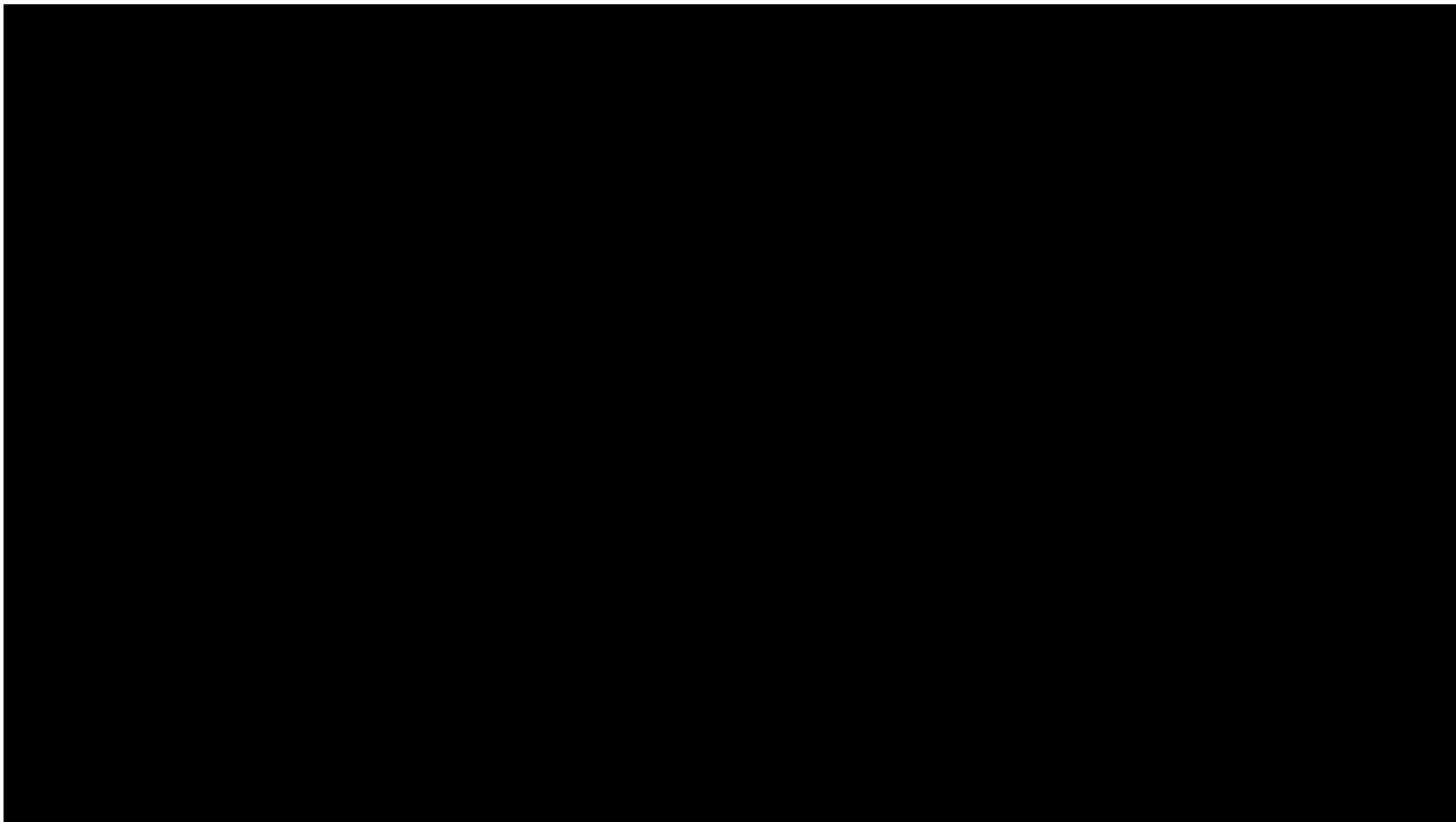
30 is the load used in kgf.

20 is loading time if it differs from 10s to 15s

Vickers values are not dependent of the test force: they will be same for 500gf and 50kgf, as long as the force is at least 200 gf.

For thin samples indentation depth can be an issue due to substrate effects. In other waysindent depth can be calculated according to:

$$h=d/2\sqrt{2 \tan(136^{\circ}/2 )}=d/7.0006'$$





# Iron Carbon Phase Diagram

Alloy metals can exist in different phases. Phases are physically homogeneous states of an alloy. A phase has a precise chemical composition – a certain arrangement and bonding between the atoms.

This structure of atoms imparts different properties to different phases. We can choose the phase we want and use it in our applications.

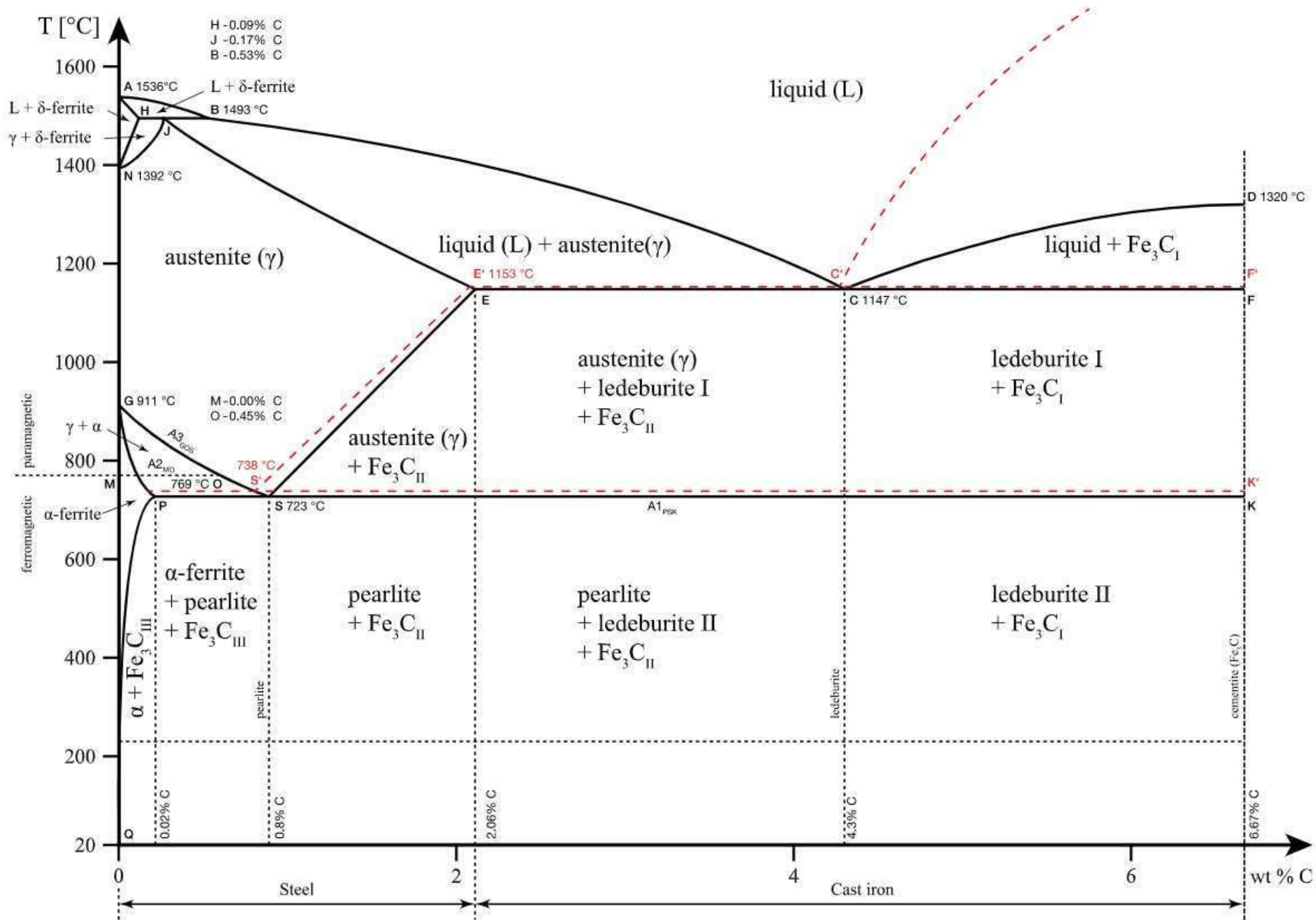
Only some special alloys can exist in multiple phases. Heating the metal to specific temperatures using [heat treatment procedures](#) results in different phases. Some special alloys can exist in more than one phase at the same temperature.

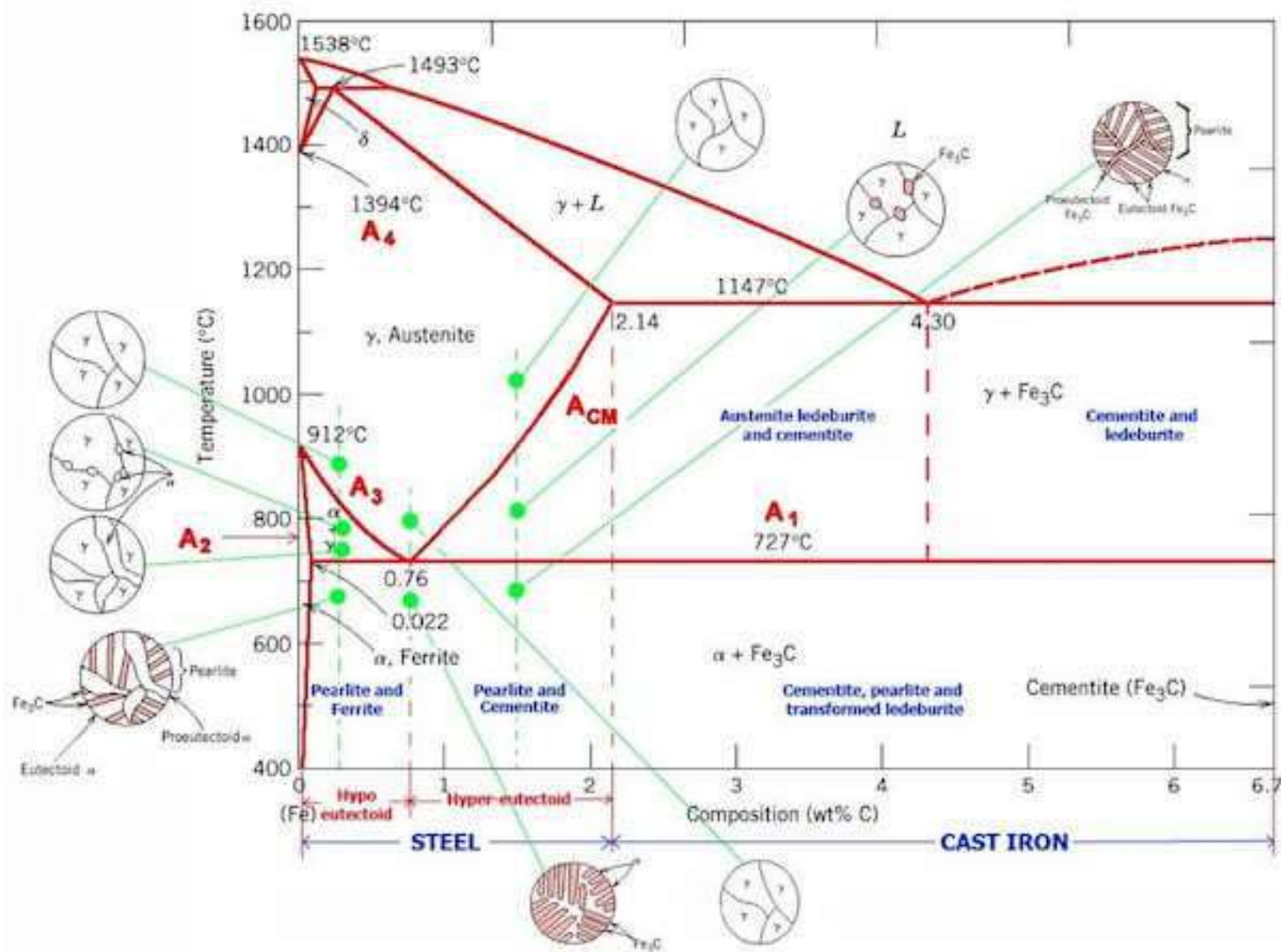
Phase diagrams are graphical representations of the phases present in an alloy at different conditions of temperature, pressure, or chemical composition.

The diagram describes the suitable conditions for two or more phases to exist in equilibrium. For example, the water phase diagram describes a point (triple point) where water can coexist in three different phases at the same time. This happens at just above the freezing temperature ( $0.01^{\circ}\text{C}$ ) and 0.006 atm.

## Using the Diagrams

- Development of new alloys based on application requirements.
- Production of these alloys.
- Development and control of appropriate heat treatment procedures to improve the chemical, physical, and mechanical properties of these new alloys.
- Troubleshooting problems that arise in application of these new alloys, ultimately improving product predictability.





The iron-carbon phase diagram is widely used to understand the different phases of steel and cast iron. Both steel and cast iron are a mix of iron and carbon. Also, both alloys contain a small amount of trace elements.

The graph is quite complex but since we are limiting our exploration to Fe<sub>3</sub>C, we will only be focusing up to 6.67 weight percent of carbon.

This iron carbon phase diagram is plotted with the carbon concentrations by weight on the X-axis and the temperature scale on the Y-axis.

The carbon in iron is an interstitial impurity. The alloy may form a face centred cubic (FCC) lattice or a body centred cubic (BCC) lattice. It will form a solid solution with α, γ, and δ phases of iron.

## Types of Ferrous Alloys on the Phase Diagram

The weight percentage scale on the X-axis of the iron carbon phase diagram goes from 0% up to 6.67% Carbon. Up to a maximum carbon content of 0.008% weight of Carbon, the metal is simply called iron or pure iron. It exists in the  $\alpha$ -ferrite form at room temperature.

From 0.008% up to 2.14% carbon content, the iron carbon alloy is called steel. Within this range, there are different grades of steel known as [low carbon steel \(or mild steel\)](#), medium carbon steel, and high carbon steel.

When the carbon content increases beyond 2.14%, we reach the stage of cast iron. Cast iron is very hard but its brittleness severely limits its applications and methods for forming.

## Boundaries

Multiple lines can be seen in the diagram titled A1, A2, A3, A4, and ACM. The A in their name stands for the word ‘arrest’. As the temperature of the metal increases or decreases, phase change occurs at these boundaries when the temperature reaches the value on the boundary.

Normally, when heating an alloy, its temperature increases. But along these lines (A1, A2, A3, A4, and ACM) the heating results in a realignment of the structure into a different phase and thus, the temperature stops increasing until the phase has changed completely. This is known as thermal arrest as the temperature stays constant.

Alloy steel elements such as nickel, manganese, chromium, and molybdenum affect the position of these boundaries on the phase diagram. The boundaries may shift in either direction depending on the element used. For example, in the iron carbon phase diagram, addition of nickel lowers the A3 boundary while the addition of chromium raises it.

## **Eutectic Point**

Eutectic point is a point where multiple phases meet. For the iron-carbon alloy diagram, the eutectic point is where the lines A1, A3 and ACM meet. The formation of these points is coincidental.

At these points, eutectic reactions take place where a liquid phase freezes into a mixture of two solid phases. This happens when cooling a liquid alloy of eutectic composition all the way to its eutectic temperature.

The alloys formed at this point are known as eutectic alloys. On the left and right side of this point, alloys are known as hypoeutectic and hypereutectic alloys respectively ('hypo' in Greek means less than, 'hyper' means greater than).

## **Phase Fields**

The boundaries, intersecting each other, mark certain regions on the Fe<sub>3</sub>C diagram. Within each region, a different phase or two phases may exist together. At the boundary, the phase change occurs. These regions are the phase fields.

They indicate the phases present for a certain composition and temperature of the alloy. Let's learn a little about the different phases of the iron-carbon alloy.



## Different Phases

### $\alpha$ -ferrite

Existing at low temperatures and low carbon content,  $\alpha$ -ferrite is a solid solution of carbon in BCC Fe.

This phase is stable at room temperature. In the graph, it can be seen as a sliver on the left edge with Y-axis on the left side and A2 on the right. This phase is [magnetic](#) below 768°C.

It has a maximum carbon content of 0.022 % and it will transform to  $\gamma$ -austenite at 912°C as shown in the graph.

### $\gamma$ -austenite

This phase is a solid solution of carbon in FCC Fe with a maximum solubility of 2.14% C.

On further heating, it converts into BCC  $\delta$ -ferrite at 1395°C.

$\gamma$ -austenite is unstable at temperatures below eutectic temperature (727°C) unless cooled rapidly.

This phase is [non-magnetic](#).

### $\delta$ -ferrite

This phase has a similar structure as that of  $\alpha$ -ferrite but exists only at high temperatures.

The phase can be spotted at the top left corner in the graph. It has a melting point of 1538°C.

## **Fe<sub>3</sub>C or cementite**

Cementite is a metastable phase of this alloy with a fixed composition of Fe<sub>3</sub>C. It decomposes extremely slowly at room temperature into Iron and carbon (graphite).

This decomposition time is long and it will take much longer than the service life of the application at room temperature.

Some other factors (high temperatures and addition of certain alloying elements for instance) can affect this decomposition as they promote graphite formation.

Cementite is hard and brittle which makes it suitable for strengthening steels.

Its mechanical properties are a function of its microstructure, which depends upon how it is mixed with ferrite

## **Fe-C liquid solution**

Marked on the diagram as 'L', it can be seen in the upper region in the diagram.

As the name suggests, it is a liquid solution of carbon in iron.

As we know that  $\delta$ -ferrite melts at 1538°C, it is evident that melting temperature of iron decreases with increasing carbon content.