Welding Metallurgy
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Lecture - 11
Introduction to Strengthening Mechanism in Metals

Welcome to the lecture on Introduction to Strengthening Mechanism in Metals. So we will discuss about the mechanism of strengthening which is there in the case of metals or alloys and we all know that we need you know strong and stronger materials for use in engineering applications and normally what we do is normally we are deforming the materials and at some point of time when we are giving the load.

When the material is subjected to any load then at some point it will start deforming. So you know you have to do certain measures to increase its strength and what are those mechanisms by which you can make the material stronger and what will be the concepts behind them or what are the prerequisites to be studied for that. So during this lecture we are going to discuss something about it.

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Metal Strengthen Approaches

- The ability of material to plastically deform depends on ability of dislocations to move.
- Strengthening techniques rely on restricting dislocation movements to render a material harder and stronger.
  - Grain boundary strengthening
  - Cold working
  - Martensite strengthening
  - Strain hardening
  - Fiber strengthening
  - Solid Solution Strengthening
  - Strain ageing

So the ability of material to plastically deform depends on ability of dislocations to move. So basically you know that dislocations are moving and that means that the material has plastically deformed and also you know if by some mechanism or by some techniques we are restricting these dislocation movements it means basically we are going to make the material harder and stronger.

So if you talk about the different methods of you know making the material stronger or harder. So in the metallurgy or material science we are going to talk about few of the methods and these are like grain boundary strengthening so as we know that grain boundaries are there when the dislocation is there so it will have you know the resistance across the grain boundaries.

So by increasing the number of grain boundaries or by in fact that is achieved by increasing the number of grains. So that way you are you know strengthening the material. So as we know that we have many techniques you know for increasing the number of grains like while casting you can have the different mold materials. So we have different mold materials like we have commonly used material mold material is sand.

And if you go for the metallic mold then and cooling rate is higher so you are going to have the finer grain structure. So that way you know the material which you get by cooling in the metallic mold so that will provide you more number of grains. So you will have you know in that case you have the strengthening developed and basically you have a certain correlations which are given you know which tells that if the number of grains are increasing or the grain size average grain size is decreasing.

In that that case the stress required to move the dislocation will be increased. So if your number of grains are more than stress required to move the dislocation will be higher and if it is less than in that case it will be less. So that is the concept of grain boundary strengthening. Similarly, you have cold working you know cold working or strain hardening basically in one case they are same.

So cold working is another method where basically the material is a cold worked material is worked below the you know recrystallization temperature and in that basically the dislocation density is increasing and it is it is seen that when the dislocation density will increase then the stress again required to move the dislocation will be higher the strength will be higher. So cold working is another you know method to strengthen the material.

And as we might have seen practically at many occasions that when a material is cold worked or even the typical example of that will be you know if you have a mild steel rod and if you are trying to bend it and unbend it many number of times then at one point of time it breaks so before that it becomes harder and harder and at one point of time then it becomes brittle and then so it breaks.

So using this cold working methods also you can have the, you know, increase in the strength, so it is also a strengthening mechanism. Martensite strengthening so this is basically because of the transformation product martensite and we know that we have studied that now when we are decreasing I mean when we are increasing basically the cooling rate so in that case after certain critical cooling rate if the cooling rate is more than that in that case you are getting martensite.

And basically martensite you know formation is because of the shear induced phenomena. So it is a diffusion less transformation. So in that case what happens you know large amount of stresses accumulate and so you have strengthening achieved in that case. Similarly, is the strain hardening so similarly that as you know that when we strain when the strain hardening induced in the metal and then and that way the stress required to move the dislocation will be higher.

Fiber strengthening is another method because in many cases you induce, you use the fibers and fibers will have more rigidity more strength than the parent matrix. So fiber strengthening is another mechanism by which you can make the material stronger. So very much lived example will be the case of composite materials where we have parent matrix will be the ductile material and then we also use we use the fiber materials.

So the fibers are the materials with high rigidity and they have high stiffness basically the same stiffness and rigidity and then it is materials the materials property increases. Solid solution strengthening it is based on the concept that when we make solid solution and if you have the atoms you know so you will have inter-atomic distances or inter-atomic voids in fact and if you try to you know alloy with the material which is very much smaller in size.

But then its size is more than the voids which is there in between the atoms in that case if you are able to you know trap these small sized materials into the matrix. So that will produce a stress field and it will be resisting you know it will be giving you a stress field and the material will have the better properties you will require higher you know stress to for the material to deform.

Another you know method which we will discuss will be strain ageing so that is another phenomena where it was seen that if you load the material, unload the material and then further if you do some heating and then you further you know do the loading so that way also some other phenomena kind of a phenomena is observed, increasing strength is observed. So yield point is increased.

So this kind of phenomenon is observed in some of the materials so that is strain ageing. So because of the ageing treatment or any heating to a lower temperature that results into. So basically these are the different you know strengthening approaches and we should know that first of all we will have a light on you know the concepts about how the material becomes harder.

What makes the material harder and as we discussed that the strengthening techniques rely on restricting the dislocations movements. So basically what happens that when you have the plastic deformation then plastic deformation will be by many mechanisms so what is the concept of that plastic deformation and then what are the modes of the deformation and then you know when you deform then how you know how this you know shear stress value has to be calculated.

And how it is a function of the, you know, shear modulus of the material and how they differ from the actual and I mean there is difference between actual and theoretical values so on that we will be having certain light. So as you know that if you talk about the plastic deformation so what we see that in the case of a plastic deformation you have that is analyzed normally using the load elongation curve or using the true stress, true strain curve. So you must have seen the proper you know load elongation curve.

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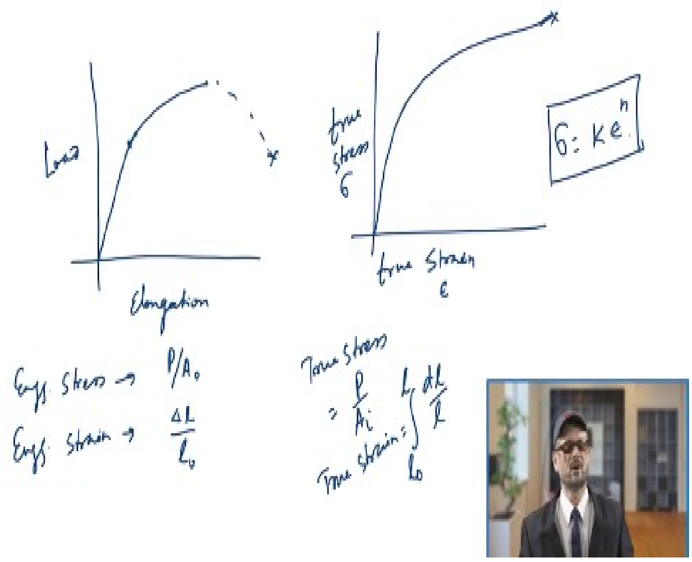

So as you know that when you typically draw the load elongation curve for a ductile material. So the load elongation curve goes so you will have straight region and then it moves so that way it was and so what you see that you know and after that it will go on decreasing also after certain time. So if you so normally you have a load and elongation curve so this is or what we do is in that. We also call it as a stress-strain diagram that is engineering stress engineering strain curve.

So what we do is we normally divide it with its original area. So you will have engineering stress and engineering strain and then that value is calculated. So if at any point P is the load so P/A_0 will be engineering stress. Similarly, the length change in length upon original length so that will be your engineering strain. So that way you will have such kind of one of the diagram is that and the maximum point will be the ultimate tensile strength.

And then you will have one is a proportional limit because up to certain point the stress will be proportional to strain and then after that you know so you give a certain value of the yielding and that will be proof value and for that basically you define the yield point and then the maximum value will be the UTS. So that what that is what is the load elongation curve.

Now in this case what happens that after this point basically there is a necking starting and then there will be basically the permanent deformation starts and also as there is permanent deformation increase in the length so certainly decrease within the cross sectional area (()) (12:55) because in the plastic deformation region your volumetric volume constant condition will also be maintained.

So you will have the change in the cross sectional area and ultimately after that time you know after this even the value stress value also will go on decreasing and ultimately at some point of time it will come and it will break so that will be fracture point. Now that is basically known as the engineering stress engineering strain curve while when you say the now what we see that in this case you are assuming that you calculating the value of stress and strain based on the actual area I mean original area A_0.

Now what happens as we have seen that when there is permanent deformation then the area will no longer be remaining constant. So in this case what happens you know so this way it will move so this is known as true stress and true strain. If you take actually the value of the stress and strain which will be depending upon the instantaneous area so that is known as the true stress true strain curve.

So you represent it as $\sigma$and ε and this if you look at this it will be similar to that going into the you know this yield point region so it maybe to the proportional limit it will come as similar one, but after that what you see is that this value does not decrease. As in the case of in this it will go on decreasing. However, in this case it does not decrease in fact and it goes on increasing till the fracture point

So that is the basically difference between the true stress and true strain curve, but you see that this zone this is the stress value is going on increasing. So it is basically increasing continuously in fact that is known as the strain hardening of the material taking place. So this way you know what we feel that so in this case this is the reason where the hardening is completing and that is what one of the mechanism is there that is strain hardening. So strain hardening is taking place in this region.

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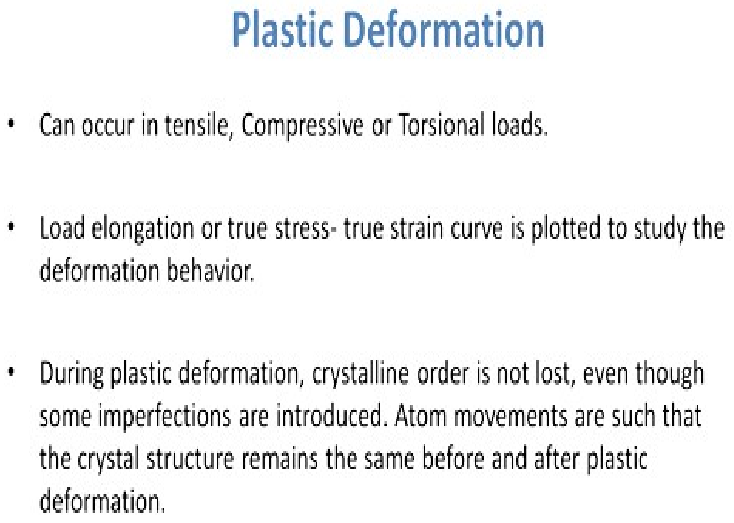

Plastic Deformation

- Can occur in tensile, Compressive or Torsional loads.
- Load elongation or true stress- true strain curve is plotted to study the deformation behavior.
- During plastic deformation, crystalline order is not lost, even though some imperfections are introduced. Atom movements are such that the crystal structure remains the same before and after plastic deformation.

So what we see so we can see that you know in plastic deformation it can occur in tensile compressive or torsional loads. Now load elongation or true stress true strain curve is plotted to study the deformation behavior. So we have already seen that you just can study the deformation behavior by studying the load elongation or true stress, true strain curve. So as you see that true stress will be load divided by instantaneous area so P/A_i that is instantaneous area.

Similarly, true strain is also defined as $\int dl/l$so that is l0 to l. So which is the original length and this is a final length so that way your true strain values are calculated. Now many a times you have different type of you know relationships which talk about the relationship between true stress and true strain and you have the power relations also you know available that is σ ¿ $K\,\varepsilon_n$.

So that talks about the you know so K is the strength you know coefficient and n is the strain hardening exponent. So this is you know this is known as power law and you know power relationship and here you know K is known as the strength coefficient and you will have you know n as the strain hardening exponent so for steel this value is something like 0.15. Now even for the strain rate parameter also you have another relationship.

And for that also you have a separate relation so that we can study you know later. Now we will talk about you know the, you know, plastic deformation. So what happens in the during the plastic deformation the crystalline order is not lost even though some imperfections are introduced and atomic movements are such that the crystal structure remains the same and after the plastic deformation.

So when the plastic deformation is taking place as you know you have crystalline arrangement of so atoms are arranged in certain order and when they will be plastic deformation then the crystalline order is basically not lost and certainly some imperfections may be introduced.

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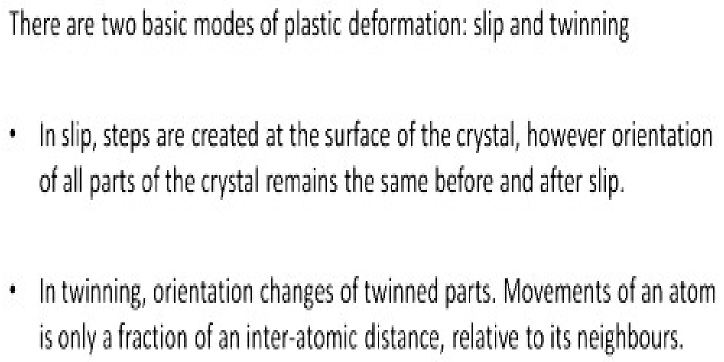

There are two basic modes of plastic deformation: slip and twinning

- In slip, steps are created at the surface of the crystal, however orientation of all parts of the crystal remains the same before and after slip.
- In twinning, orientation changes of twinned parts. Movements of an atom is only a fraction of an inter-atomic distance, relative to its neighbours.

So basically if you talk about the mode of deformation you know there are two modes of deformation the slip and twin. Now how the slip and twins look like. So you know in the case of slip you know what happens that you have the arrangement of atoms so what you can see by you know the figure.

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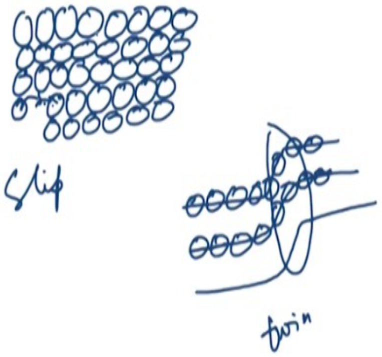

So in the case of slip suppose you have atoms like this so you have the arrangement of atoms you know like this and then you have another arrangement like this way. So now in the case of you know slip there will be you know movement of the atoms you know from you know one side. So it will be so before the slip or twin you will have the structure like this, but once there will be slip.

So what may happen is that your this one may go from here so your next will be from here so that way. So this will be the example of slip so basically this is you know this is going to that position so from here it is going to this position. So your next to you know level will be like it will go like that so this is the example of you know slip. Now in the case of twinning what happens that you know in certain region.

So in the case of twin what will happen that you will have the atoms arranged and then you will have you know the movement of atoms will move like this. So you know you have atoms here so all these are you know so this is so in this zone so this type of mechanism is known as by twin. So this is by slip and this is by twin now this is the twined zone and what you see that in the case of slip you know before or after slip the arrangement of atoms the way they are the orientation does not change.

Whereas in the twined zone you have the orientation is changing. So that is the in slip you have steps created at the surface of the crystal. However, there will be orientation of the parts of the crystal remaining the same before and after the slip. In the case of twinning you have the orientation changes of twin parts as we see, but the movement is only a fraction of the inter-atomic distance whereas in that it may be few of the atoms they may be slipping. So that is the difference between you know the you know slipping and twinning.

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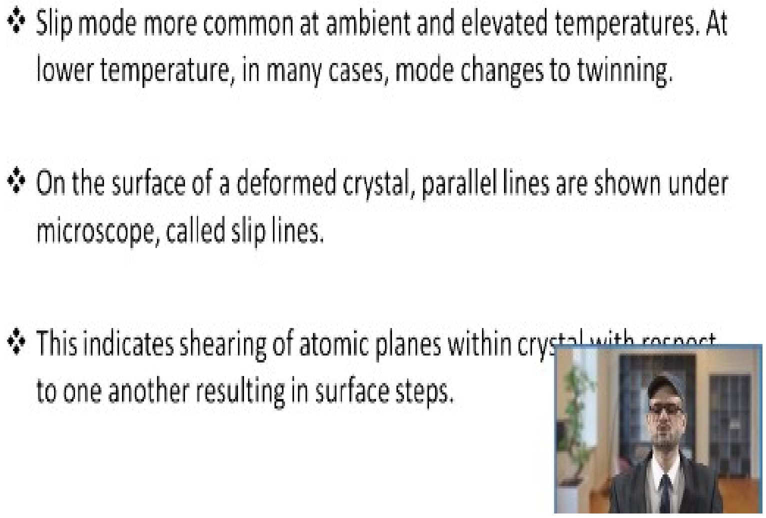

- Slip mode more common at ambient and elevated temperatures. At lower temperature, in many cases, mode changes to twinning.
- On the surface of a deformed crystal, parallel lines are shown under microscope, called slip lines.
- This indicates shearing of atomic planes within crystal with respect to one another resulting in surface steps.

The slip mode will be more common to ambient elevated temperature and at lower temperature in many cases the mode will be changing to the twinning. Now if you talk about deform the crystal and if you look at the surface of the crystal and if you see under the microscope then you will be showing the parallel lines. Now these lines are known as the slip lines and this lines will be indicating the shearing of atomic planes within crystal with respect to one another resulting in the surface steps. So you will have you know those formations.

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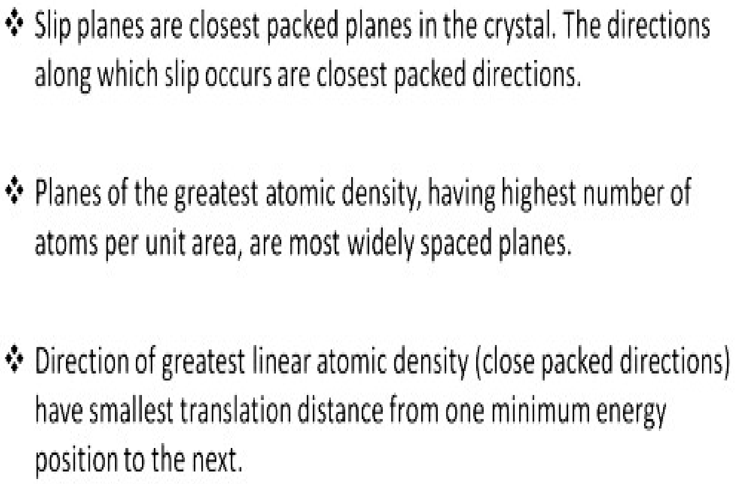

- Slip planes are closest packed planes in the crystal. The directions along which slip occurs are closest packed directions.
- Planes of the greatest atomic density, having highest number of atoms per unit area, are most widely spaced planes.
- Direction of greatest linear atomic density (close packed directions) have smallest translation distance from one minimum energy position to the next.

These slip planes which we find so will have you know the concept about how these deformations should be studied. So we know that these slip planes are the closest packed planes in the crystal and also the direction along which the slip occurs they are the closest packed directions. So the plane of the greatest atomic density having highest number of atoms per unit area they are the most widely spaced you know plane.

And also you will have the direction of greatest linear atomic density that is close-packed directions have smallest translation distance from one minimum energy position to the next. So these are the basically the traits of you know the slip type of deformation which occurs in the case of metals. Now when if you talk about the ionic crystals so basically energy you know point has to be kept into mind.

And it is always seen that the ions or the same polarity they should not be juxtaposed as nearest neighbors because in that case there will be big increase in the potential energy. So the slipping will be in such a manner that after you know positive iron you will have a negative iron and then again positive iron like that and the slip plane and the slip direction together they constitute a slip system.

So basically if you talk about the slip system so as you know that if you talk about one FCC you know system.

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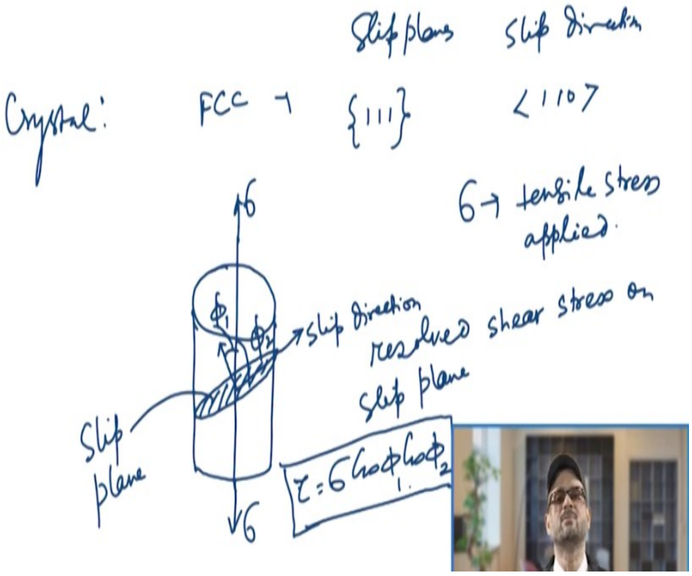

So if your crystal is say you know FCC having you know a structure in that case you have slip planes as we know that you have slip planes of {111} and similarly you have slip direction so that is also that is <110>. So that way you have combination of this slip plane and slip direction they constitute you know the slip system. So similarly for BCC system also you have {110} is the slip plane and <111> is you know slip direction.

So that is more than you know common and also you have less common also slip planes like {112} or {123} or so. So that also is available you know similarly is the case for even hcp materials. So that way they form these slip system.

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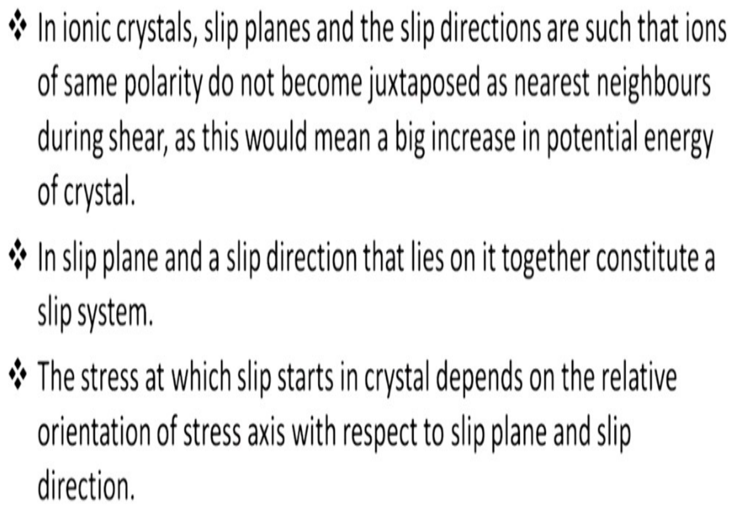

- In ionic crystals, slip planes and the slip directions are such that ions of same polarity do not become juxtaposed as nearest neighbours during shear, as this would mean a big increase in potential energy of crystal.
- In slip plane and a slip direction that lies on it together constitute a slip system.
- The stress at which slip starts in crystal depends on the relative orientation of stress axis with respect to slip plane and slip direction.

Now what we need to study is that the stress at which this slip starts in crystal depends on the orientation of stress axis with respect to the slip plane and the slip direction. So suppose if you talk about you know the, you know, plastic deformation so if suppose you are applying you know load along as tensile axis. So suppose you apply the stress so if suppose this is the tensile axis and this is the stress now if you talk about the you know one of the planes.

So if suppose this is your slip plane so and this is the, you know, slip normal plane here and this is your slip direction. So you know for such cases if you look at so you will have you know if you apply the tensile stress so σ so if this is the tensile stress applied. So the shear stress so resolve shear stress basically that is on a slip plane so resolved shear stress on slip plane.

So as we know that this is the you know slip plane and it is normal basically is this making angle $\varnothing_1$ with this tensile axis and this angle is you know $\varnothing_2$. So if $\varnothing_1$ is the this normal making angle with the tensile axis and $\varnothing_2$ is with the stress axis in that case. So in that case so and know $\varnothing_1$ is that which is making with the stress axis and slip direction is inclined at an angle $\varnothing_2$.

In that case if you take the you know resolve the component so that is shear stress because the deformation is because of the shear so this will be basically component of $\cos\varnothing_1$ and $\cos\varnothing_2$ and the critical resolved shear stress value basically now you know you require this shear stress value to reach some critical value and to start the deformation so that value is known as the critical resolved shear stress.

So if you come to the presentation here so the stress at which slip starts in crystal depends on the relative orientation of stress axis with respect to slip plane and slip direction. So what we have seen that we have different planes at inclined at different you know angles and the deformation will start you know.

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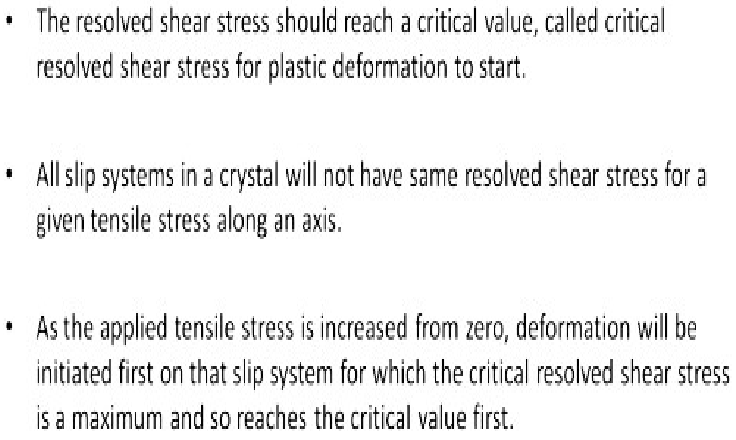

- The resolved shear stress should reach a critical value, called critical resolved shear stress for plastic deformation to start.
- All slip systems in a crystal will not have same resolved shear stress for a given tensile stress along an axis.
- As the applied tensile stress is increased from zero, deformation will be initiated first on that slip system for which the critical resolved shear stress is a maximum and so reaches the critical value first.

So the slip system in the crystal will not have the same resolved shear stress for a given tensile stress along the axis and the deformation will be initiated first on that slip system for which the critical resolved shear stress is maximum and so reaches the critical value first. So that is basically the point that for whichever you know wherever this critical resolved shear stress will be maximum the deformation will start there.

Then also comes a point that you know many a times we see that we can also do the analysis and we can see that how you know with this stress required you know when there will be a slip in any system. So for any slip how there will be change in the potential energy and you know how the shear stress will vary. So assuming that to be a sinusoidal curve because if it is moving from one to other and it is coming again in between the two atoms the atom is taking its position.

So bring that as the point the final one. Now it is also proved that if you take it as a sinusoidal type of curve so you know the value of tau will be a function of also the you know Burgers vector then you will have you know other inter-atomic distances into common and from there it has which was seen that you can have an idea about the you know the stress required to move the dislocation.

Now and you have the shear strength of the crystal also you can have that, but what we see that the ideally the strength which the material should have it does not show that. So normally it should be $\mu/6$ suppose, but in actual case it becomes you know that that factor becomes more than thousand or even thousands so up to 20,000 or so or even more. So that reason is because of the presence of dislocations.

And also there has been studies on that showing that when we talk about the viscous or where the dislocation is not there in that case the strength is quite high and once you induce dislocation then the strength becomes quite small. So that way you know that is the concept of having you know the dislocation or the concept of plastic deformation and that is what we will have, we will study the mechanism by which you can see that you know there must be proper strengthening so that the barrier to dislocation movement is there.

So we will be talking about different mechanisms in our coming lectures. Thank you very much.