Materials Science
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Lecture No 29
Plastic Deformation (Contd.)

In the last class we are talking about the plastic deformation and I defined.

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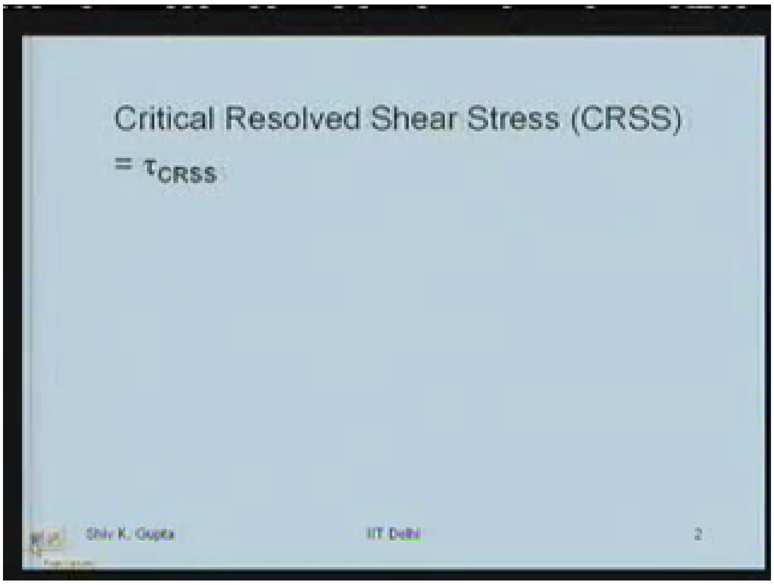

The critical resolved shear stress, is the minimum value of the stress at which plastic deformation occurs in the material and we saw that why we are talking about resolved shear stress mechanism of deformation by enlarge is a slip in most materials as most temperatures and then we saw that.

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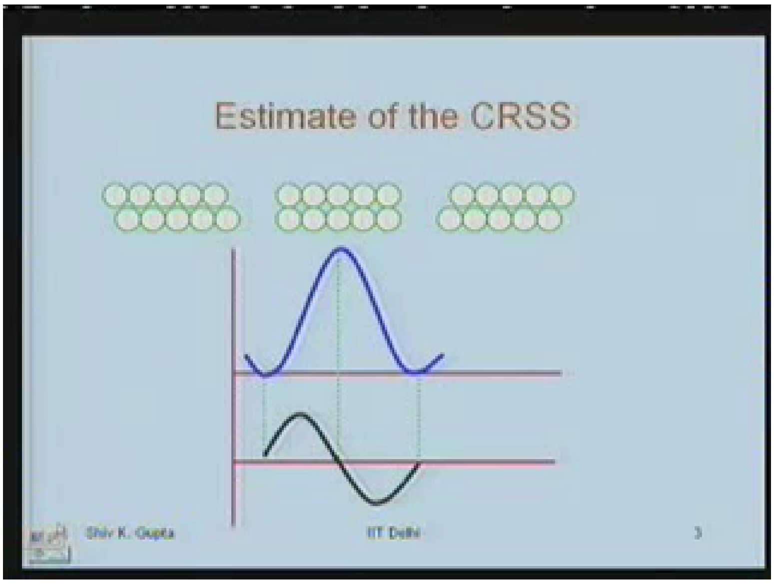

The estimate of the resolves shear stress require to make the plastic deformation begin in the material or the cause a slip in the material made a very simple estimate and that turn out to be, Mu is a shear modules and therefore this a minimum value of the stress required should be this and I should be able to apply that much stress in the elastic region but but our observations are to the (())(2:25)

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And before I talk of the role of dislocations I'll show the what is that contrast in the observation as compare to.

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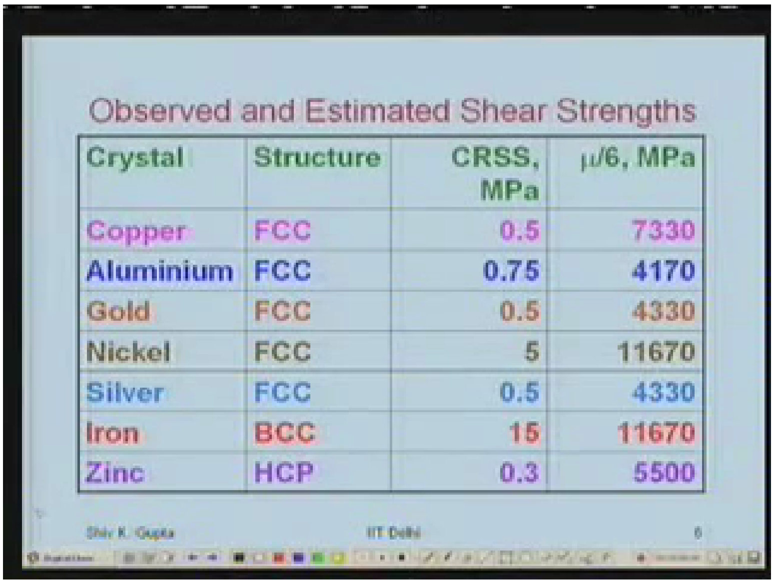

Observed and Estimated Shear Strengths

Crystal	Structure	CRSS, MPa	$\mu/6$, MPa
Copper	FCC	0.5	7330
Aluminium	FCC	0.75	4170
Gold	FCC	0.5	4330
Nickel	FCC	5	11670
Silver	FCC	0.5	4330
Iron	BCC	15	11670
Zinc	HCP	0.3	5500

The value of the resolved shear stress the critical value we work out. These are the different materials commonly used materials copper, aluminium, gold, nickel, silver, iron and zinc there crystal structures are given here and the critical resolved shear stress what we observed is 0 point 5 mega pascal while a let me again remind you that this course and also internationally all the strength values of the part of the material are given in terms of mega pascal whether it is yield strength or the tensile strength or the flow stress.

While it comes to defining the modules it is always define in giga pascal units. Well here I give the Mu by 6 on the last column which big turns out to be for copper 7330 instead of 0 point 5 that means its more than 14000 times is the value of the Mu by 6 the actual value what we observed in copper is 1 up on 14000 its more than 4 orders of magnitude less difference on most of them you will find is 3 to 4 order of magnitude.

This is a large difference where I have gone wrong I made a simple estimate there could be a small factor of 1, 1 point 5,2, 2 point 5 things like that I if I made an error some way though I made a very small simple estimate still thats a very good estimate really speaking and the values what I observed are very different much much less.

Right so thats where we a start to think what is wrong in our estimate and what is going, what is happening in the real materials. What we find is that this critical resolved shear stress which I have worked out at the most I should call it the ideal strength of the perfect crystal.

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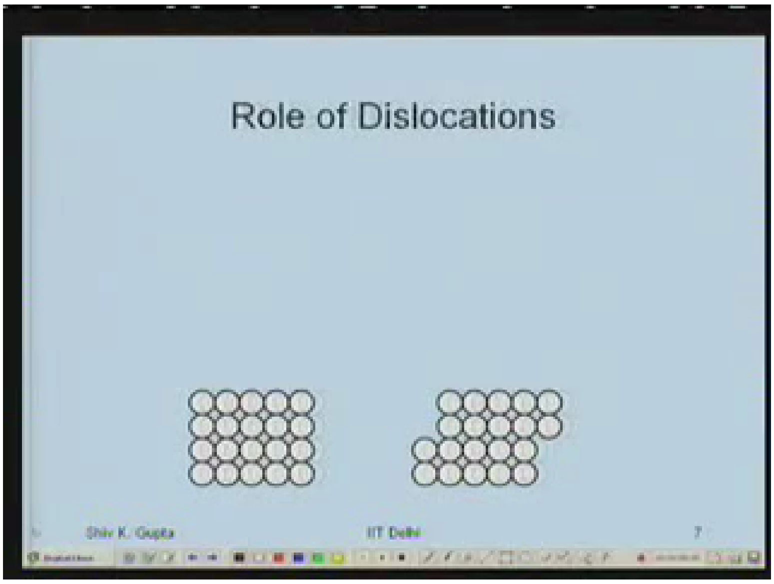

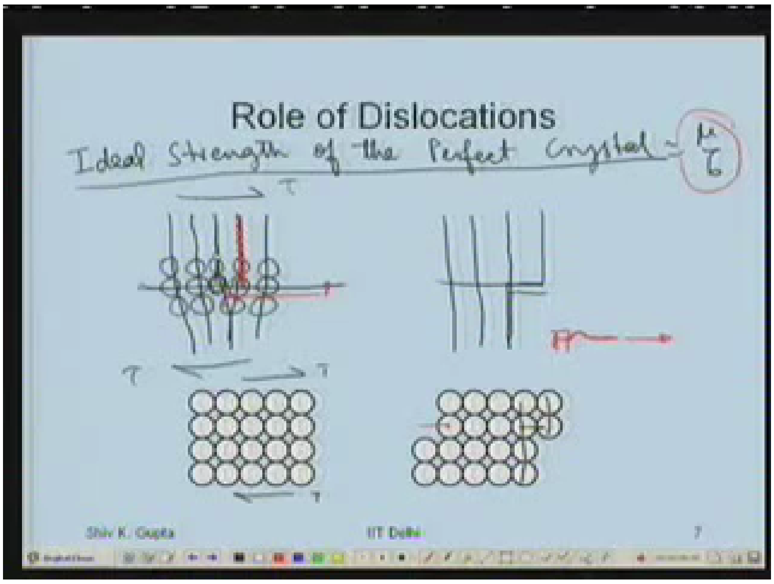

And this is how the slip or the deformation occurs in a material the semi fact can also be produced if I have and edge dislocation like this and I apply the shear stress in this manner so here also I am applying the shear stress in this manner and then it deform like this and you don't call that when I talked about slip motion of the dislocations this dislocation can go out ultimately and cause a permanent step like this.

So this deformation which I got here this deformation here I am able to get by the slip motion of the dislocation so by the slip motion of the dislocation able to get that but in slip motion what is the effort required that has to be seen. Discussed this earlier when this happens these atoms which are above the slip plane in the start to move slightly to the right and the once which are here that moves to the left.

And as a result this is able to form the bond with this and this becomes the part plane. Part plane goes there and this moment of the atom is a very small moment and for this I do not require a very high stress of that kind I require a very small stress but this has happened dislocation configuration is moved but I have not got the deformation outside I will not see any deformation till the dislocation comes out like this.

Student: (())(8:00) let this

Professor: Dislocation is slipped by one entrepreneur spacing, dislocation of lip by entrepreneur space one entrepreneur spacing but externally I will not see any plastic deformation. Plastic deformation only when the dislocation gets out to the surface. Then I'll see the permanent change in the shape of the material so in the words if there are thousands planes from the surface to this dislocation this dislocation has to move thousand steps.

Right also slip thousand steps before it can come to the surface and I can see the permanent change in the shape of the material so whole effort got divided into thousand, ten thousand or billion steps what we are getting in one single stroke going from 1 equilibrium position to the next equilibrium position like this that whole effort is divided into 10000 or millions step right.

So that kind of effort with required no effort required is less it is something like in this big flow I have a big carpet line and I want to move it by six inches no one of you can do it. Yes if I give you 8-10 people you can lift it and shifted by six inches and place it but even a younger child can do this if I provide him a stick.

You have to only slide the carpet at one end like this make a small hump and keep with this stick keep forcing this some to go on the other side and ultimately it will reach the descent and the carpet would have moved by 6 inches. That is effort is divided into number of steps though each step may not be just let us say they are 10000 steps it is not X divided by 10000 efforts.

Effort may be more than that but the actual effort required he force required is much less at any steps and that remains the same at all steps. So that is the stress or that is the strength of the material thats why it is much less and thats 3 to 4 out of the magnitude difference what we saw in the values is because of this. This is also the situation you find analogues situation if you have worst seen the caterpillar or the snake moving it doesn't slide against the surface.

Surface on which they travel sometimes very rough and they do not get scratches on their body so because they are creating a hmm muscle is pulled up and down so muscle is all the time moving up and down. Its not gliding against but the result is if it is gliding against the surface same thing is here.

The this location is moving in a material exactly the same fashion your effort at each step is much much smaller and as a result connect strength of the material of the critical resolved shear stress of the material is the effort which we require to move from one step to the next. And it and its up in getting me a plastic deformation must the dislocation gets to the surface. Is this clear alright. If so then if I have a crystal.

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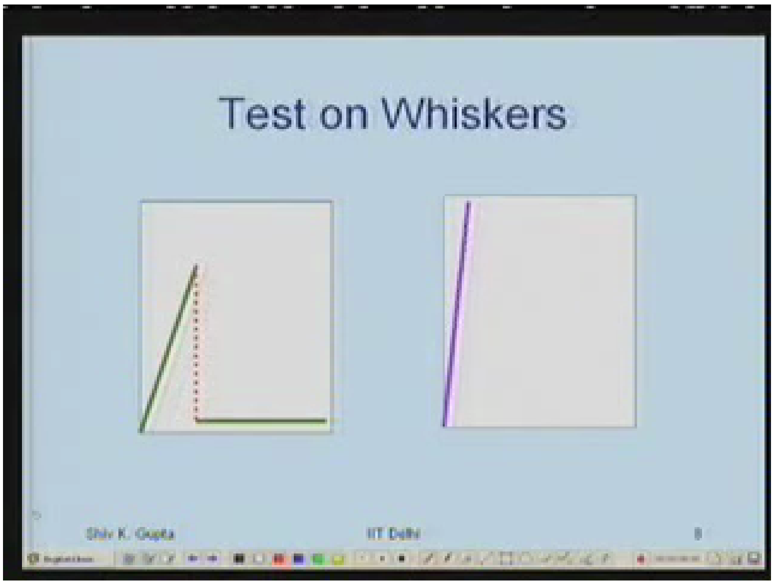

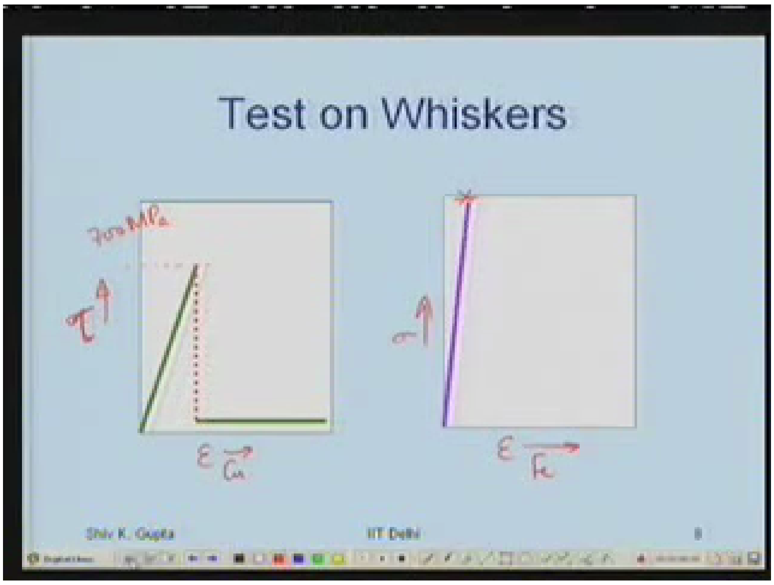

Without a dislocation I should be able to reach somewhere near Mu by 6. If not Mu by 6 I should be able to reach somewhere there if there is no dislocation right, its difficult to get real crystals without the location as I have been telling again and again they are always there however people have tried and gone viscous. Viscous are just single crystal just like your hair diameter is very small fraction of a micro meter.

And the length is long such crystals of copper and irons were made. And they were tested this is the stress and this is the strain on this axis. In the case of copper it went almost up to 700 mega pascal and that is when a dislocation got introduced on the surface and suddenly fell down to your value 0.5 okay. So this is I am talking about the okay lets put a critical resolved shear stress (())(13:22) just put it tou only.

But then this is this is the value of the critical resolved shear stress actually see here what you got because this location got introduced on the surface. Well in the case of iron it went on and on and on and ultimately the high value the (())(13:46) into powder. That means I was able to pull all the bonds between art of this and snapped all the bonds once the bonds are snapped its atomizes it became a powder and therefore exploded into powder in case of iron that goes to show that when dislocation got introduced it became very low plastic deformation was there.

Here it goes on elastic deformation only. So plastic deformation would have began had I reach new basics but by that time I have brakeun broken all the bonds and got atomized right. That goes to tell us that yes this location are re responsible for such a low strength of the material so my estimate was not the bad estimate but it was for a perfect (())(14:40) and never considered the dislocation there all right then can I make an estimate now with the help of when the dislocation is there while lots of efforts has been made by people.

But then none of the models is good enough to explain so therefore I will not give the models in terms of numbers but the facts which have been considered in working out the resolved shear stress.

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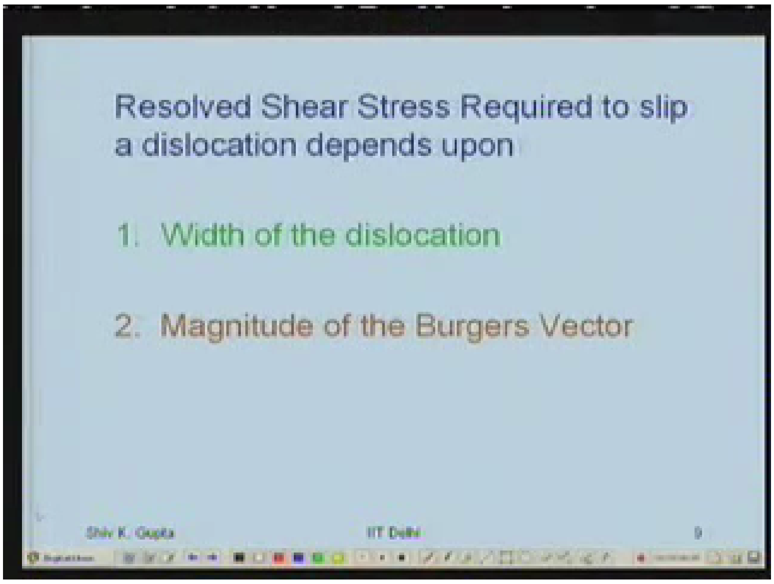

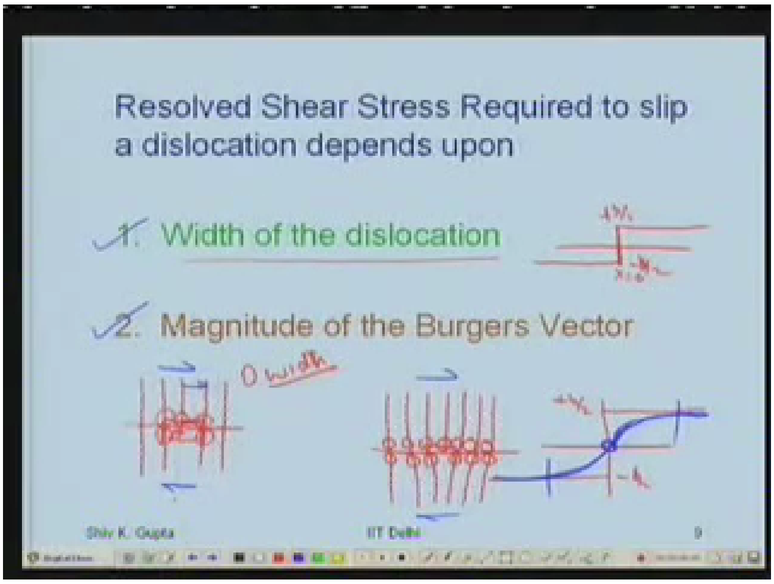

Which is required for a dislocation to sleep depends upon 2 things one is the width of the dislocation. Let me tell you what is the width of the dislocation just see one consideration here and just another consideration here. What you see? They are not distortions all planes are flat, vertical. The words the distance between the atoms which are here is that the bond length.

The distance between the atoms which are here they are two bond lengths. As if there is a slip here in a material somebody has removed that plane but they are not come closer. Where are the displacement located in this? They are the displacements we talked about the dislocation line as a boundary between slip part and the absolute part.

And there is a displacement of that slip what we call the bug inspector all the displacement we call it to the magnitude the bug is vector where is it located. Its located right here (()) (17:14) if I show here alright this is X equals to zero whether dislocation is minus B by 2 displacement here plus B by 2 displacement there and total displacement is right here this is similarity there that way at one spot such a dislocation has a zero width in this if you notice displacement are carrying over to 10, 20 planes depending upon how ductile the material is or how flexible amount are these bonds are very rigid probably like in diamond bond angles cannot change.

But here the bond angles they have changed you see because the flexible bond is not such a rigid bond in typical material it can go up to even up to 500 thousand planes like copper this is a dislocation which is high width and displacements here lets say this is minus B by 2 thats plus B by 2 they go like this. You can see the width of the dislocation is very large.

Displacements are spread over from this and to that end around the dislocation line and dislocation line is right here so such a dislocation has a high width now you can tell me where I have to apply the shear stress at this situation or I have to apply the shear stress in this situation how much moment I have to make for this atom so that it bonds with the next one.

Student: The burgers vector

Professor: Equal to the Burgers vector right away and that is what the model I took when I try to work out how much stress is required to make the dislocation slip what I call the critical resolved shear stress or just for the ideal strength of the perfect crystal thats what is going to happen here. This 0 width dislocation is a notice dislocation I have to put lift the whole plane and put it to the next equilibrium position.

But near the effort required is fraction of the radius and this will not add up giving me displacement right. So effort here is much less than the effort there so more the width of the dislocation less is your critical resolved shear stress. Or the minimum stress required to make the dislocation slip now so essentially now critical resolved shear stress is that value the stress or that minimum value the stress at which a dislocation can slip to the given crystal.

And that will be less here (())(20:51) it will be almost Mu by 6 here at will be less here and thats the effect the width of the dislocation second thing is the magnitude the burgers vector. Is a burger vector is large even at the dislocation is high width it displacement in 1 step which are required will be little more effort will have to be more and the burgers vector dislocation is small at every step I have to move on very small moment effort will be less.

So these are the two things which control the critical resolved shear stress or stress required to make the dislocations slip. So if the width of the dislocation is small stress required will be high applied stress are and the magnitude the burgers vector is large again I have to apply high stress so material will be stronger strength would be or yield strength would be higher for this material if the width of the dislocation is small.

And the make sure the burgers vector is large. On the other hand the width of the dislocation is large and the magnitude the burgers vector is small I shall have a lower value this (()) (22:15) okay. Alright now let us look at this 3, 2 things in covalently bonded crystals. Covalently bonded crystal typical one is.

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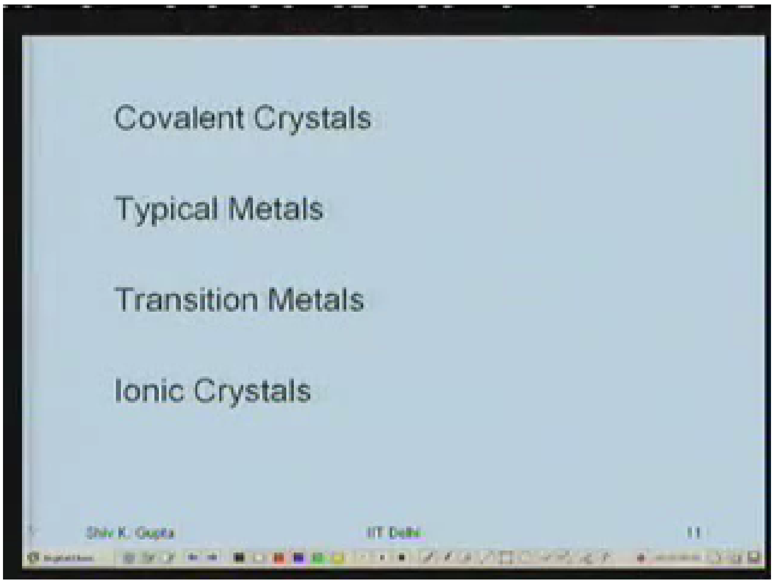

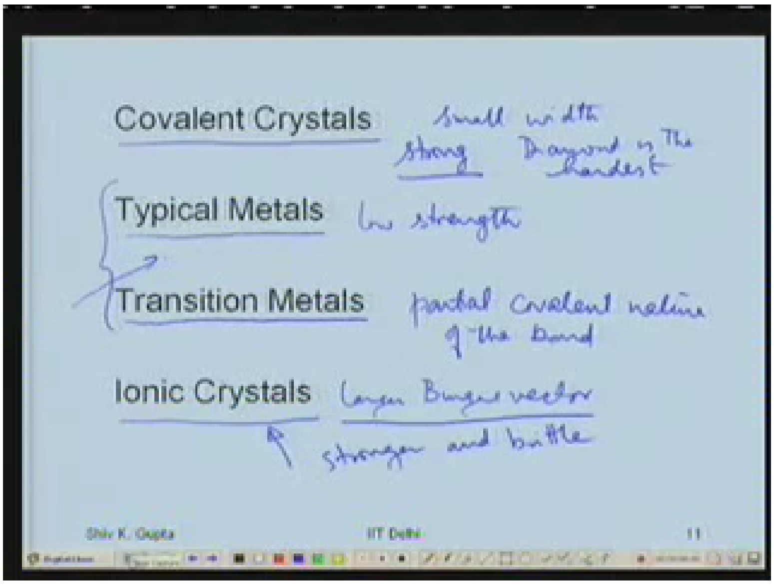

Co diamond which is a all primary by SP3 bonds in three dimensional otherwise most of them have some security bonds also there is a property have to (())(22:51) by them and secondary bonds are providing the low strength to the material the width of the dislocation is very narrow. Covalently bonded crystal small width burgers vector is whatever is the diameter but in diamond it is more than that, more than the carbon diameter why?

The direction they formed with bond there is no close pad direction because of lots of space after two atoms there is space for two atoms then there are two atoms and space for two atoms. So slip will be more easy if it is done along the face diagonal which is the smaller distance then 2 diameters but its more than 1 diameter definitely so because of that this slip occurs in the direction 110 rather than, 111 in the diamond cubic right.

So therefore the burgers vector is also little larger it is very strong material very hard material as a matter of fact diamond is the hardest. In typical metals like copper, aluminium, gold, silver, platinum the width of the dislocation is large and now the burgers vector is also small just (())(24:46) diameter right. FCC and BCC matters most of them we have low strength sorry soft materials you can deform them.

Then transition metals have partial covalent nature the bond they are stronger than this typical metals and titanium, nickel, manganese, chromium all this transition metals tungsten, vanadium they are stronger metals because the partial covalent nature of the bond its the width of the dislocation which is small not the burgers vector. Burgers vector still they (())(25:40) or the atomic diameter but it is the width of the dislocation which is narrow in the case of tension matters because the partial covalent nature of the bond.

There strength are higher would have seen that the steel mild steel you tasted as compare to the aluminium you have tasted okay. Then we have ionic crystals here its not so much the width of the dislocation but the burgers vector its not the nearest distance between 2 ions just like in diamond if I make the nearest distance between two ions then when there is a slip taking place or there is a formation of dislocation 2 ions with the same size just come opposite each other.

And there will be strong repulsion so width of the burgers vector is larger here in ionic crystals. So in this case is the burgers vector which is larger causes the strength to go up and these materials are also stronger but at the same time brittle. Like the covalently bonded material.

Alright now having seen this effect of the width of the dislocation and the burgers vector once we understand that we have to look at the transition metals and typical metals where the plastic deformation occurs by enlarge and we deal with this materials as structural materials as engineers we explain them.

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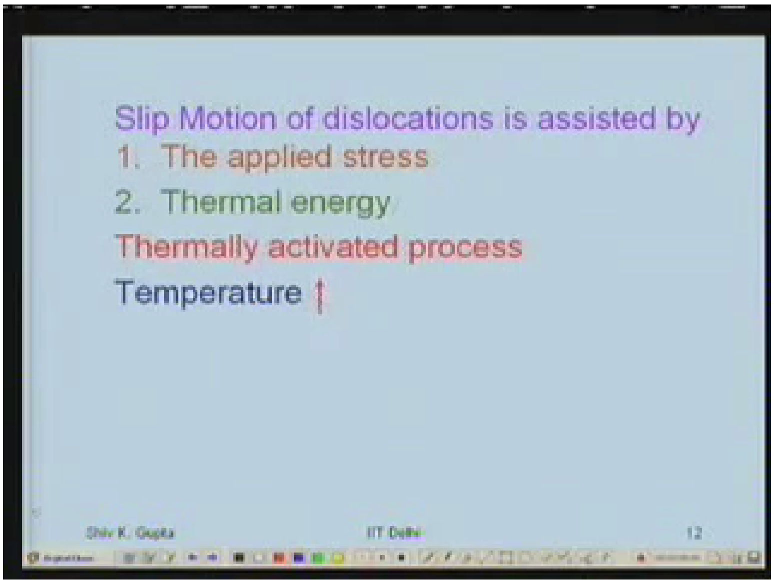

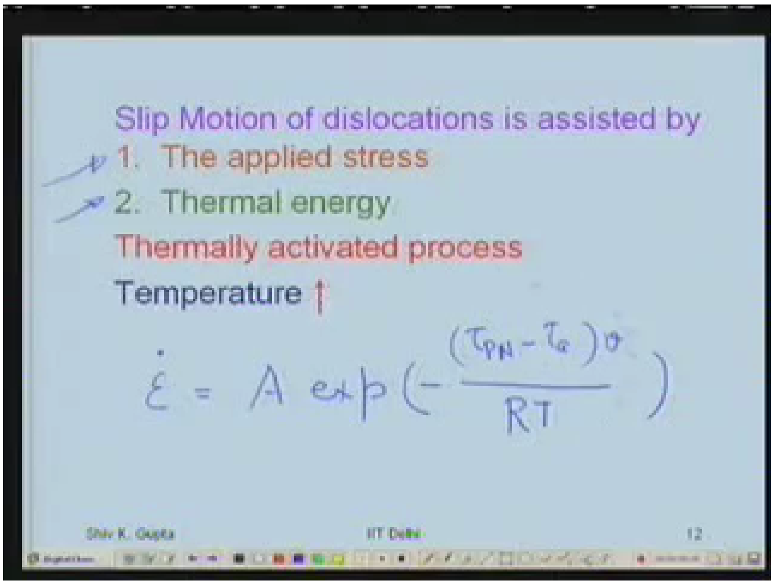

Now the slip motion of the dislocation is also thermally activated process but thermal energy provides the jump in all possible direction to the dislocation so net result is dislocation doesn't move its stays where it is because the thermally activated process thermal energy provide its for random happenings atoms are jumping randomly to the right to the left, up , below so as a result dislocation remains where it is net result is zero moment only when the applied stress is there it provides a direction then thermal energy also assist.

So the slip motion dislocation is assisted by the applied stress and of course there is role of thermal energy because the thermally activated process so as the temperature goes up there is more role of the thermal energy so applied stress becomes less effort because thats the only provide the direction as a temperature is lower applied stress has to go up because thermal energy is providing less effort to less in a low energy available so low effort from there and if it is thermally activated process its also possible for you to write like a (())(29:19) relationship the rate of deformation which you get in a material.

Okay while its possible let me clear it for you the strain rate can be written as some constant tans exponential of minus Q by RT, Q is the thermal energy thermally activated process activation energy what is provided by the thermal energy essentially and that has to be pulse and (())(29:54) stress that is a stress active thermal activation required zero Calvin minus the applied stress at any other temperature to convert this into stress into energy I multiply by the activation volume activation volume is volume around the dislocation.

Where the effort has to be applied by the thermal energy divided by RT we should be able to explain many things how the applied stress changes with temperature and things like that suppose I maintain the constant strain rate at all temperature when you are testing did a test by (())(30:39) the hand your strain rate was not uniform any way but if you put a lets say consider a motor there with moves that a same speed so strain rate will be uniform whether it is tested at room temperature you tested at 200 degree centigrade or tested just below the melting point okay.

So if that is the case strain rate is constant then once the applied stress as a function of temperature that means this number should be constant for this number to be constant the numerator tou Pulse and (())(31:19) thats T tou PN minus tou A applied stress this difference must be this divided by temperature must be constant so temperature increase is that difference must increase that means applied stress must go down so thats a constant, thats a constant of the material.

So as a temperature rises stress require to cause plastic deformation material decreases and over the strength yield strength of the material goes down as the temperature increases. Right thats what I have shown here.

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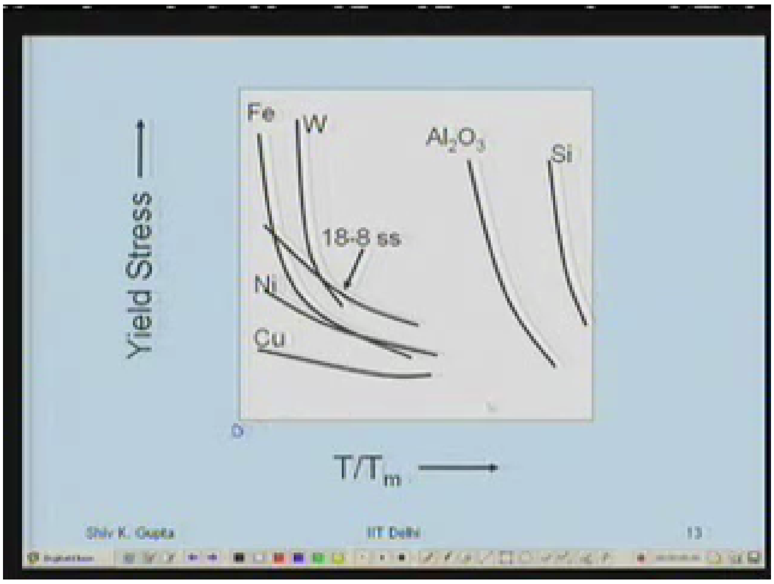

I plotted temperature divided by melting point this could be zero Calvin zero here and melting point it would be 1. Okay for typical matters like copper which is FCC, nickel which is FCC, 18-8 stainless steel that is 18 percent chromium 8 percent nickel this is normally the stainless steel which we use thats FCC material austenitic stainless steel these three FCC materials you see have a very small dependence on temperature except in stainless steel little more and nickel also because the end of the a transition metal.

But copper is also the transition metal its dependency is very low on the temperature. It doesn't increase, in increase is alright because as the strain rate says that should so therefore that is a dependency (())(33:01) how when you go to a typical (())(33:03) metal like iron or tungsten it increases very rapidly as the temperature lowered at high temperature again the small dependence but lower temperature dependency is very strong.

Partial covalent nature of the bond plays role there but theseAL2O3 and silicon Al2O3 is ionic bond, silicon is a covalent bond see that dependency is very strong on temperature so very strong dependence on temperature over these materials. While here the dependence is lower the high temperature but very strong at low temperatures very close to the (())(33:45) right so thats the dependence on temperature thats what on the yield strength of the material.

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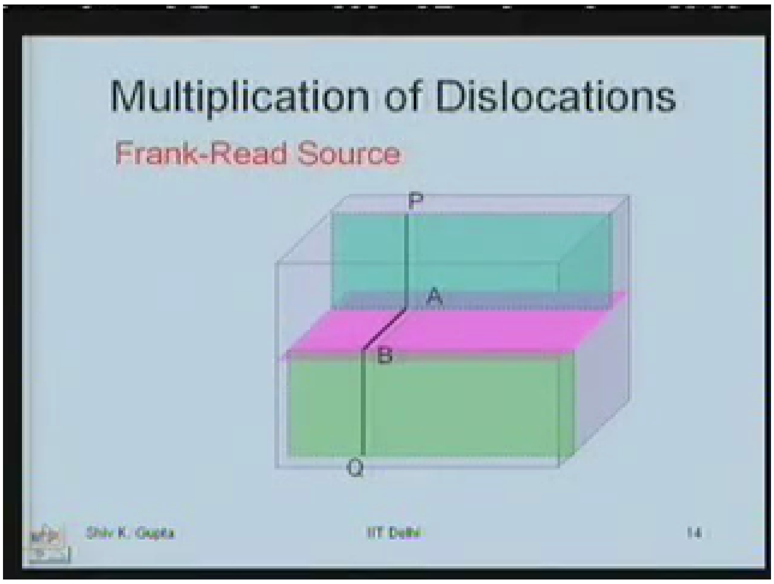

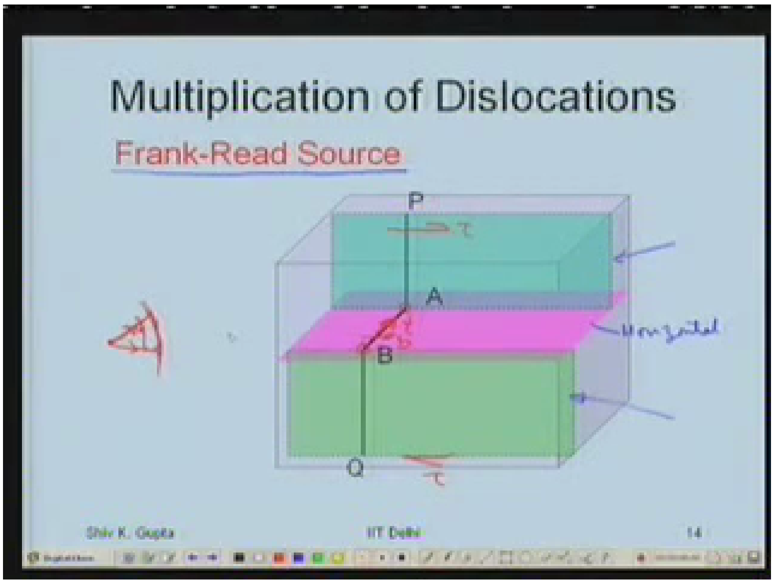

Wow, if that is the case that dislocations are responsible for causing plastic deformation in a material and once a dislocation gets out of the crystal is no more available to slip it can not cause any more further deformation so any dislocation which is present in the crystal gives me a step over equivalent to one burgers vector which is a permanent change in shape of the crystal only one burgers vector if I have let us say 100 dislocation in a crystal I'll get 100 burgers vector.

And the dislocation is out now I am left with perfect crystal to get more deformation now I'll should go apply the strain stress of the order Mu by 6 and that the strain which you will get is very small negligible strain even if I have a dislocation density of 10 to the power 10 meter per cubic meter in a crystal I will not get more than point 2 percent strain very small strain I shall get.

But you are deform this solid like steel they are deform like aluminium get quite a few percent of elongation you get strains you get are very high okay how do we get that. That means they should be a supply of dislocation and (())(35:25) crystal. Dislocation rather multiply when we start deforming material and number keeps increasing that I shall demonstrate with the help of until what I call the Frank read source there could be variety of sources in material that is just worry about 1.

And you see the (())(35:47) that how the dislocation number increases when they dislocation begins to slip we know that all dislocation which are present in the solid they are not straight line, screw or edge dislocations they are zigzag curvy linear lines mixed dislocation kind of things. Right so I show you here amongst that zigzag a simpler model of a dislocation which is possible for to get that dislocation line PQ which is actually PABQ, PA lies on the vertical plane which is shown there.

And AB lies in a horizontal plane which is this pink plane and BQ lies on this another one which is in a front vertical plane so there is a dislocation PABQ which lies on 3 planes one part of it lie on the plane PA another plane vertical plane rather I should say thats a vertical plane this is also a vertical plane but this is the horizontal plane AB part lies on this lets say on this crystal I apply the shear stress in this fashion.

I am trying to top part to the right and bottom to the left okay shear stress is always shown by 2. It has to be this okay. Never by one arrow single arrow doesn't show that indication right so this is the stress shear stress which I apply what is the result component of this shear stress on the plane in which I have the component PA. I applied this that is on this vertical plane shear stress on that will be zero and what is the shear stress component on BQ?

Student: Zero

Professor: Zero, there is no stress on component PA there is no (())(38:15) stress on the component BQ they will not select. But there is a shear stress applied on to the AB it would like to slip. Funny situation part of the dislocation would like to slip other parts don't want to slip.

Point A and B shall remain intact because there is continuity of the dislocation line, dislocation line cannot end up the (())(38:41) inside a crystal that continuity has to be maintained at A and B, displacement of the displaced side not displaced side has to be maintained at the boundary and therefore A and B shall remain fix. It is the middle part of the AB somewhere here which will find that its not tied to A or tied to B this will like to move it will like to move forward.

And as I told you earlier a dislocation line slip all ways perpendicular to itself under this suppose I consider this as the okay this is the mad stress so lets consider this to be a dislocation line T vector in this direction and screw dislocation sorry adjust location the burgers vector in that direction so T is in that direction B is in this direction and I apply the shear stress which direction should the dislocation moves suppose A and B are not tied. This is negative edge or positive edge?

Student: Positive

Professor: Positive edge, which way it should move?

Student: sir, in this direction.

Professor: To the right.

Student: Right

Professor: It should move to the right, right. Alright so that middle component of the AB which is not feeling tied shall try to move forward right so dislocation move perpendicular to itself what happens to the neighbouring parts of that component they were also like to jump in that direction cause they go to next equilibrium position but when by the time you reach A this cannot move B it cannot move.

But at the same time component of the dislocation which is close to A and B can rotate. Rotation also provide (())(40:35) slip motion perpendicular to the dislocation line T. See if I have something like this which rotates in this manner direction of motion is been all the time perpendicular to the radius thats a tangent you draw anyway so rotation is also slip motion.

So at A and B dislocation begins to rotate so in between A and the middle part B and the middle part components rotate as well as jump. So the neck motion remains perpendicular dislocation line okay so what happened is lets now show it here.

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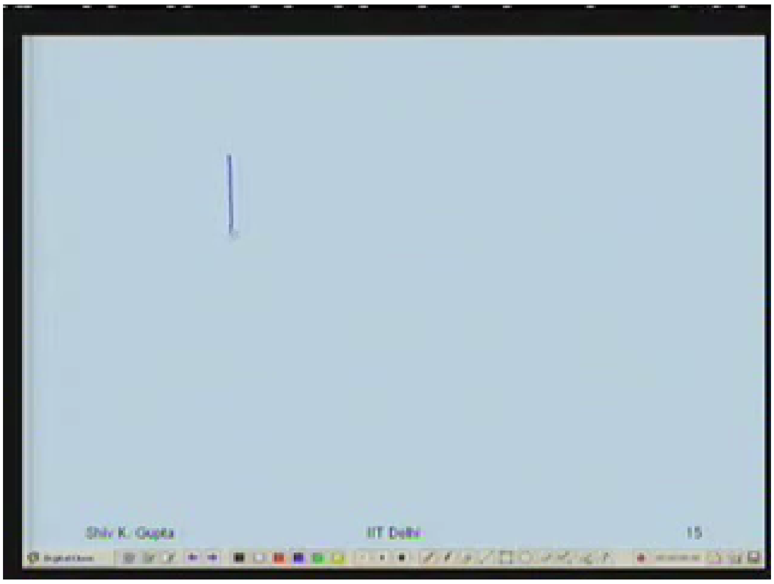

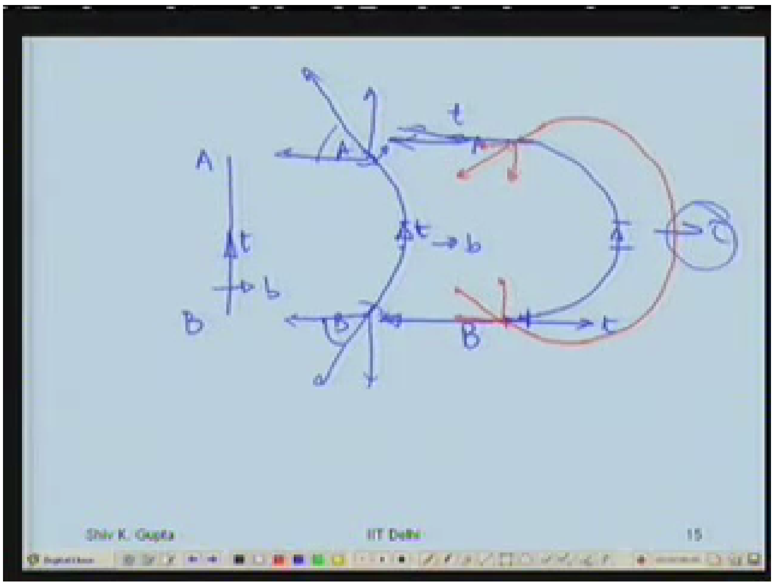

So what happens is between A and B this is looking at begins to (())(42:01) like this once you does that actually this component which is here as nearly rotated this component which is here as rotated its only the middle part which has moved balanced step or other parts have rotated and moved this is the only part here which is rotated this goes on under the applied shear stress which is like this till it becomes a semi circle.

Once it become the semi circle the T reactor here in this direction and T vector here is in this direction. You see this is still the edge dislocation all others are become mixed dislocation this has become the screw dislocation while this has become the first screw that has become the negative screw. This is the stage where you have reached here here apply the maximum possible stress to reach here even applied.

Once you have done that further motion while why it is the maximum stress here apply this because thats the time line tension which is acting in this direction sorry is a 100 percent opposing it in this direction the line tension 100 percent was not opposing to applied stress only this component was opposing the applied stress and this component was cancelling itself you know.

So line tension is now fully opposing it so applied stress has to be maximum at this point now when it further moves slightly this point further rotates upward this one now rotates like this taxi shape beyond this now you notice that the line tension is becoming small again like in the previous case when it is not become the semi circle and this vertical component is cancelling otherwise the stress you applied is more than enough to bring it to the stage.

Well it is like that good enough even to the bring it to this stage because this component shall keep rotating you know it shall keep rotating like this, this component shall keep rotating like this. And now as a matter of fact the line tension is helping you because component in the direction will begin to help you applied stress the words that like I am talking about the slip.

After you reach a stage where there is they are not reached over the maximum of the potential energy (())(45:56) inflection point beyond that reaching the maximum and further moment is automatic because you apply the maximum stress possible so maximum stress you applied when it becomes semi circle rest to the things will be all automatic okay. Now let me take you to another step which is very close to