INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
NPTEL
NPTEL ONLINE CERTIFICATION COURSE

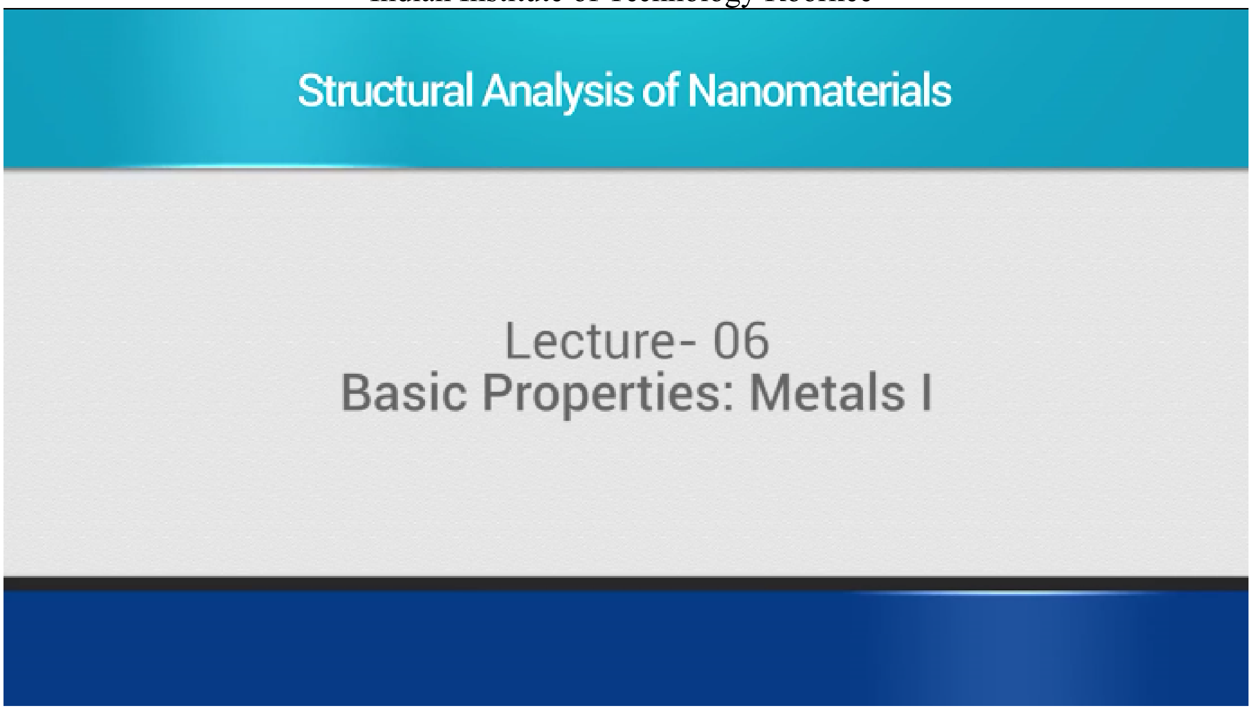
Structural Analysis of Nanomaterials

LECTURE – 06

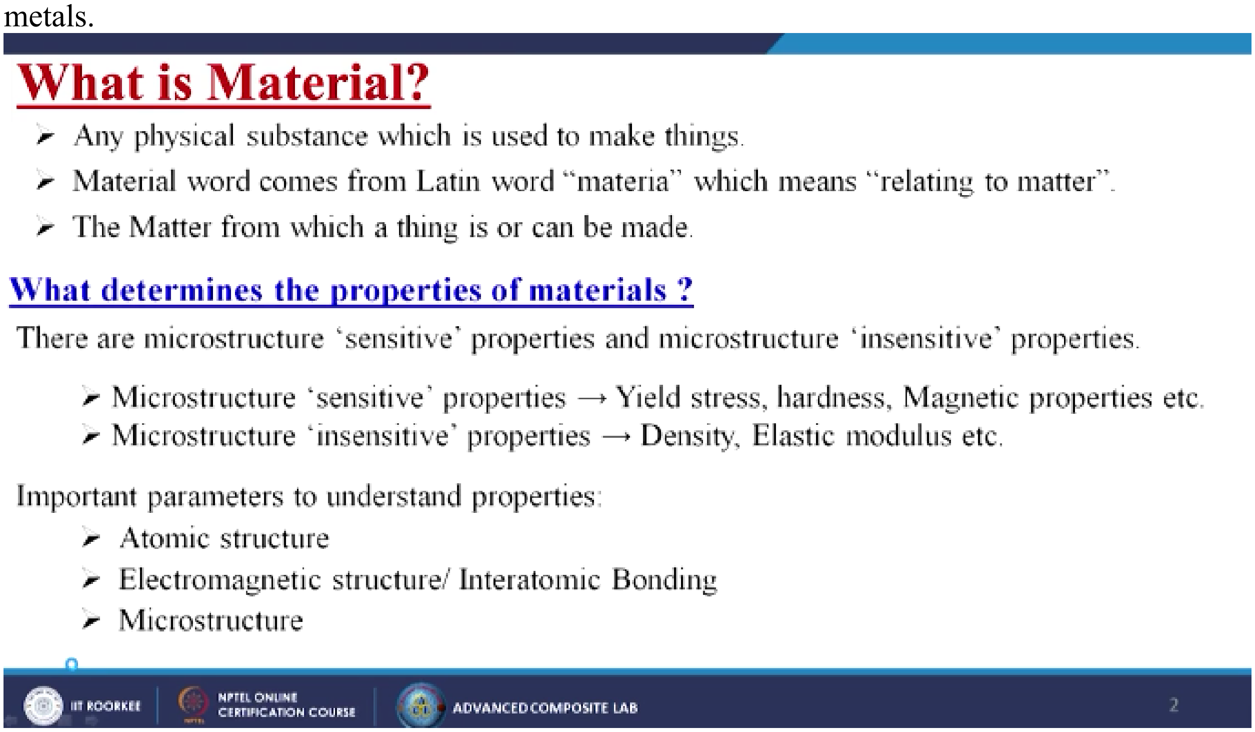
Basic Properties: Metals

With

Dr. Kaushik Pal
Department of Mechanical & Industrial Engineering
Indian Institute of Technology Roorkee

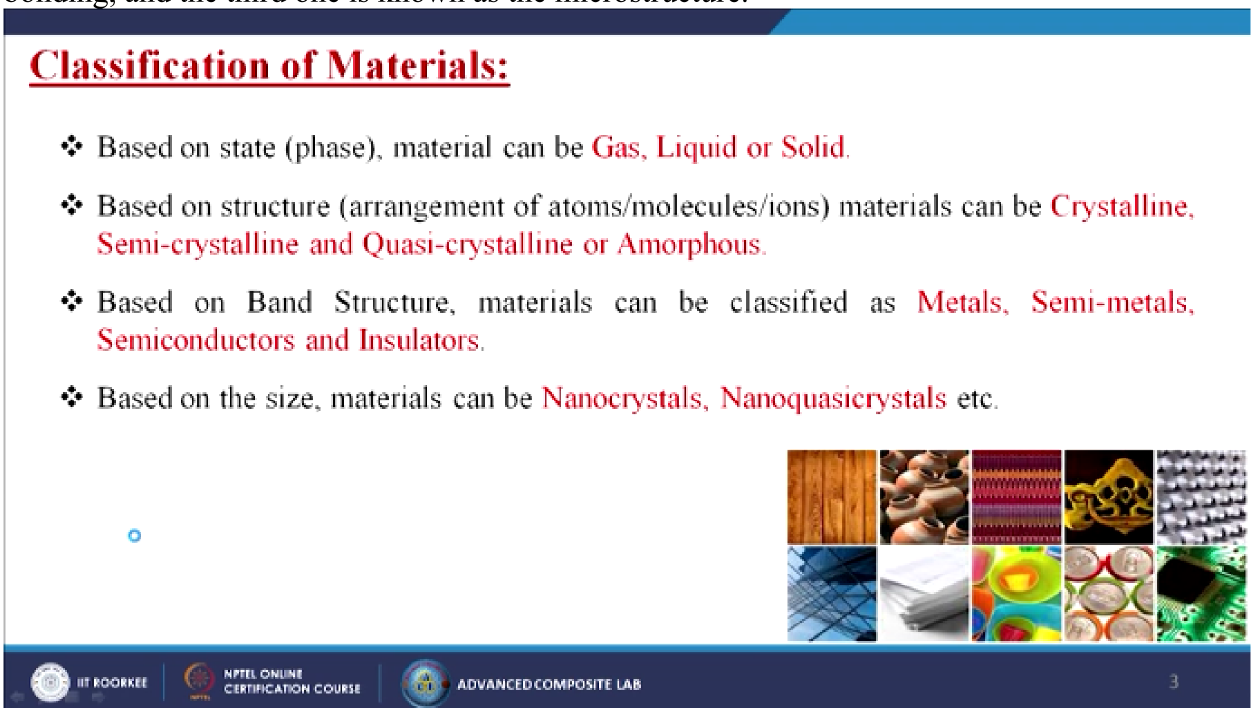


Hello, in our previous lectures we have discussed about the crystal structures and interatomic bonding of materials. So in this particular chapter we'll discuss about the basic properties of metals.

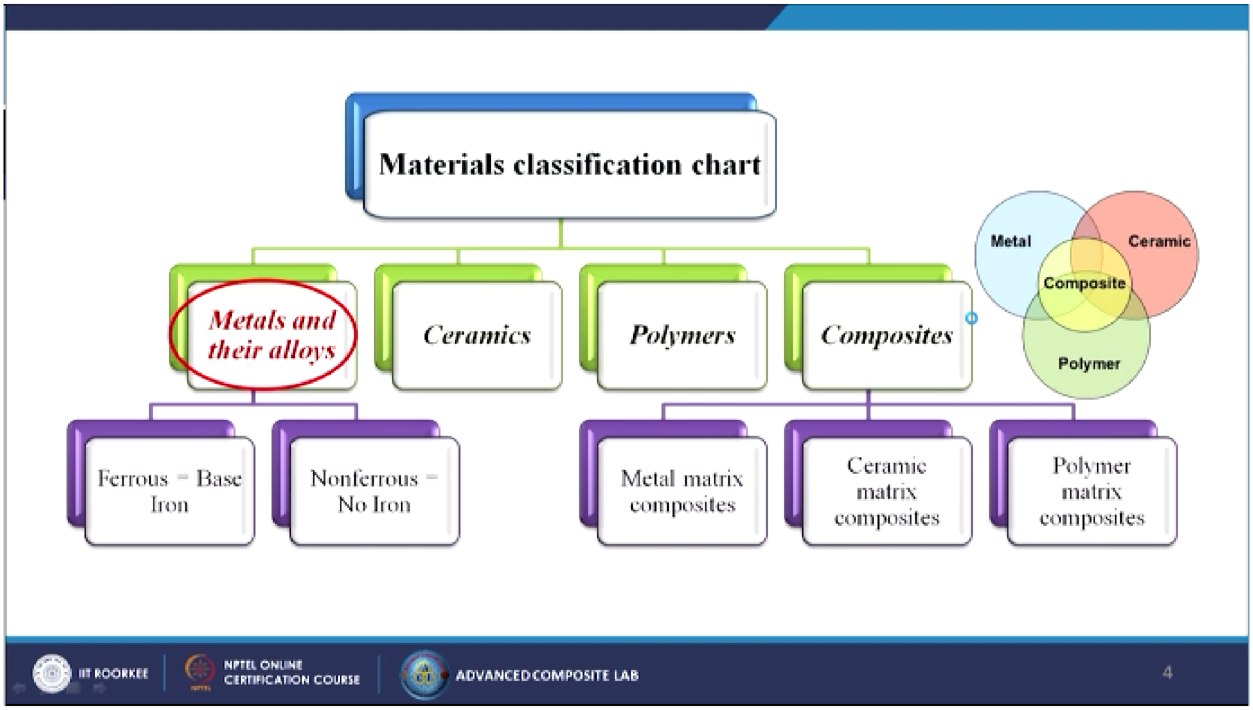


So before going to start about the metals, first let us know what is materials? So materials means it's any physical substance which is used to make things, material word come from actually it's a Latin word, means materia which means the relating to matter, the matter from which a thing is or can be made, so that means from materials we can make something, some product.

What determines the properties of materials? So there are, actually on the basis of microstructure there are two properties one is called the sensitive properties, another one is called the microstructure insensitive properties. When we are talking about the microstructures sensitive properties it is known as the yield stress, hardness, and the magnetic properties. And when we are talking about the microstructure insensitive properties that means density elastic modulus which we cannot directly get from that particular materials, but we can calculate by some other input parameters. Important parameters to understand the properties, first one is known as the atomic structure, second one is known as the electromagnetic structure or maybe the interatomic bonding, and the third one is known as the microstructure.

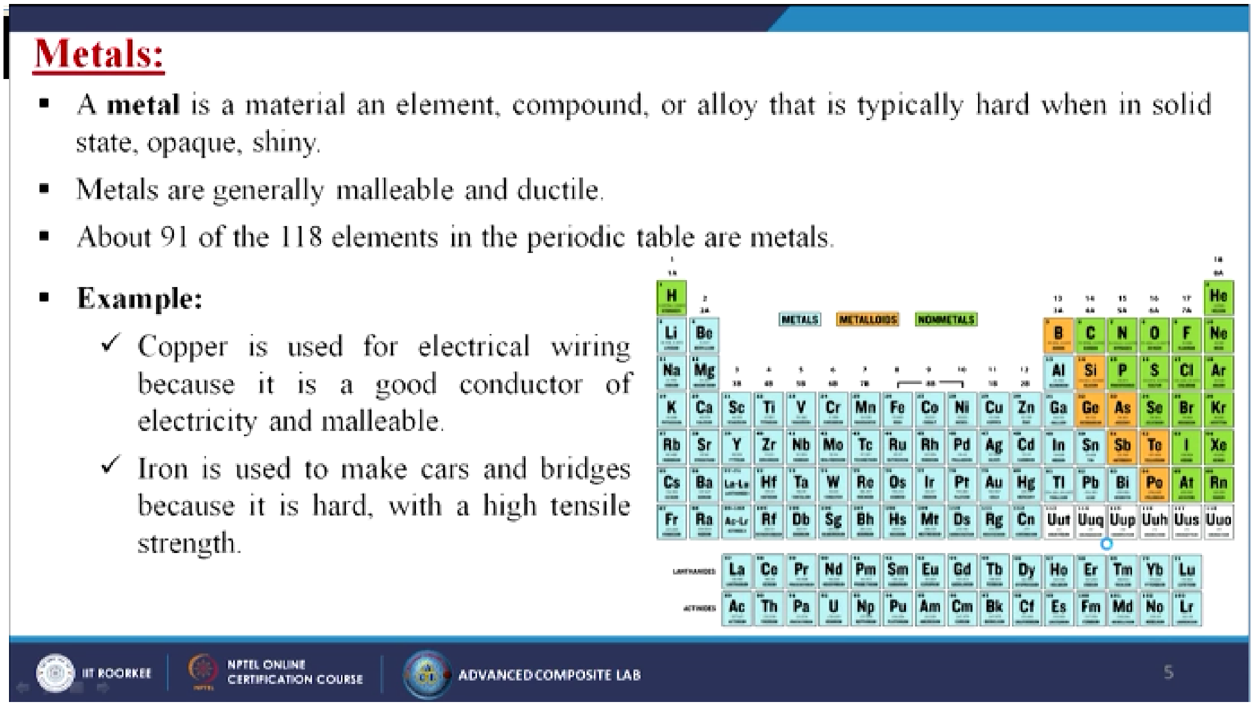


Now we'll discuss about the classification of materials, so classification of materials if we do it by based on state or maybe the phase, the material can be gas, liquid, or maybe the solid, based on structure, structure means arrangement of atoms or maybe the molecules or maybe the ions, materials can be crystalline, semi-crystalline, quasi-crystalline or amorphous, based on band structure materials can be classified as metals, semi-metals, semi-conductors and the insulators.

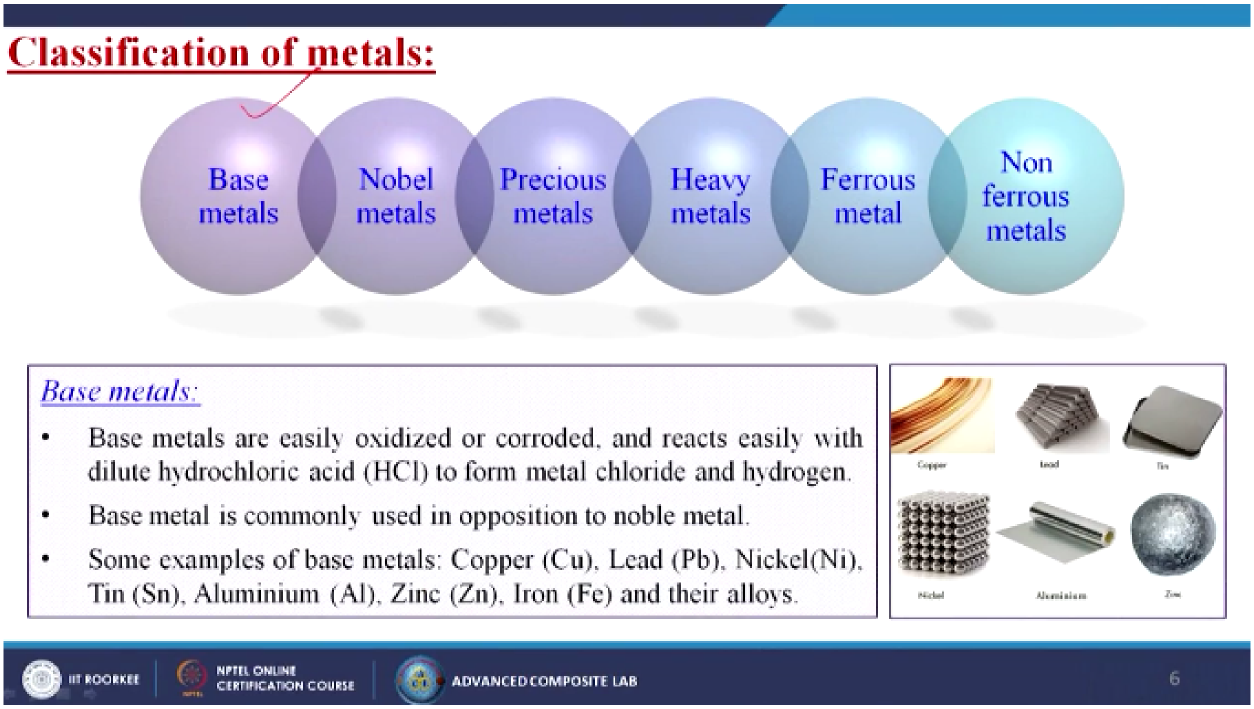


Today we are going to discuss about the metals. Based on the size, materials can be nanocrystals, and nanoquasicrystals, so here just it is a brief one about the materials classification chart, so first if we divide the materials, generally it is divided into four parts, one is called the metals and their alloys, then ceramics, then polymers, and another one is called the composites, I'll discuss about the composites in later, so when we are talking about the metals and their alloys generally this is two types, one is called the ferrous, generally ferrous means where the iron presents are there, and another one is called the nonferrous means there is no iron.

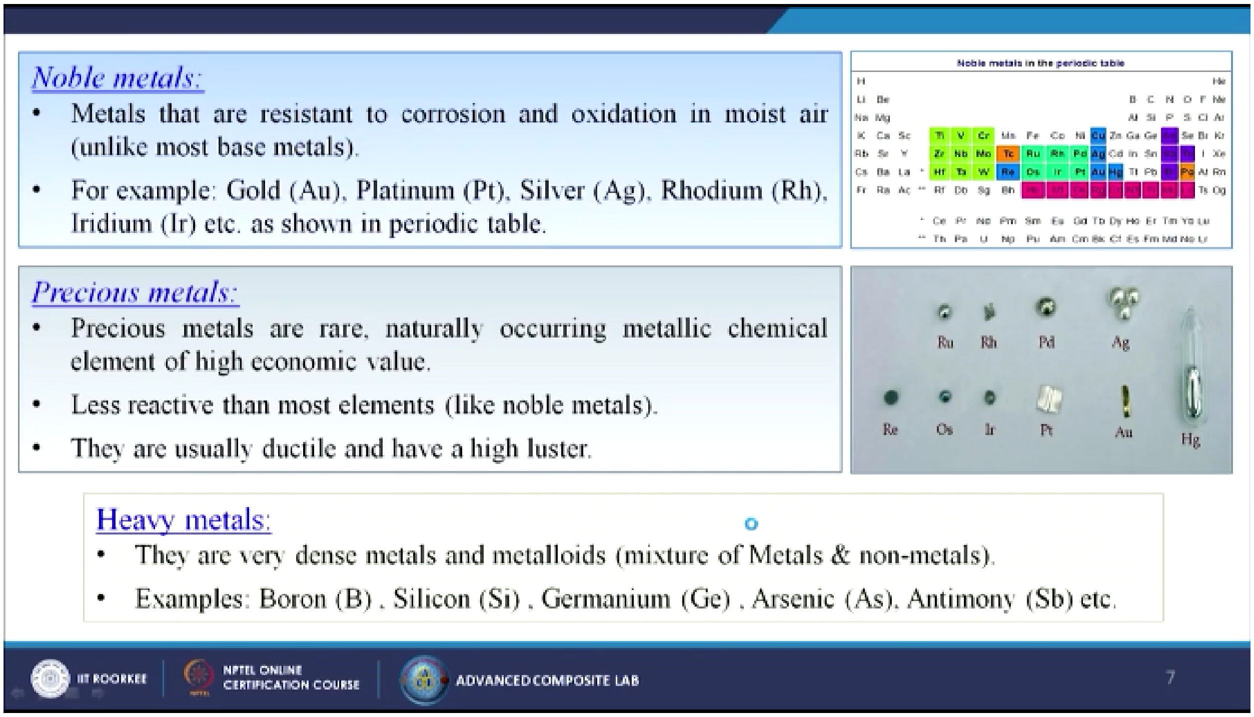
When you are talking about the composites, so composites it's a combinations of either maybe metals or maybe the ceramics, or maybe the polymers, so composites it's actually, it's a mixture of either metals or maybe the ceramics, or maybe the ceramics or maybe the polymer, or maybe the metal or/and polymer. So when you are talking about the composites, composites is also divided into three parts, one is called the metal matrix composites, then ceramic matrix composites, and the polymer matrix composites.



So now we will briefly discuss about the metals, so what is metal? A metal is a material and element, compound or alloy that is typically hard when in solid state, opaque and shiny, metals are generally malleable and ductile, I'll discuss about what is, what is malleable. About 91 of the 118 elements in the periodic table are metals, so if you carefully see the periodic table of materials, so you can find that blue in colour all are generally telling about the metals, so there are total 91 elements which is talking about the metals, what is the example? So copper, copper is used for the electrical wiring, because it is very good conductor of electricity and malleable. Iron is used to make cars, bridges, generally you can understand or maybe you know that generally iron we are using for the structural applications, so because it is too hard with the high tensile strength.



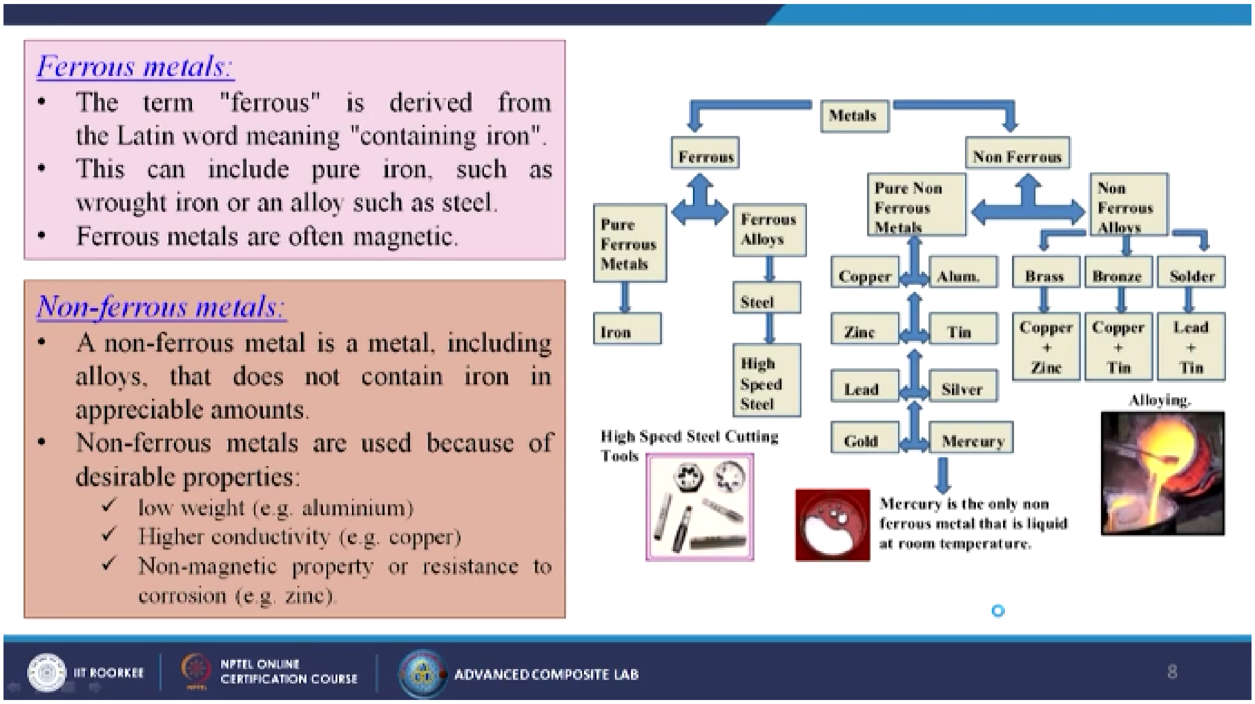
Now we'll go into the deeper of classifications of the metals, so if we divide the metal into different sections, so first one is known as the base metals, then noble metals, then precious metals, heavy metals, ferrous metal and the nonferrous metals, so what is base metal? Base metal are easily oxidized or corroded and reacts easily with dilute hydrochloric acid to form the metal chloride and hydrogen, so generally the base metal it can react with some other acids or maybe the base, base metal is commonly used in opposition to noble metal, what is noble metal? I'll come into the subsequence slide some examples of the base metals are copper, lead, nickel, tin, aluminum, zinc, iron and their alloys, so right side this image is generally giving the pictorial view of different types of base metals.



Now we'll discuss about the noble metals, so metals that are resistant to corrosions and oxidation in moist air unlike most base metals, so that is the beauty of that noble metals, they generally don't react with the air or maybe the environmental moisture, for example gold, platinum, silver, rhodium, iridium etcetera are shown in periodic table, so from this periodic table you can see that this metals are known as the noble metals.

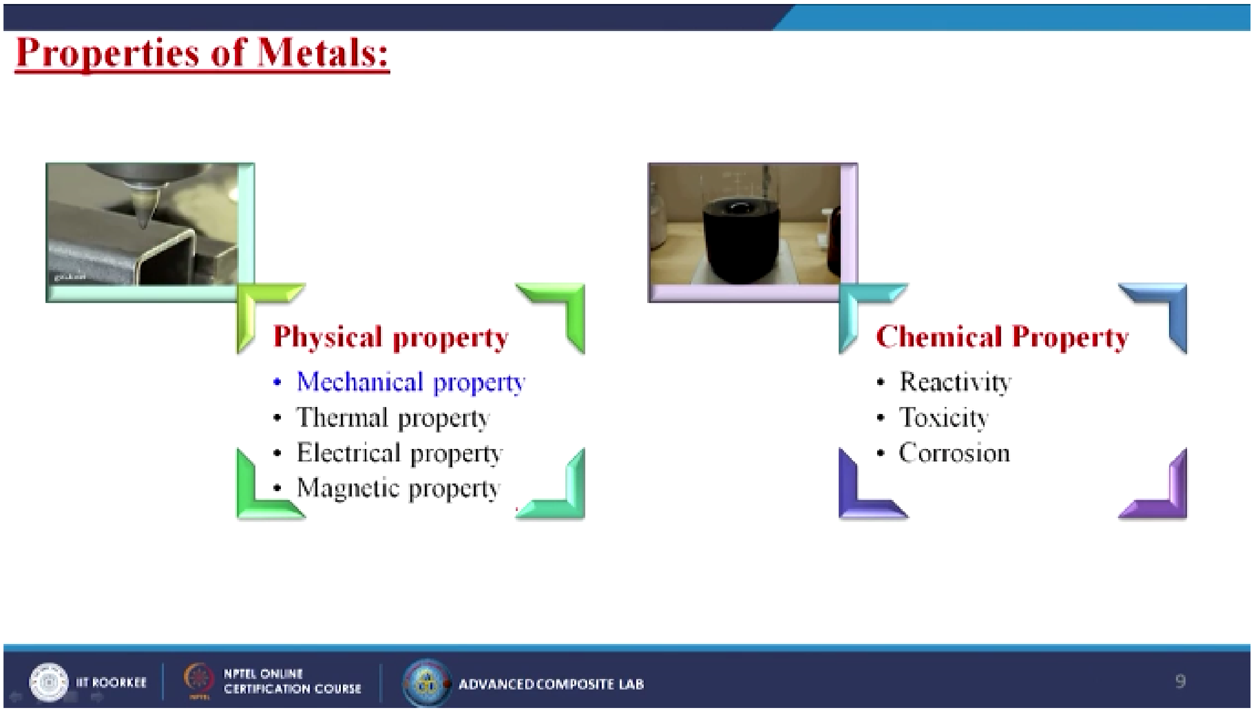
Now there is some precious metals, precious metals from the name itself you can understand that, that is not easily available, so precious metals are rear, naturally or correct metallic chemical element of high economic value, because of course it is very, very expensive, less reactive than most elements like noble metals, they are usually ductile and have a high luster means the shininess of that material, a metals are very, very good.

Now we will discuss about the heavy metals, they are very dense metals and metalloids, metalloids is nothing but the mixture of metals and the non-metals, examples boron, silicon, germanium, arsenic, antimony etcetera.

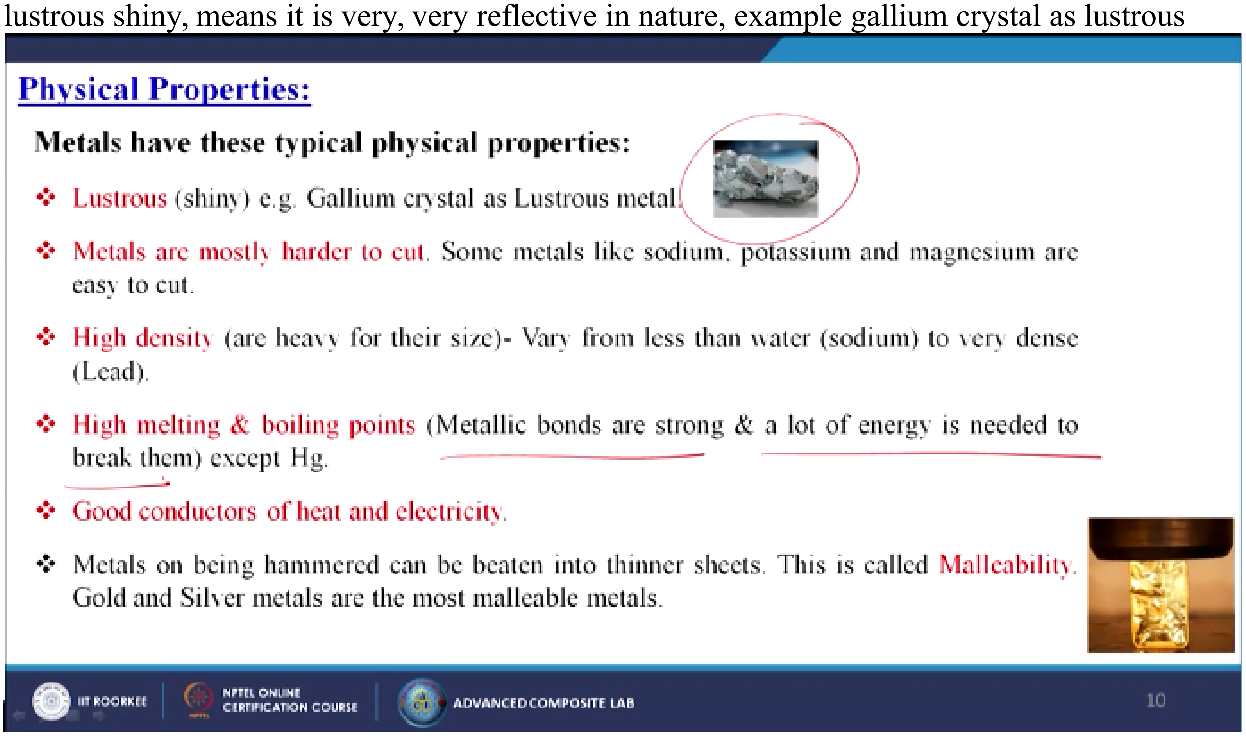


Now we'll discuss about the ferrous metals, as I already told ferrous metals means the iron content is there, so the term ferrous is derived from the Latin word meaning containing iron, this can include pure iron such as wrought iron or an alloy such as steel, because steel the iron percentage is more. Ferrous metals are often magnetic in nature, in nonferrous metal is a metal including alloys that does not contain iron in appreciable amounts, we are not telling that iron will be not present over there, maybe a near amount of iron maybe present but that is in very, very negligible.

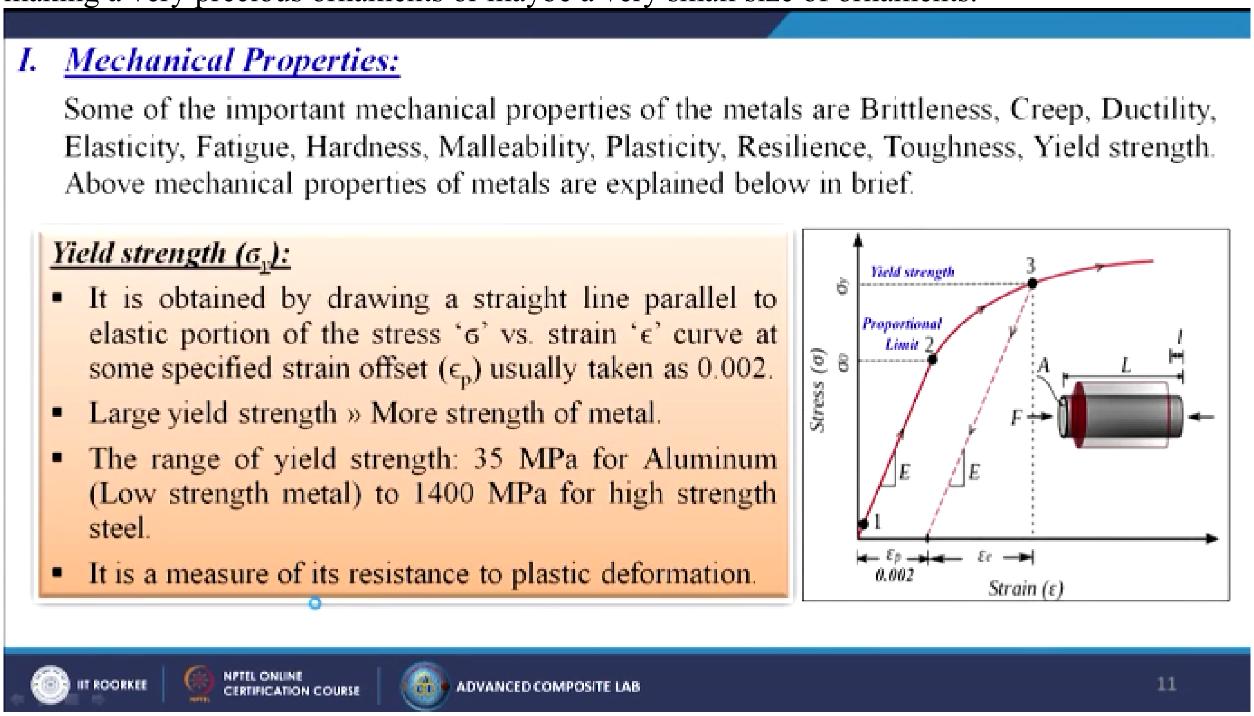
Nonferrous metals are used because of desirable properties like low weight, like aluminum, so that's why we are using the aluminum for the aerospace applications, higher conductivity copper that's why we are making any kind of electrical wiring or maybe the wire by this copper. Then next one is called the nonmagnetic property or resistance to the corrosion, zinc, so that's why we are doing the zinc plating so that, that material can, the service life of that material can increase.



Properties of metals, so in this particular lecture we'll discuss about the physical properties of this materials, so first we will discuss about the mechanical property, then thermal property, electrical property and magnetic property, and if we talk about the chemical property, chemical property depends upon reactivity, toxicity, and the corrosion. So first we will discuss about the physical properties of metals, so metals have this typical, physical properties, first is called the lustrous shiny, means it is very, very reflective in nature, example gallium crystal as lustrous



metal you can see this image, metals are mostly harder to cut because there strength is too high, some metals like sodium, potassium, and magnesium are easy to cut, yes of course there is some limitation also, high density are heavy for their size vary from less than water, like sodium to very dense like lead, high melting and boiling points, metallic bonds are strong and a lot of energy is needed to break them except the mercury. Good conductors of heat and electricity already I have discussed, metals on being hammered can be beaten into thinner sheets, this is called the malleability, this is a one good properties of the metals, so this is known as the malleability, gold and silver metals are the most malleable metals, that's why we are using it for making a very precious ornaments or maybe a very small size of ornaments.



Now we will discuss about the mechanical properties, so when we are discussing about the mechanical properties there are so many small half properties may come and all together is known as the mechanical properties, so some of the important mechanical properties of the metals are brittleness, creep, ductility, elasticity, fatigue, hardness, malleability, plasticity, resilience, and toughness, yield strength, so these all combinations is known as the mechanical properties of the metals. So above mechanical properties we will discuss in one by one.

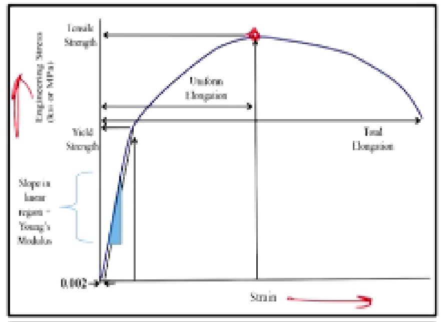
So first we will discuss about the yield strength of the metals, it is obtained by drawing a straight line parallel to elastic portions of the stress sigma versus strength epsilon curve at some specified strength offset epsilon P usually taking as 0.002, so from this particular graph if you can see that X axis is denoting the strength, and Y axis is denoting the stress and we are getting a stress strain curve of the metals, and just from that particular 0 0 or maybe the intersect if we give the space of 0.002 and then we are just drawing a parallel, just along with this one and then this line is touching the stress strain curve at this particular point, and that is known as the yield strength of particular metals. Large yield strength means more strength of metal. The range of yield strength it's an example, so generally 35 megapascal for aluminum, low strength metal to 1400 megapascal for high strength steel, it is a measure of its resistance to plastic deformation.

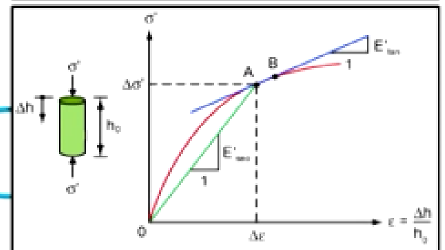
Tensile strength (σ_{TS}):

- It is the stress at the maximum on engineering stress-strain curve.
- The range of Tensile strength: 50 MPa for Aluminum (Low strength metal) to 3000 MPa for high strength steel.
- At σ_{TS} a small neck begins to form at some point. After this, the deformation is confined at this neck. This phenomenon is called necking. Fracture ultimately occurs at neck.

Typical stress-strain behavior in metals:

- Linear elastic behavior in Stress-strain curve obeys Hooke's law.
- In some metals (e.g. gray cast iron), stress-strain curve is non-linear. In this case, we define tangent (E_{tan}) or secant (E_{sec}) modulus of elasticity.
- Temperature 'T' dependence of Elastic modulus 'E' of metals: E↑ as T↓.





Stress-strain diagram showing non-linear elastic behavior

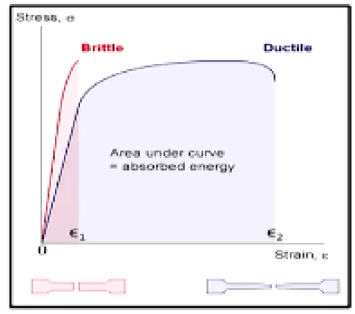
Now we'll move to tensile strength, so what do you mean by tensile strength, so it is the stress at the maximum on engineering stress strain curve, so if you see this particular figure same, the strain is denoting into the X axis and the elastic engineering stress is denoting the Y axis, and if you plot the stress strain curve, so as per the definitions so it is the maximum value on engineering stress strain curve is known as the tensile strength of that particular metals, so the range of tensile strength generally 50 megapascal for aluminum, low strength metal to 3000 megapascal for high strength steel.

At sigma TS a small neck begins to form at some point after this the deformation is confined at this neck, this phenomenon is called the necking, so when we are trying to stress the materials after certain time its diameter is going to be decreased so that is known as actually the necking, fracture ultimately occurs at neck, because it's totally depends upon the elastic properties, so after certain time when that neck is going to be bigger and bigger and then after that the material will fell at that particular point. Typical stress strain behavior in metals so linear elastic behavior in stress strain curve obeys the Hooke's law because it is normal that, generally all the metals generally follows the Hooke's law, in some metals like gray cast iron, stress strain curve is nonlinear, in this case we define the tangent or secant so if you see this picture so first we are getting that E prime tan and E prime secant, so generally we define it as a tangent or secant, modulus of elasticity, so if the temperature dependence on elastic modulus of metals if elastic modulus will increase so automatically the temperature is going down, in opposite word if I can say that if we increase the temperature of any metals, so automatically the elasticity of the metals is going down.

Ductility:

- It is the measure of the degree of plastic deformation upto fracture.
- A material that has a very little or no plastic deformation upon fracture is called brittle.
- The tensile stress-strain behaviors for both ductile and brittle materials.

$$\int_0^{\epsilon_2} \sigma \, d\epsilon >> \int_0^{\epsilon_1} \sigma \, d\epsilon$$



- The quantitative measure of ductility are:

    i. % Elongation $(\% EL) = \frac{(l_f - l_o)}{l_o}$ X **100**

    where; l_o = Original gauge length, l_f = Fracture Length (Total Length after fracture)

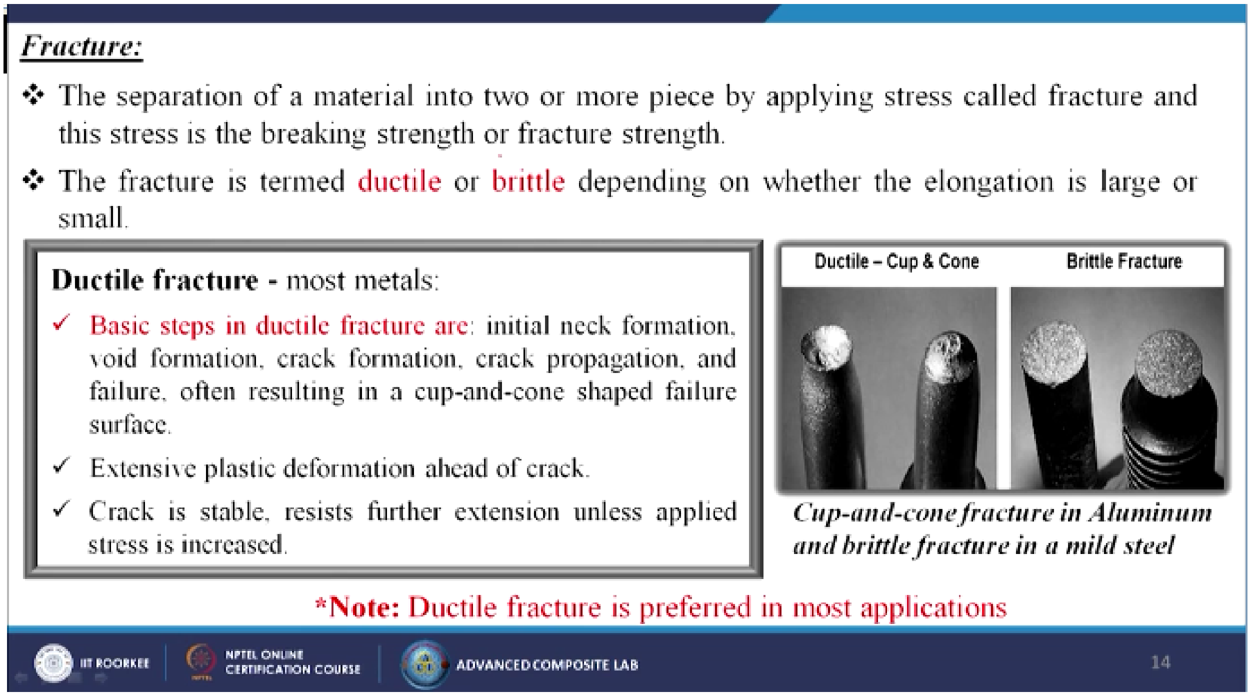
    ii. % Reduction in area **(% RA)** = $\frac{(A_o - A_f)}{A_o}$ **X 100**

    where; A_o = Original cross-sectional area, A_f = Cross-sectional area at the point of fracture

IIT ROORKEE | NPTEL ONLINE CERTIFICATION COURSE | ADVANCED COMPOSITE LAB

Now we will discuss about the ductility, so ductility it is the major of the degree of plastic deformations up to fracture, material that has a very little or no plastic deformation upon fracture is called the brittle, so generally the ductility means when we are trying to stretch that materials the material is stretching, if the material is stretching up to certain point we can say that the ductility of the material is very good, but if we are going to stretch that materials and at the time of stretching, initial stretching if the material will break generally we are calling it as a brittle material, so the tensile stress strain behavior for both ductile and brittle materials is integration 0 to epsilon to sigma DE always greater than integrations 0 to epsilon 1 sigma DE, so in this particular graphic you can see that the epsilon 1 is denoting the brittle materials and epsilon 2 is denoting the ductile materials, the quantitative measure of ductility are percentage elongations, generally we are defining as a percent EL = LF – L0/L0 x 100, so where L0 is the original gauge length LF is the fracture length, total length after the fracture, so in this particular graph we can see that at epsilon 2 the, after that the material has failed.

Now we will discuss about the percentage reduction in area, generally we are denoting it by the percentage RA = A0 – AF/A0 x 100, so where A0 is the original cross sectional area, AF is the cross sectional area at the point of fracture, so of course at the time of point of fracture your cross sectional area is going to be narrow down which is nothing but known as the necking.



Now we will discuss about the fracture, so the separation of a material into two or more pieces by applying stress called the fracture, and this stress is the breaking strength or maybe known as the fracture strength, the fracture is termed ductile or brittle, depending on whether the elongation is large or small, as I already discussed.

Now we will talk about the ductile fracture, generally we pray for the ductile fracture for the most metals, basic steps in ductile fracture are initial neck formations, void formations, crack formations, crack propagations and failure often resulting in a cup and cone shaped failure surface, so in this particular figure you can see that cup and cone structure has been formed, so from this particular picture we can assume that this material is ductile in nature, extensive plastic deformation ahead of crack, crack is stable resist further extension unless applied stress is increased.

Note ductile fracture is preferred in the most applications as I already discussed, but when you are talking about the brittle fracture you find that it’s a simple types of cracking, there will not be, there is no formations of any cup and cone shape, so simple the material will break at certain point.

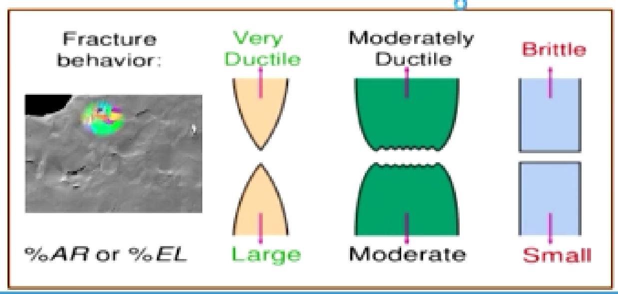
Brittle fracture- ceramics, ice, cold metals:

- ✓ Relatively little plastic deformation.
- ✓ Crack is unstable, propagates rapidly without increase in applied stress.

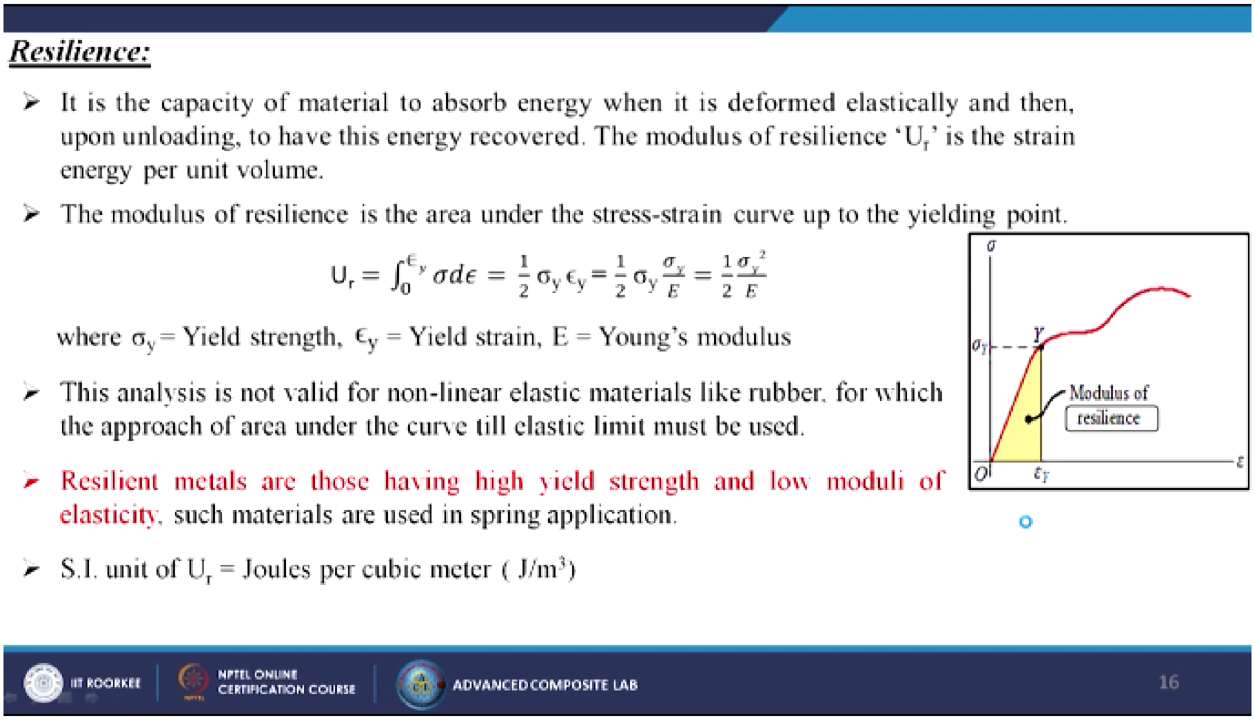
Example: Pipe failures

- Ductile: one piece and large deformation.
- Brittle: many pieces and small deformations.

Ductile fracture | Brittle fracture



Now we will discuss about the brittle fracture, already I have given you the examples in the last slide but what does it mean? Brittle fracture ceramics, ice, cold metals, relatively little plastic deformations, cracks is unstable propagates rapidly without increase in applied stress, examples we are giving the pipe failures, generally most of the pipes generally we are making it by the cast iron, so ductile 1 piece and large deformations, brittle many pieces and the small deformations, so if the material or maybe the pipe is made by any ductile materials, so you can find that there a crack formations has been taken place, but if it has been made by some kind of brittle materials, so after fracture you can find that has been broken into very small, small, small, small parts. Here when you are talking about the fracture behavior so you can find that there are different types of fracture is taking place, so area reductions, and elongation break is taking place, so if it is very ductile you can find a very sharp cup and cone type of structure over there, if it is moderately ductile you can find a very less area of cup and cone as structure, but if it is brittle you can find that there is a sharp break of that particular metals.



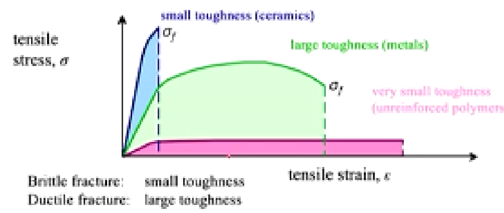
Now we are talking about the resilience, so resilience it is the capacity of material to absorb energy when it is deformed elastically and then upon unloading to have this energy recovered, the modulus of resilience generally denoted by capital U, subscript Ur is the strain energy per unit volume, the modulus of resilience in the area under the stress strain curve up to the yielding point, so in this particular graph you can see the yielding point is here at Y, so Ur = integration 0 to epsilon Y, sigma D epsilon = 1/2 sigma Y epsilon Y = 1/2 sigma Y/E = 1/2 sigma Y square/E, so here the sigma Y is the yield strength, epsilon Y is the yield strength and E is nothing but the Young modulus, this analysis is not valid for nonlinear elastic materials like rubber, because rubber is a amorphous materials for which the approach of area under the curve till elastic limit must be used, resilient metals are those having high yield strength and low moduli of elasticity, such materials are used in spring applications, because they are having some damping factor, so SI unit of the resilience is joule per cubic meter.

Toughness:

- It is a measure of the ability of a material to absorb energy up to fracture.
- It is the area under σ - ϵ curve up to fracture.

$$\int_0^{\epsilon_f} \sigma d\epsilon, \text{ where } \epsilon_f \text{ is the true strain at fracture.}$$

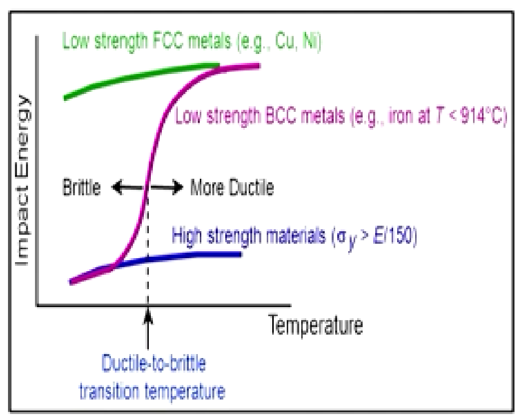
- For a material to be tough. It must have
  i. High Yield strength (σ_y)
  ii. High ductility (% Elongation must be large)
  iii. High Tensile strength (σ_{TS}).
- Even though brittle material has higher yield & tensile strength, it has lower toughness than the ductile one by virtue of lack of ductility.



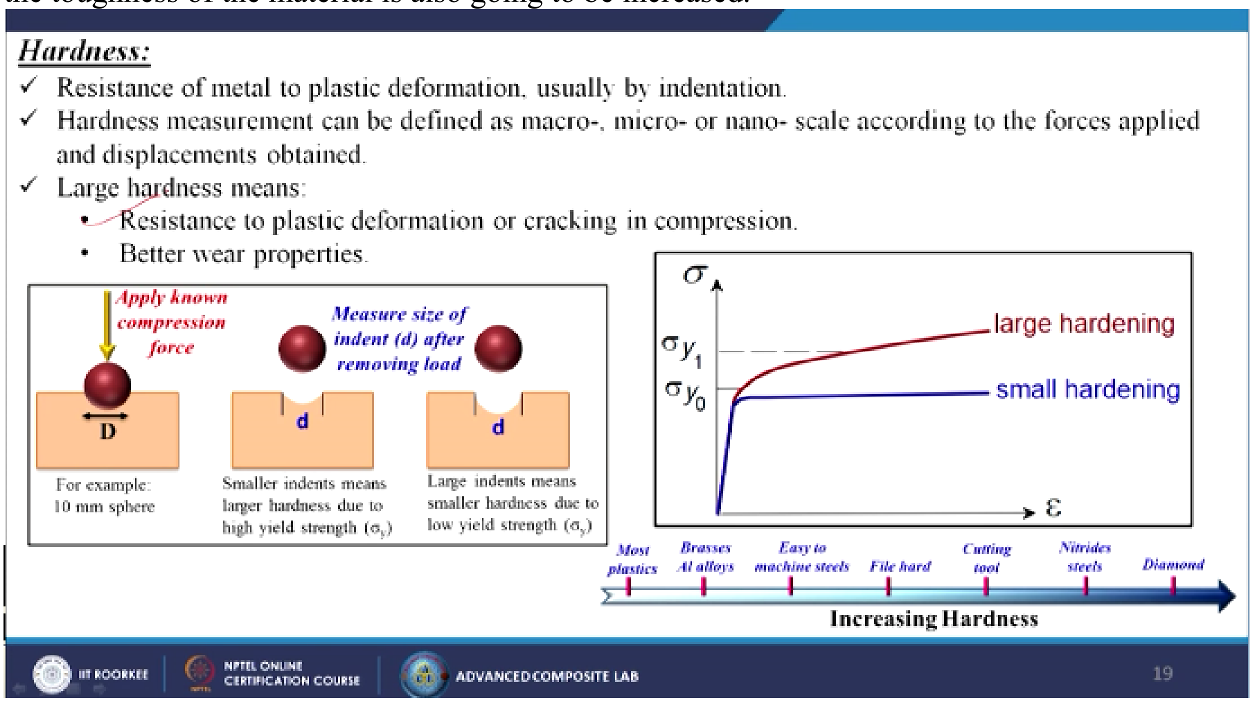
Now we will discuss about the toughness, so it is a measure of the ability of a material to absorb energy up to fracture, it is the area under sigma to epsilon curve up to fracture, so generally we are talking about the area. Now it is a formula is integrations 0 to epsilon F, sigma D epsilon where epsilon if is the true strain at fracture, for a material to be tough it must have high yield strength, high ductility percentage elongation must be very very large, high tensile strength even though brittle materials has higher yield and tensile strength it has lower toughness than the ductile, one by virtue of lack of ductility.

Effect of temperature on toughness:

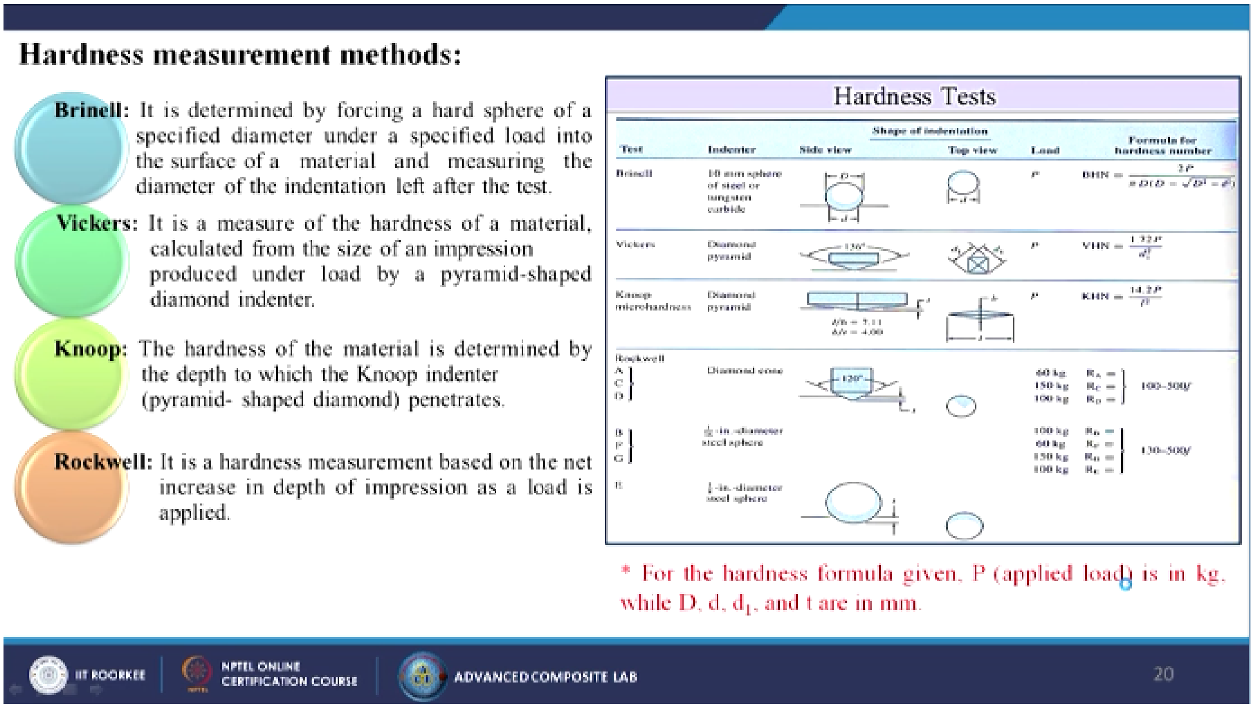
- ✓ As Temperature increases, the toughness of a metal increases.
- ✓ At low temperatures the materials is more brittle and toughness is low.
- ✓ At high temperatures the material is more ductile and toughness is higher.
- ✓ Transition temperature is the boundary between brittle and ductile behavior and this temperature is often an extremely important consideration in the selection of materials.



Now we will discuss about the effect of temperature on toughness, as temperature increases the toughness of a metal increases, at low temperatures the material is more brittle and toughness is low, at high temperatures the material is more ductile and toughness is higher, transition temperature is the boundary between the brittle and ductile behavior and this temperature is often an extremely important considerations in the selection of materials, in the right hand side if you see this particular graph you can find that X axis is denoting the temperature, Y axis is denoting the impact energy, and if we are talking about any materials, so say suppose at normal temperature the material is showing the brittleness, but when we are increasing the temperature, so automatically it is crossing the transient line or maybe the transit temperature and it is going into the ductile side, so in this particular case we are rising the temperature up to 940 degree centigrade, so when we are rising the temperature from room temperature to more than 900 degree centigrade so automatically the material is converting from brittle to ductile in nature, and the toughness of the material is also going to be increased.



Now we will discuss about the hardness of the metals, so resistance of metal to plastic deformations usually by the indentation, indentation is nothing but a it is a one kind of method or maybe it's a one kind of things by which we are making any indent on to the metal itself, hardness measurement can be defined as macro, micro or nano-scale according to the forces applied and displacements obtained. Large hardness means resistance to plastic deformation or cracking in compression, better wear properties, so for this particular image if you see that we are having a metals and then we are putting a compressive force by a ball having 10 millimeter diameter it's a sphere in shape and we are giving a just impact or indent onto the metal itself. Then smaller indent means larger hardness due to the high yield strength because it is not allowing that ball to go inside, and if there is some larger indents that means smaller hardness due to the low yield strength, the same thing has been proven over here also, so when you are talking about the large hardening so automatically the hardness of that particular material is going to be increased, and then small hardening means the hardness of that particular material is going to be decreased, if you see the material wise hardness so first the plastics is the lesser hardness as well as the diamond is the most harder materials in the material series, so it's followed like plastics, then brasses, aluminum alloys easy to machine steels, file hard, cutting tool, nitrate steels, and the last one is the diamond which is the most harder one.

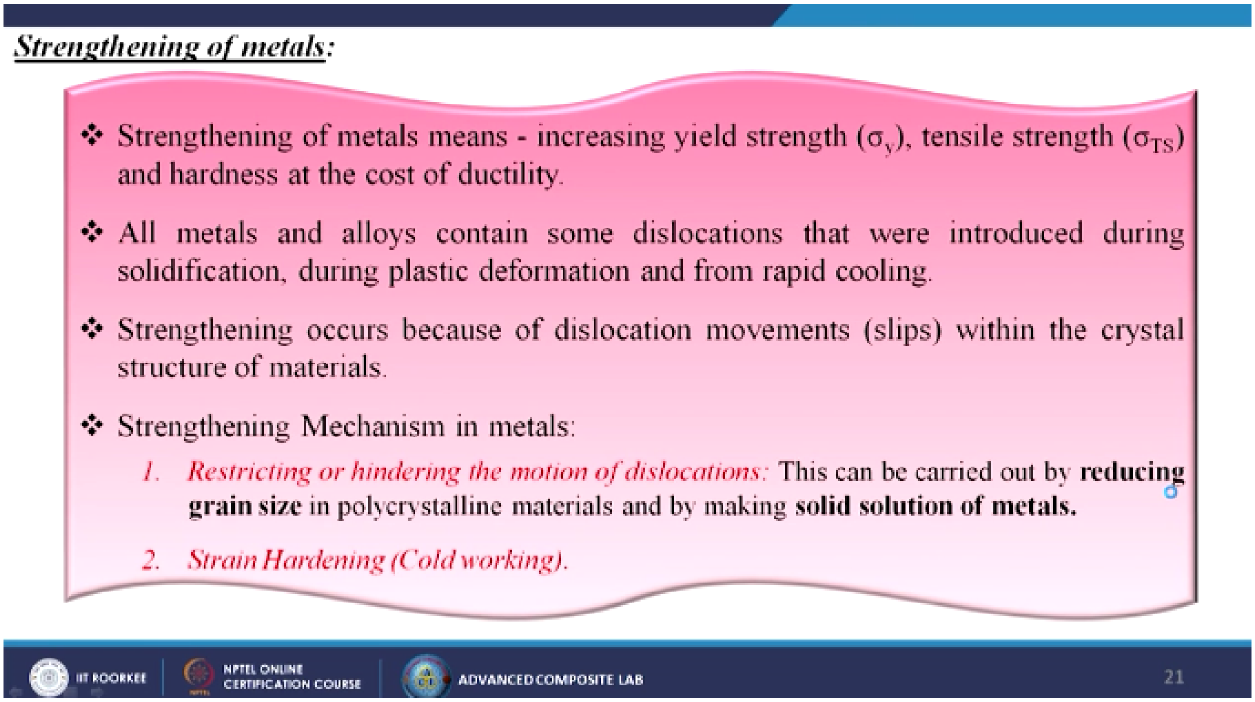


Now we will discuss techniques about the hardness measurement, there are four types of techniques generally we are using to measure the hardness of any kind of metals, first one is known as the Brinell, followed by Vickers, Knoop, Rockwell, so Brinell it is determined by forcing a hard sphere of a specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation left after the test, so in this particular case generally we are using a round shape ball and we are following that ball from a particular height and after that just we are checking that how much depth, how much depth it has gone inside the material.

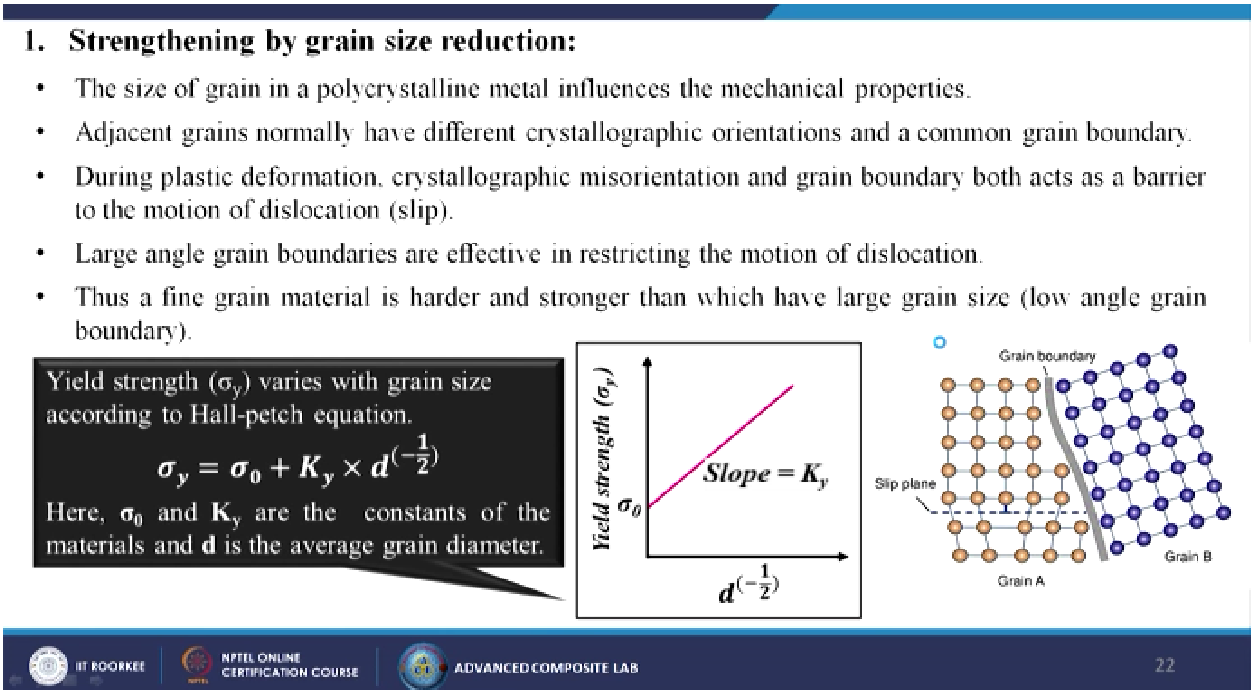
Vickers, it is the measure of the hardness of a material calculated from the size of an impression produced under load by a pyramid shaped diamond indenter, in this particular case we are using one pyramid shaped diamond indenter.

Knoop, the hardness of the material is determined by the depth to which the Knoop indenter pyramid shaped diamond penetrates, so in this particular case we are going to do by the diamond pyramid shaped.

And the last one is known as the Rockwell, so it is a hardness measurement based on the net increase in depth of impression as a load is applied, so for the hardness formula given P is the applied load over here is in KG, while capital DD, small d1 and t are all in the millimeter, so by getting this value, by putting those value in this particular equations you can easily calculate what is the hardness value of different metals.

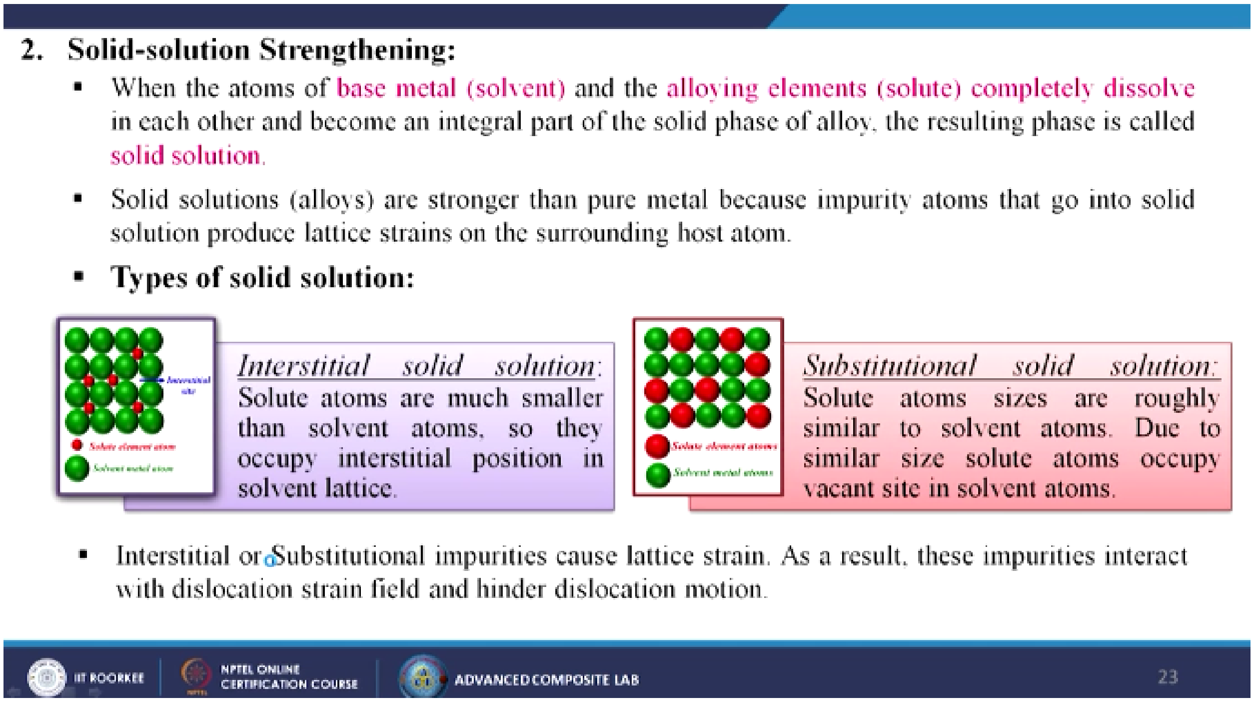


Strengthening of metals, that is also an important parameters, so strengthening of metals means increasing the yield strength, tensile strength and hardness at the cost of the ductility, of course when we are going to increase the strength so automatically the ductility of that metal is going to be decreased, all metals and alloys contains some dislocation that where introduced during solidification, during plastic deformation, and from rapid cooling, strengthening occurs because of dislocation movements like slips within the crystal structure of materials, strengthening mechanism in metals, first restricting or hindering the motion of dislocations, this can be carried out by reducing grain size in polycrystalline materials and by making solid solution of metals, and the second one is that strain hardening which is nothing but known as the cold working process.

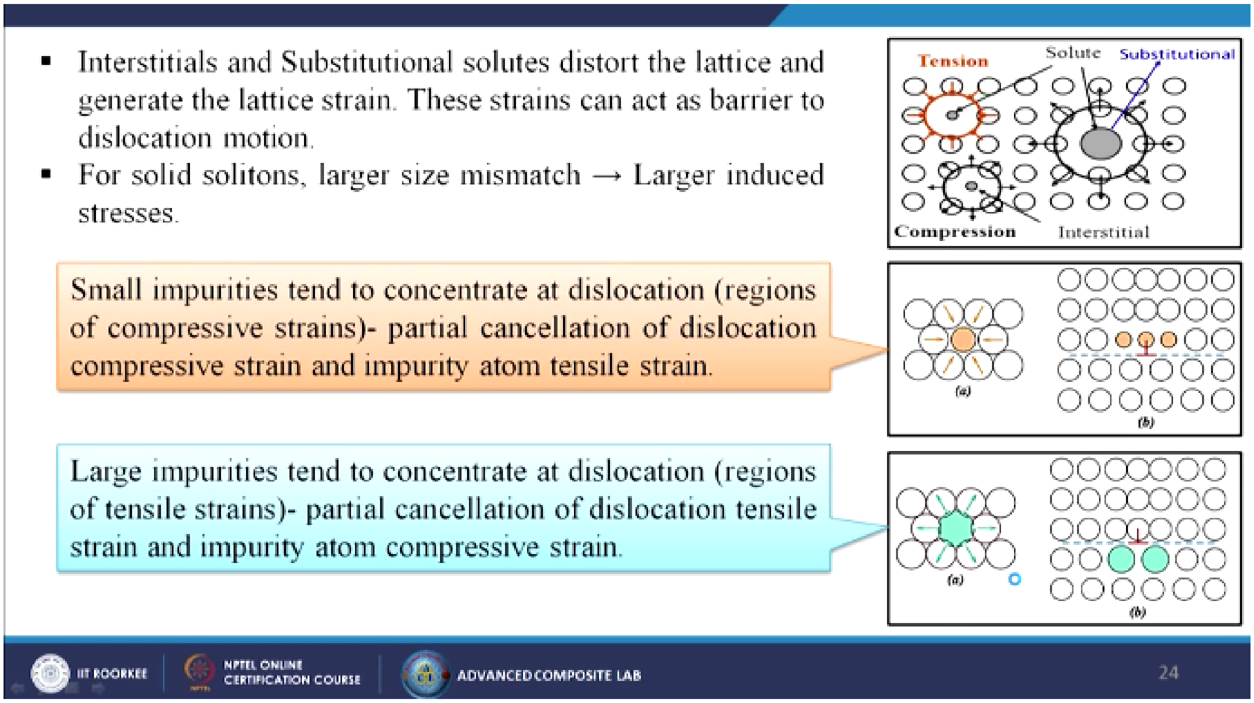


So first we will discuss about the strengthening by grain size reduction, so the size of grain in a polycrystalline metal influences the mechanical properties, adjacent grains normally have different crystallographic orientation and a common grain boundary, so from this particular image you can find that there are two different grain structure and this is known as the grain boundary.

During plastic deformation, crystallographic misorientation and grain boundary both acts as a barrier to the motion of dislocations or maybe the slips, so this is known as the slip plane over there. Large angle grain boundaries are effective in restricting the motion of dislocation, thus a fine grain material is harder and stronger than which have large grain size, low angle grain boundary, so yield strength generally sigma Y varies with grain size according to the Hall-petch equation, sigma Y = sigma 0 + KY x D to the power -1/2, where sigma 0 and KY are the constants of the material and D is the average grain diameter.

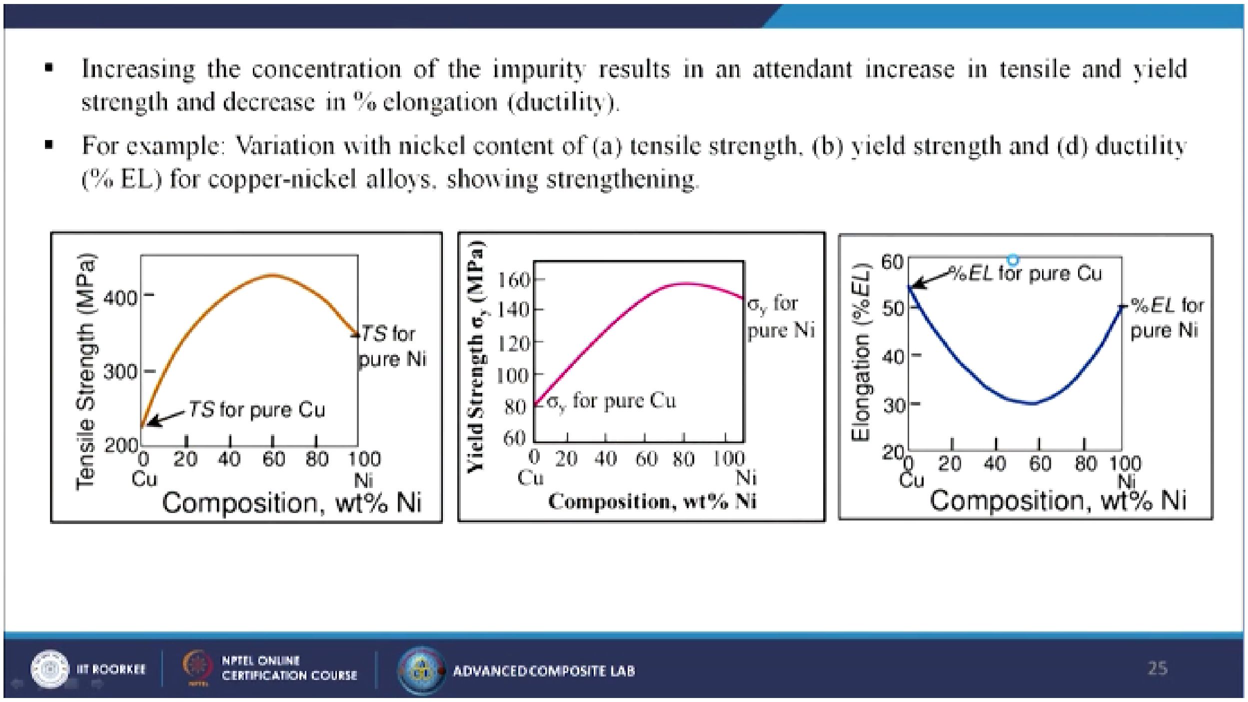


Now we will discuss about the solid solution strengthening, so when the atoms of base metals like solvent and the alloying elements like solute completely dissolve in each other and become an integral part of the solid phase of alloy, the resulting phase is called the solid solution. Solid solutions generally, it's a alloy, because it's a mixing of two different materials are stronger than pure metal because impurity atoms that go into solid solution produce the lattice strains on the surrounding host atom, so there are two types of solid solutions, first one is called the interstitial solid solutions, second one is called the substitutional solid solutions, when you are talking about the interstitial solid solutions, solid atoms are much smaller than solvent atoms, so they occupy the interstitial position in solvent lattice, so from this particular case you can find that this is known as the interstitial site where the solute atoms is going and staying over there, and when you are talking about the substitutional solute solutions, solute atom sizes are roughly similar to solvent atoms, due to similar size solute atoms occupy the vacant site in the solvent atoms, so simple this site was initially vacant and that place has been taken care by the solute atoms.



Interstitial or substitutional impurities caused the lattice strains, as a result these impurities interact with dislocation strain field and hinder the dislocation motion of the metals, interstitial and substitutional solutes distort the lattice and generate the lattice strain, how? These strains can act as barrier to dislocation motion, for solute solution larger size mismatch, larger induced stresses.

So now we will discuss that how it is happening, so small impurities tend to concentrate at dislocation here, if you see this image dislocation, regions of the compressive strains, partial cancellation of dislocation compressive strains and impurity atom the tensile stress. Large impurities tend to concentrate at dislocations, regions of tensile, here you can see the size of the atoms is much bigger than the interstitial site space, so what happened? Partial cancellation of dislocation tensile strain and impurity atom compressive strain, so here the impurity atom is giving the compressive strain to the surroundings, and in this particular case the impurity atom is getting the tensile strain from the surroundings.



Increasing the concentrations of the impurity results in an attendant, increase in tensile and yield strength and decrease in percentage elongations which is nothing but known as the ductility, so now we are trying to give one example so that you can better understand, for example variation with nickel content of a tensile strength, yield strength and ductility for copper nickel alloys showing the strengthening, so in this particular case you can find that the, it is starting with the copper and then it is going with the nickel 100%, so copper 0, 20, 40, 60, 80 and 100, and nickel in this particular case is 0, and nickel percentage is going to be increased in this particular directions, so in this particular case you can find the maximum tensile strength in this particular zone, that means it is more or less 60% of the copper, and 40% of the nickel, the same thing we are getting for the yield strength also, so for the yield strength, generally we are getting it for the 80% of the copper, and the 20% for the nickel, and the elongation at break we are getting generally for the 58% of copper, and rest maybe the 42% of the nickel.

3. Strain Hardening (Cold working):

- It is the process to produce plastic deformation in ductile metals by working at low temperature.
- % cold working (% CW) is

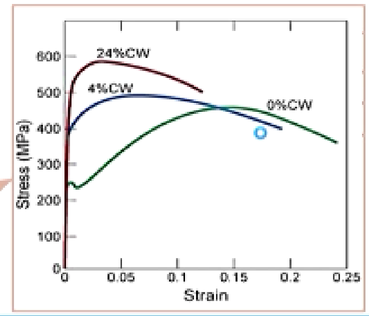
$$\%CW = \frac{A_o - A_d}{A_o}$$

where, $A_o \rightarrow$ Original cross-sectional area, $A_d \rightarrow$ Area after deformation.

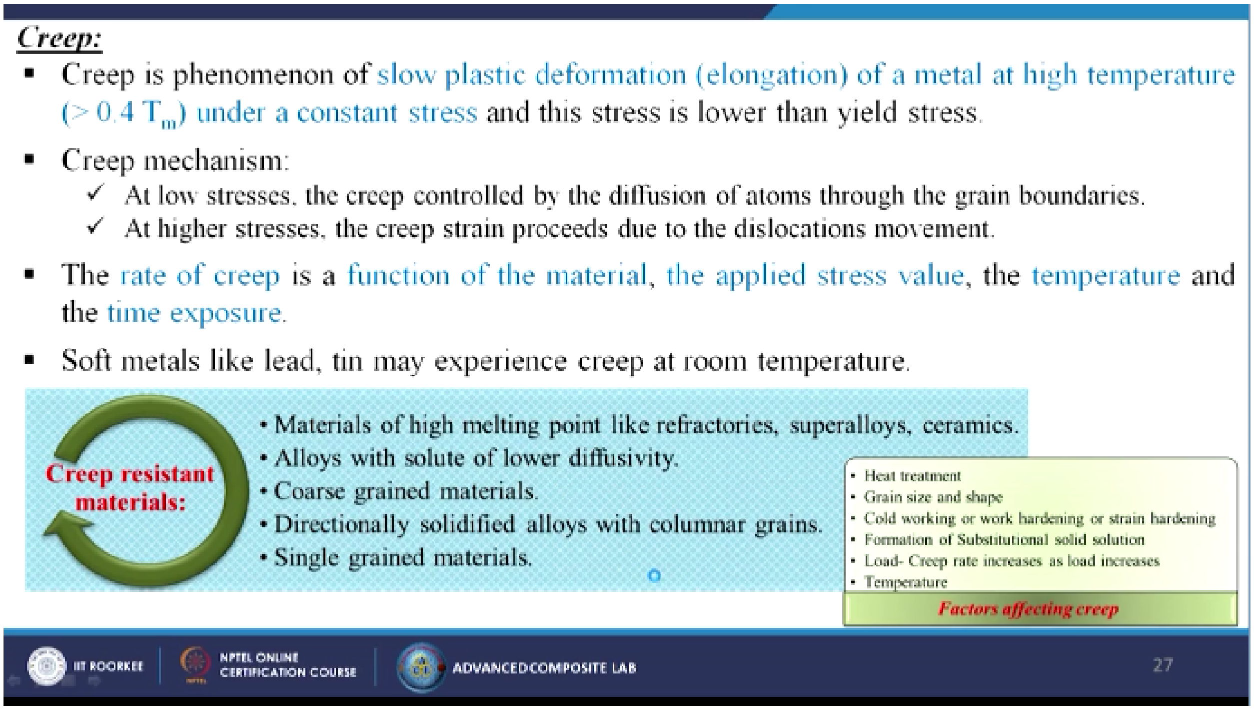
Effect of cold work:

As cold work is increased

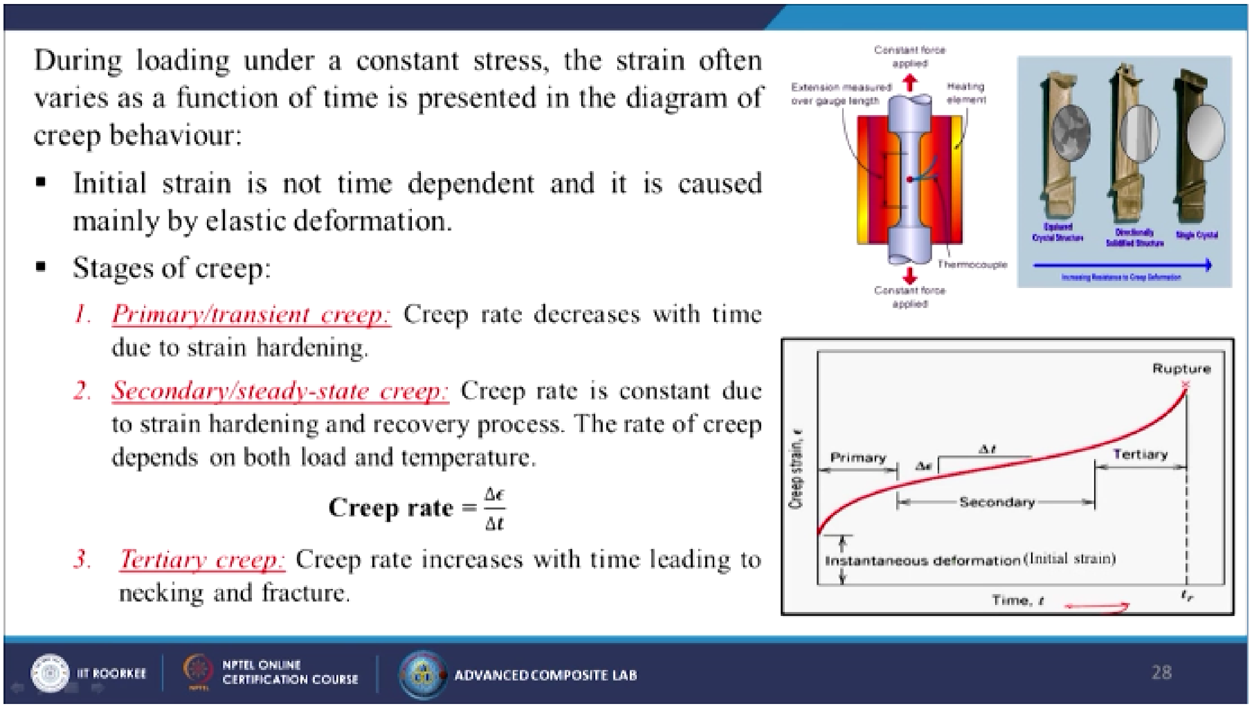
- Yield strength (σ_y) increases
- Tensile strength (σ_{TS}) increases
- Ductility (% EL or % AR) decreases



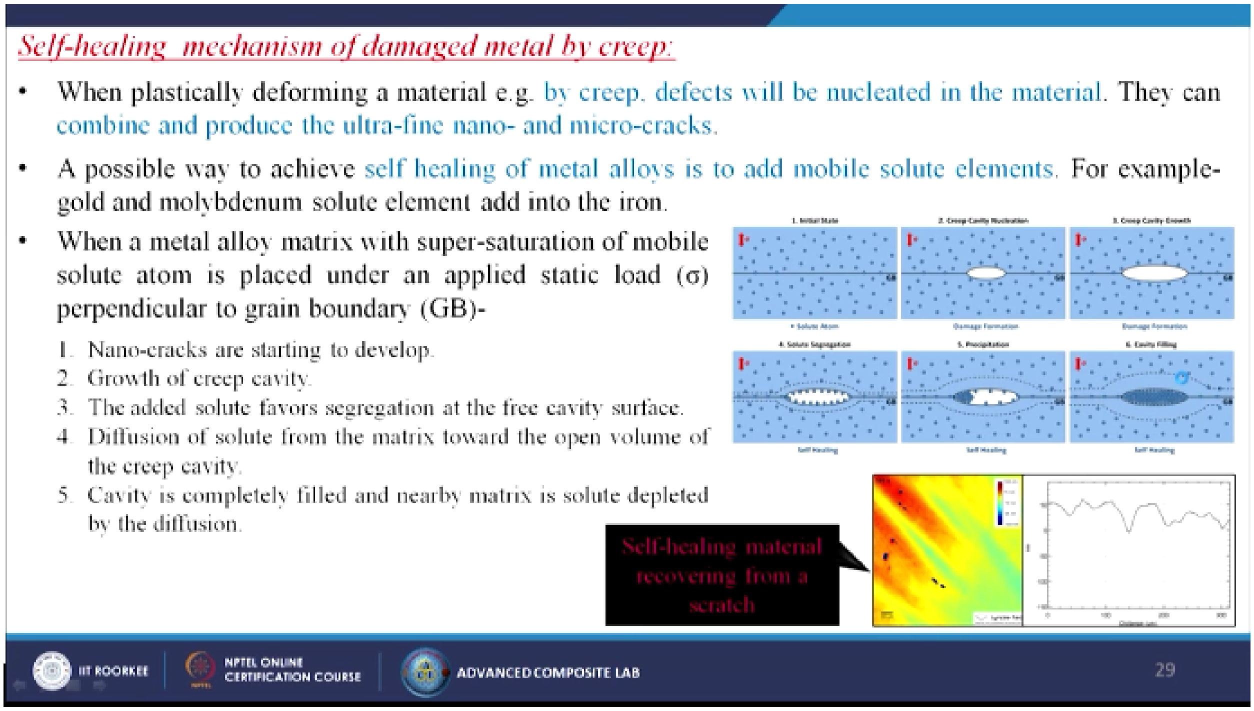
Now we'll discuss about the strain hardening which is nothing, already I told you is known as cold cracking, so or maybe the cold working, so it is the process to produce the plastic deformation in ductile metals by working at low temperature, so percentage cold working is known as the A0 – AD/A0, where A0 is the original cross sectional area, AD is the area after deformations, so generally from this particular stress strain curve you can see that when you are doing the 24% cold working, so automatically the strength of that particular material is going to be increased, but when we are doing the less cold working or maybe the no cold working, so automatically that strength of that particular material is going to be decreased. So effect of cold work, as cold work is increased yield strength increases, tensile strength increases, ductility decreases that is the main parameter.



Now we'll discuss about the creep, so what is creep? Creep is phenomenon of slow plastic deformations or maybe the elongations of a metal at high temperature, generally it's the, more than 0.4 times of the melting temperature under a constant stress, and this stress is lower than yield stress. What is the creep mechanism? At low stresses the creep controlled by the diffusion of atoms through the grain boundaries, at higher stresses the creep strain proceeds due to the dislocation movement, the rate of creep is a function of the material the applied stress value the temperature and the time of exposure, soft metals like lead, tin may experience creep at room temperature, so there are some creep resistant materials also, materials of high melting point like refractories, superalloys, ceramics, alloys with solute of lower diffusivity, coarse grained materials, directionally solidified alloys with columnar grains, single grained materials, so what are the factors which effecting the creep? First one is known as the heat treatment, then grain size and shape, then cold working or work hardening or strain hardening, formation of substitutional solid solutions, load-creep rate increase as load increases, and last one is known as the temperature.



During loading under a constant stress, the strain often varies as a function of time is presented in the diagram of creep behavior, so generally the creep strain is denoting into the Y axis, the time is denoting at the X axis. Initial strain is not time dependent and it is caused mainly by the elastic deformation, so there are three stages of creep, first one is called the primary or maybe the transient creep, creep rate decreases with time due to the strain hardening, in this particular case so here het time as it is increasing the creep rate is decreasing, secondary or maybe the study state creep, creep rate is constant due to strain hardening and recovery process, the rate of creep depends on both load and temperature, so here the creep rate is known as the del epsilon by del T, so in this particular case you can find that it is almost like a proportion, and last one is known as the tertiary, creep rate increases with time leading to necking and the fracture, so in this particular case again it is increasing very rapidly.

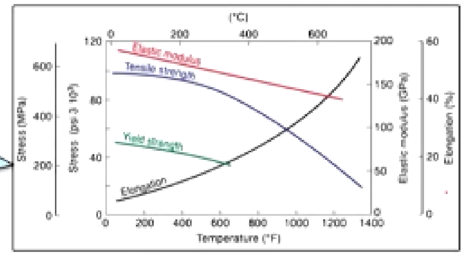


Now we will discuss about the self-healing mechanisms of some damaged metal by creep, so plastically deforming a material, example by creep defects will be nucleated in the material, they can combine and produce the ultra-fine nano or maybe the micro-cracks, a possible way to achieve self-healing of metal alloys is to add mobile solute elements. For example, generally we are using gold and molybdenum solute elements add into the iron. When a metal alloy matrix with super saturation of mobile solute atom is placed under an applied static load, perpendicular to the grain boundary what happen? Nano-cracks are starting to develop, so in this particular case you can find that the nano-cracks has been started. Growth of creep cavity is taking place, the added solute favors the segregation at the free cavity surface, in this particular case you can find that diffusion of the solute is taking place.

Now diffusion of solute from the matrix towards the open volume of the creep cavity, so fully diffusion has been taken place, now after certain time you can find that completely, cavity is completely filled and the nearby matrix is solute depleted by the diffusion, so in this particular graph you can find the self-healing material requiring from a scratch, so after certain time you can find that the how the creep is going to be decreased.

Temperature effects on stress–strain curve:

Increasing temperature
- ✓ ↑ Ductility and ↑ Toughness
- ✓ ↓ Yield stress and ↓ Tensile strength
- ✓ ↓ Modulus of elasticity
- ✓ ↓ Strain hardening exponent (n)

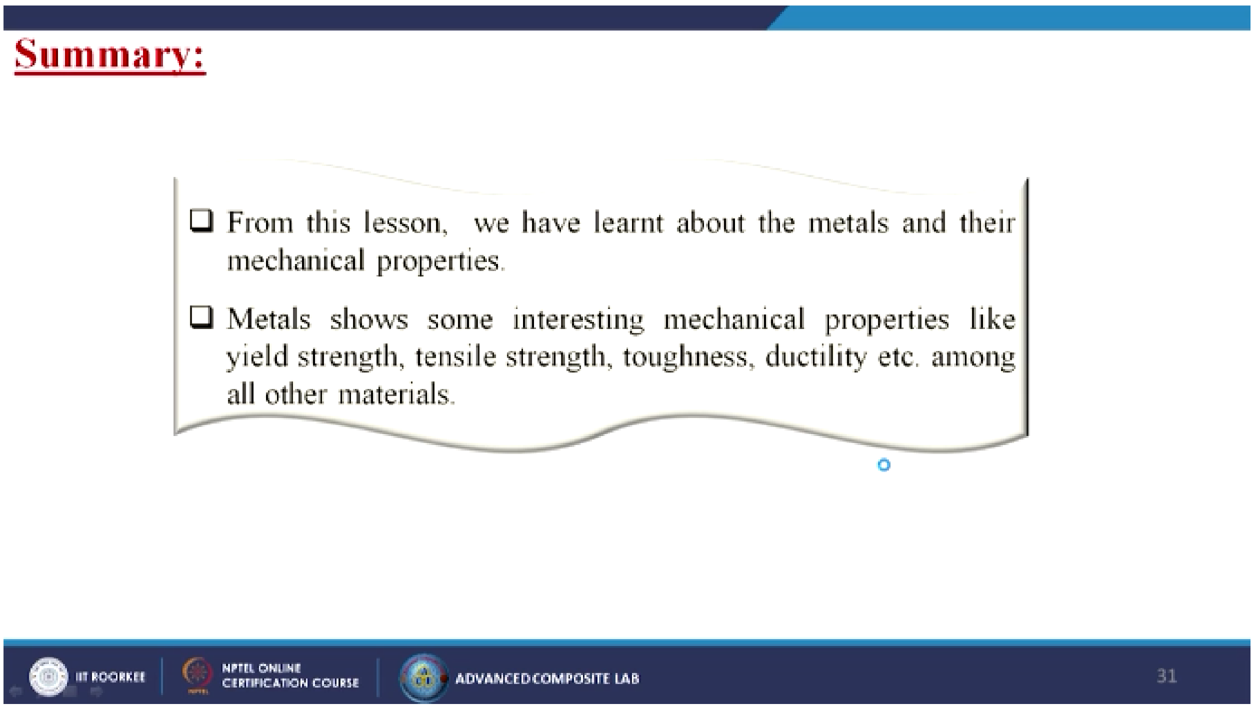


Note**

- ❑ Strain hardening or work hardening is the strengthening of a metal by plastic deformation.
- ❑ Modulus of elasticity (E), also known as Young's modulus, can be thought as the stiffness or the resistance to elastic deformation. Young's modulus is the ratio of Stress and strain called Hook's law.

$$E = \frac{Stress\ (\sigma)}{Strain\ (\varepsilon)}$$

Temperature effects on stress strain curve, so if we increase the temperature so ductility and toughness will increase, yield stress and the tensile strengths is going to be decreased, modulus of elasticity is going to be decreased, strain hardening exponent is also going to be decreased, so in this particular graph you can find that, for example so when we are trying to increase the temperature its elongation is going to be increased, but it's elastic modulus is going to be decreased, tensile strength is also going to be decreased, and the yield strength is also going to be decreased, so strain hardening or maybe the work hardening is the strengthening of a metal by plastic deformation, modulus of elasticity also known as the Young modulus can be thought as a stiffness or the resistance to elastic deformation, Young modulus is the ratio of stress and strain called the Hooke's law which I have already discussed earlier. So generally the Young modulus or maybe the modulus of elasticity which is denoting by the capital E is known as the stress by strain.



So now we almost, we have finished this particular lecture, now if we summarize the whole lecture we can found that from this lesson we have learned about the metals and there mechanical properties, metal shows some interesting mechanical properties like yield strength, tensile strength, toughness, ductility, etcetera, among all other materials and we have already covered all this sub branches of the mechanical properties in this particular lecture. Thank you.

For Further Details Contact
Coordinator Educational Technology Cell
Indian Institute of Technology Roorkee
Roorkee-247 667

E Mail:- etcell@iitr.ernet.in, etcell@iitrke@gmail.com
Website:- www.nptel.iitm.ac.in
Acknowledgement
Prof. Ajit Kumar Chaturvedi
Director, IIT Roorkee
NPTEL Coordinator
Prof. B.K Gandhi
Subject Expert
Dr. Kaushik Pal
Department of Mechanical and Industrial Engineering
IIT Roorkee
Produced By
Mohan Raj. S
Graphics
Binoy. V.P
Web Team
Dr. Nibedita Bisoyi
Neetesh Kumar
Jitender Kumar
Vivek Kumar
Dharamveer Singh
Gaurav Kumar
An Educational Technology Cell
IIT Roorkee Production