

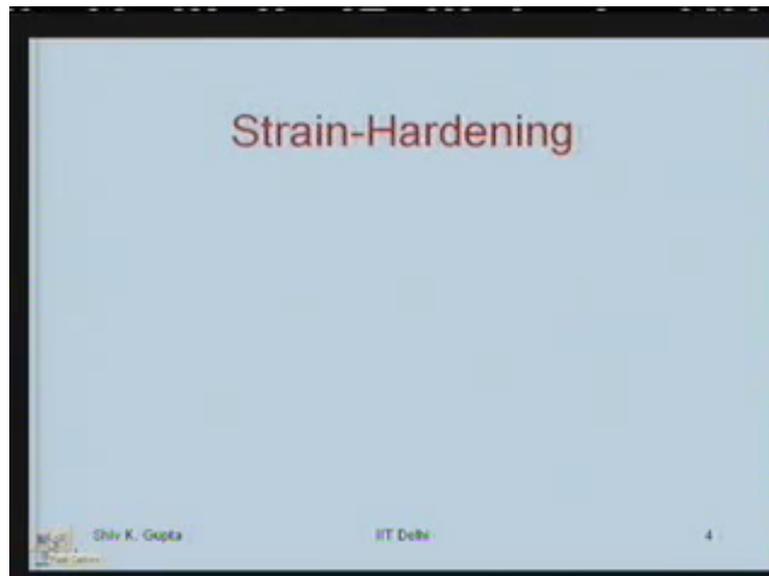
Material Science
Professor S. K. Gupta
Department of Applied Mechanics
Indian Institute of Technology Delhi
Lecture No 30
Plastic Deformation (Contd.)

(Refer Slide Time: 1:03)



Well we were talking about the plastic deformation and we saw that plastic deformation mostly occurs in materials by the slip motion of the dislocation and when these dislocation began to slip in the materials they also begin to multiply the number in the solid, the stress required to make the dislocation slip, we refer to it as critical resolved shear stress and now we shall begin to see how is it possible for a material to resist the slip motion of the dislocation thereby increase the critical resolved shear stress or in other words increase the yield strength of the material. These are referred to as various strengthening mechanisms in materials.

(Refer Slide Time: 2:08)



And first of all we shall look at the strain hardening. Strain hardening as you have seen in the tensile test that when plastic deformation occurs in the material after a certain amount of strain if you want to further deform it or further strain you will have to apply more stress. Now when a dislocation is causing this deformation of the material suppose I have a crystal like an HCP material or HCP crystal where the slip planes are only hexagonal planes and they are all parallel.

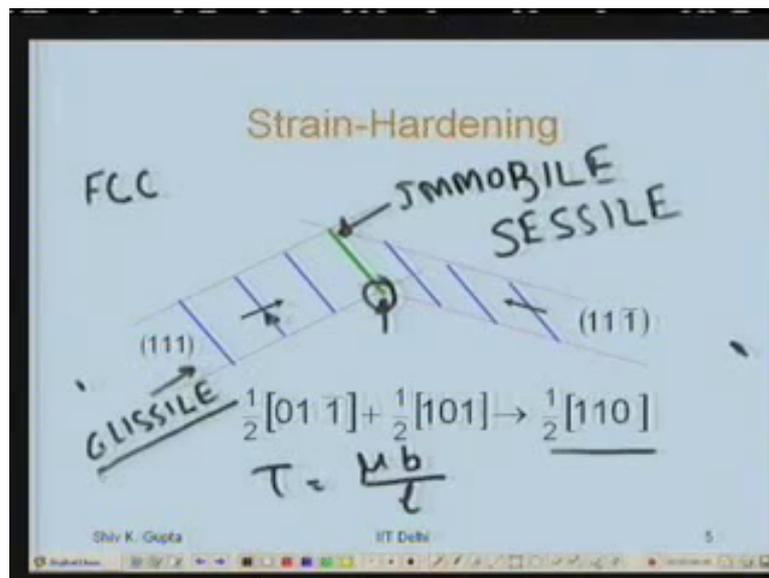
Therefore once a dislocation of a Frank-Read source begin to operate on one of the planes that continues to operate and dislocation one after the other keep onto the surface and keep causing the plastic deformation in the material. There is no problem in such situation, if there is Frank-Read source also operating because it is also of the same size but lies on a different slip plane that is also possible. They two Frank-Read sources will not interfere with each other.

Student: The strain will continue to happen but the stress will remain the same.

Professor: Stress will remain the same, yes. There is no strain hardening basically taking place there that is what I am trying to hint at because nobody is able to resist the slip motion of the dislocation. So there is no strain hardening whatsoever, it goes on at a constant level of stress, whatever the result shear stress require operating the Frank-Read source and that Frank-Read source keeps operating. You recall that Frank-Read source requires depending upon its size.

The length of the Frank-Read source it requires the stress. However slip planes are not parallel in all crystals. FCC and BCC, FCC has the family 111 which are 4 members which are known parallel. BCC has 110 family whereas 6 known family members and such slip planes do intersect each other, there is a common line, common direction, which are not parallel, they will intersect in space, in the crystal itself they will... And suppose there are two Frank-Read sources operating in two such planes which are not parallel to each other what shall happen, that is what we shall look in the strain hardening.

(Refer Slide Time: 4:50)



Let us say I have a FCC crystal. This is a 111 plane on which some Frank-Read sources are operating somewhere here and giving us loops after loops, and 111, 11 bar 1 plane and the Frank-Read source is operating somewhere there and it is giving loops after loops. These planes intersect at this line, the green line and the leading dislocation from this source reaches here and the leading dislocation from here reaches here and when they reach together here there is an interaction between them.

A dislocation line is a strain field along the line in the crystal. 2 strain fields always go interact if it is possible for them to lower the free energy and I am showing you one such reaction, not always such thing can happen. Half 01 bar 1 is the Burgers vector the dislocation which lies on this plane. Half 101 is a Burgers Vector dislocation which lies on this planes or the Frank-Read source that is operating there, that is the Burgers Vector.

These two Burgers vectors, means the two strains will add up and give me the resultant strain on the green line, green dislocation line and this is half 110. You see the magnitude the

Burgers vector is the same. So energy of the two dislocations has become equal to the energy of 1 dislocation when they interact like this and some energy is lost, energetically favorable process, alright.

But when I get a dislocation like this formed with a Burgers vector half 110 check whether this dislocation line can slip on 111 plane or it can slip on the $11\bar{1}$ plane because there is enough resolved shear stress on this there is enough resolved shear stress on this, can it move on anyone of those planes it can continue moving on this or it can continue moving on this one. Is it possible for it to...? What is slip plane? Slip plane is defined as one containing the T vector and the B vector this is the dislocation line that is the T vector and this is a B vector both lie on the plane this is a slip plane.

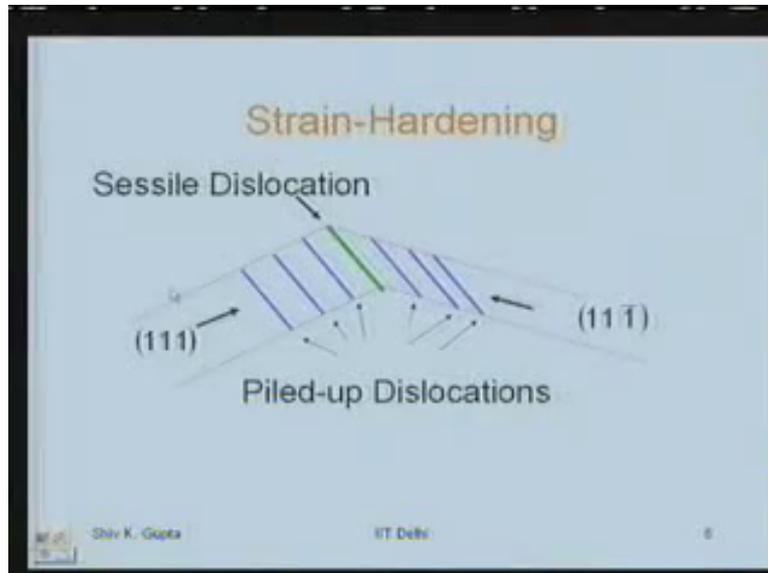
Now 110 does not lie on 111 plane, 110 does not lie on the $11\bar{1}$ plane, so the resultant Burgers vector is out of these 2 planes. Therefore some other plane on which this dislocation line lies now, it does not lie on the slip plane it does not lie on that slip plane and on the 3rd slip plane I may not have enough resolved shear stress and this dislocation will not be able to move at all after this if there is no enough resolved shear stress there and I call it an immobile dislocation, an immobile dislocations are also called sessile dislocations they cease to move and all this dislocations which are moving which are slipping are called glissile dislocation they are gliding.

In other words when they are Frank Read sources operating on 2 nonparallel slip planes it is possible for me to form immobile dislocations. Once this immobile dislocations form any dislocations coming from behind here will be obstructed by this it will not allow it to slip further and similarly any dislocation coming from this will be stopped by this and as a result there shall be a pileup of dislocations starting from here right up to the Frank Read source will be a pileup of dislocations starting from here right up to the Frank Read source and these are all dislocations with the same sign starting from the Frank Read source till the leading dislocation here they are all of the same sign start repelling each other and this is not allowing it to move further.

So they cannot push this one out because this is resisting its motion and as a result there is a back pressure on to the Frank Read source and Frank Read source stops operating it does not produce any more loops it does not produce any more dislocations. Now you will have to apply a higher stress may be to operate a smaller Frank Read source which lies on some other plane because this Frank Read sources are becoming inoperative and there is one explanation

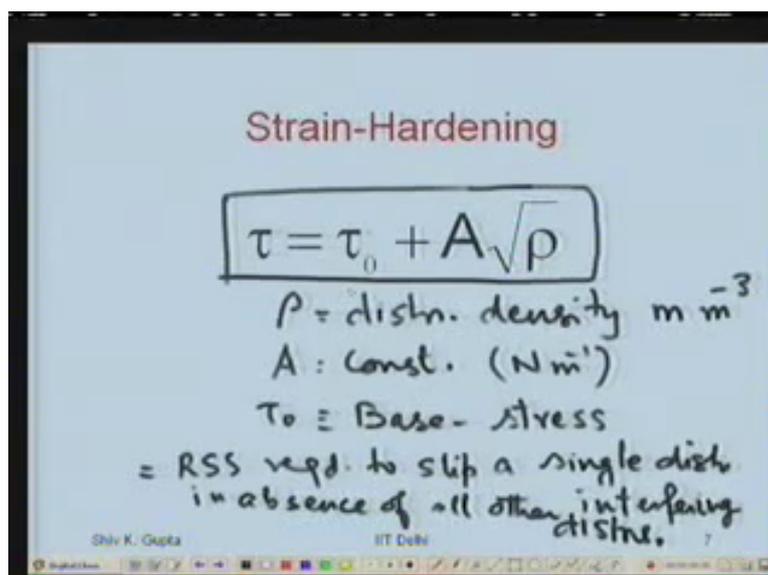
for the strain hardening. Now you will have to operate a small frank read source at first small frank read source we have to apply more stress τ is smaller so τ will be larger you have to apply more stress alright that is one explanation for strain hardening right.

(Refer Slide Time: 10:51)



That is what I said this is called a Sessile dislocation and this is a pileup right up to the frank read source and the pileup the first dislocation is always called the leading dislocation and the rest of them are trailing dislocations. Leading dislocation is being pushed by the trailing dislocations and this is being stalked by Sessile dislocation.

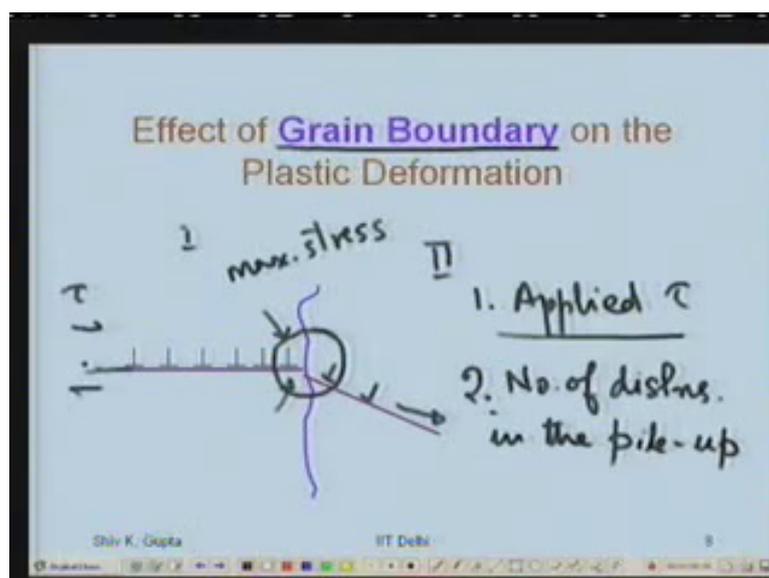
(Refer Slide Time: 11:17)



Empirically we have found out that as we deform the material the dislocation density in the material goes up and the relationship of the resolved shear stress (τ) (11:29) or critical resolved shear stress for making the dislocation slip is a linear function of the root or under root of the dislocation density. Here ρ is the dislocation density and dislocation density you know is expressed as length of the dislocation line per cubic meter of the crystal. A is proportionality constant as a unit of Newton per metre and τ_0 we referred to as base stress. What is this base stress equal to actually physically what does it mean? When is the critical resolved shear stress equal to τ_0 ? No dislocation perfect crystal?

It is a perfect crystal and a perfect crystal is μ by 6 very high already then how is it increasing by or strain hardening taking place? You should not forget that we have already said that plastic deformation in a material is caused by the slip motion of the dislocation, so I have to refer to the slip motion of the dislocation. So this is the stress required to slip a dislocation in absence of any other interfering dislocation in the crystal. Only when there is an interfering dislocation the density there should be formation of sessile dislocations (τ) (13:24). So when there is no interfering dislocation a single dislocation keeps slipping without problem that is what is called the base stress okay that is resolved shear stress required to slip a single dislocation in absence of all other interfering dislocations. So this is only an empirical relationship you can see the dislocation density is more there will be more interactions possible and there will be more formation of sessile dislocations okay.

(Refer Slide Time: 14:37)



So that the effect of cold working or strain hardening we have also seen in experiment and if you give you the material which is cold worked maybe its yield stress gone up but it may

not give you the percentage, elongation and tensile test as much as un-deformed would have given. If you deform it more it may be its yield strength make go still up but the percentage elongation it gives before the failure will be less that will keep decreasing that means materials while becoming stronger is becoming less ductile becoming less and less ductile okay that is usually the case when material becomes stronger generally it becomes less ductile or it becomes brittle.

Now let us look at the another mechanism which increases the strength or resist the motion of the dislocation that is the presence of grain boundaries in the material means the poly crystalline solid. Presence of grain boundaries... What is a grain boundary? I have a crystal one here I have a crystal 2 here that is grain. These 2 have a different orientation. Let us say I have shown a slip lane if it is (111) material 111 plane is here another second crystal the 111 plane is a different orientation. Orientation is different the 2 crystals they are not parallel, if they were parallel this would not be the boundary between them it would be the same crystal there right but these 2 crystals have a different orientation therefore I have a boundary.

Now when frank read source is operating somewhere on this frank read source are on the slip plane here it is giving rise to loops after loops and this is the leading dislocation here and a pileup is formed. When it comes here it does not know where to go it is a grain boundary and this slip plane does not continue in the solid it gets obstructed in the grain boundary. Now as a result this is a grain boundary and this is obstructed by the grain boundary well if something can be accommodated we get lost but some other thing else will come, so therefore there is a leading dislocation here which is obstructed by ultimately a grain boundary here it does not know where to go.

As I said all the dislocations of pileup are all of the same I have shown them all the positive dislocation. Somebody could have shown them all positive (111) dislocations and they are repelling each other, so the maximum stress once you have applied this resolved shear stress to operate this frank read source let us say like this there shall be the maximum stress under this and is trying to push it out that maximum stress because all the dislocations are pushing it out but there are all repelling and in turn this is all repelling each other and the frank read source is getting obstructed right but let us look at the situation this stress onto this leading dislocation. Leading dislocation means this region the stress which is being applied by these all the dislocations of the same sign here they are doing this and it is like you are standing in a queue depends upon the length of the que and a push when it comes the person

on the front is the one who is going to fall flat and if standing in front of a counter he will topple over-the-counter.

It is a question of how much push is coming if there are 100 people there will be more push if there are 50 there will be less push, so in other words depending upon the number of dislocations in the pileup depends upon the stress which is developed here. If the number of dislocations of pile up is more, more stress is developed here. Number of dislocations of pileup is less there will be less stress developed here. Now what dictates number of dislocations in the pileup? The distance of this leading dislocations in other words a grain boundary from the Frank read source. The distance from the Frank read source of the grain boundary is more there will be more dislocations in the pileup, if the distance is less there will be less number of dislocations in the pileup.

So if the distance is shorter there will be less stress developed here or concentration of the stress I should say will be less, if there are more distance there will be more stress developed here and of course whatever the applied stress resolved shear stresses here which is making the Frank read source operate that is what you have applied. If that is more that concentration will also be more okay or the concentrated stress here will be more, so it depends on 2 things we applied stress and the number of dislocations of pileup.

Let us say there is a certain value of stress required here so that the resolved component is good enough for the dislocations to move onto this slip plane, so plastic deformation would be continued under the neighbouring grain and it can provide more space for these dislocations out of the (())(20:41). So the plastic deformation would continue if it continues in neighbouring grains otherwise it was stop here itself and you would not see the plastic deformation externally, so I need a certain value of stress here so that stress of this becomes enough and the dislocation begin to slip on this plane which may be present in this crystal here.

Student: (())(21:06)

Prof: That depends upon the grain what is the dislocation or the slip plane (())(21:14), what is the slip plane for that? See the stress you are applying maybe a tensile stress or sometimes the compressive stress this becomes the resolve shear stress of this slip plane. Similarly it is possible for that become resolved shear stress of this slip plane and that is what is going to make my dislocation slip on this but I need a certain value of this concentrated value here

which will depend upon 2 things as I said number 1 the applied stress and 2nd thing it depends upon the number of dislocations in the pileup.

Student: () (22:11)

Prof: Yes right here that shall tell me uhh see because once I have developed that stress shall be able to know that whether there is enough resolved shear stress for dislocations slip here and that shall be a certain value depending upon the orientation difference between them okay. So once let us say this whatever the structure I have whatever is the orientation of the 2 grains are I need that value. Now it shall depend upon the applied stress and the number of dislocations from the Frank read source up to the boundary in the pileup okay. Now tell me when is the distance from the Frank read source is more and when is the distance of the leading dislocation from the Frank read source is less? When is it less and when is it more?

Student: () (23:10)

Prof: Will depend upon what? It will depend upon the average diameter of the grain, if I have a very big grain the distance on an average will be more, if I have a small grains distance on an average will be less, so for small grains to have the same concentration of the stress here it is this which will have to be more. For big grains for the same concentration to be here this has to be less recall that I said fine grain materials are better mechanical properties I am going to tell you 3 aspects of that today I have told you only one.

That fine grain material will require higher applied stress for plastic deformation to go on the word yield strength of such material is going to be high. () (24:22) materials the yield strength is smaller because plastic deformation in a material is visible if not only one grain is deforming plastically, all the grains are deforming plastically and you can see it externally the change in shape and there are millions of grains, so therefore I have just considered 2 if the plastic deformation was here and it stopped this must continue simultaneously for that I need a stress developed here and that stress depends upon not only the applied stress also the number of dislocations are pileup. In a fine grain material number in the pileup is less, so applied stress has to be more and in the () (25:08) material number of dislocation of pileup is more, so there is more push by the dislocation themselves applied stress can be less right, so therefore we again have developed an empirical relationship through the experimental observation.

(Refer Slide Time: 25:28)

Hall-Petch Relation

$$\sigma_y = \sigma_i + kd^{-1/2}$$
$$\sigma_y = \sigma_i + \frac{k}{\sqrt{d}}$$

Hall-Petch
Constant
 $d =$ grain diameter
 $k = N m^{-3/2}$
 $\sigma_i =$ yield strength of the Single crystal

Shiv K. Gupta IIT Delhi

For this what we called the Hall-Petch Relation and this Hall Petch relation can be written σ_y is the yield strength of the material σ_i is a constant plus k is another constant what we call the Hall Petch constant and d is the grain diameter. Well units of k are going to be interesting Newton meter raise to power minus 3 by 2 or meter raise to minus 3 by 2 is Newton per square metre under root of meter comes from the d so it becomes Newton per square metre because after all it has to be a stress value. What is σ_i ? It is a constant but what is that? I have written it in a different way d raise to minus half as under root d the denominator that is a different thing. (27:05) what is σ_i ? When is σ_y is equal to σ_i ?

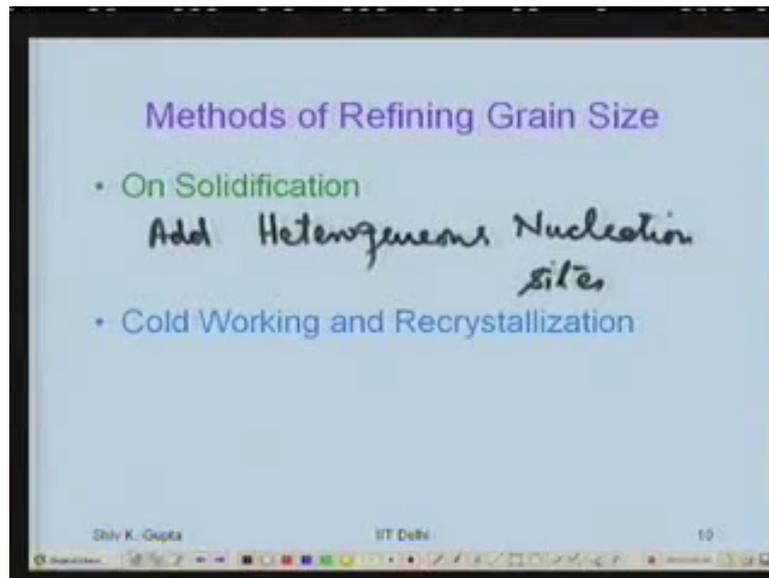
Student: (27:16)

Prof: What is the infinite grain diameter?

Student: Single crystal.

Prof: Single crystal yes, so σ_i is a yield strength of the single crystal alright this is again empirical relationship works well and the effect is found to be very dominant in steels with the grain size because k value is large for that. So to improve the strength of the material you would like to define their grain size something we have already talked about.

(Refer Slide Time: 28:09)



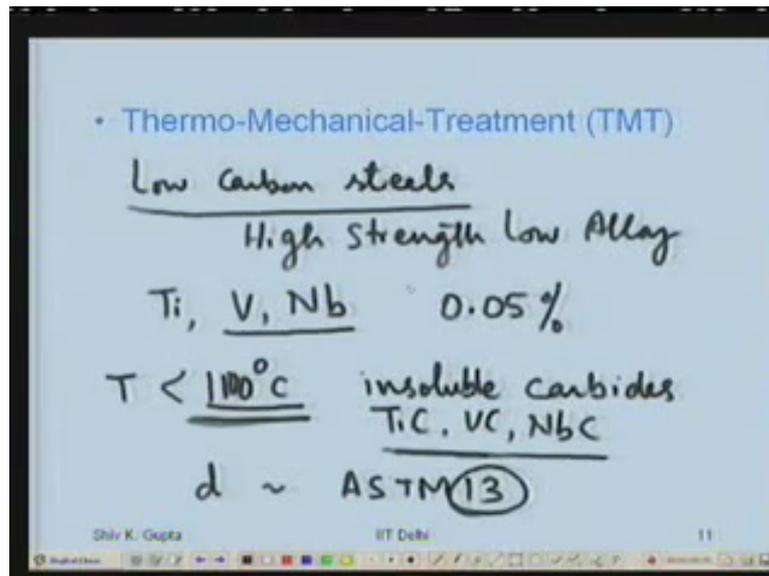
I just want to talk about one method which is a new method but before that I would like to consolidate all of them. How can you define the grain size on solidification while the liquid metal is solidifying how do you define the grain size?

Student: By slow cooling.

Prof: By slow cooling, slope cooling will give you (())(28:42) grains with slow cooling you will have high growth rate and low nucleation rate. You have had more heterogeneous nucleation sites and I have discussed this with reference to steel as well as with reference to aluminium. In steel we have aluminium or silicon powder which forms with the leftover oxygen, silica or alumina which act as a catalyst for the formation of the uhh (())(29:22) grains. Similarly in aluminium there is some carbon from the electrodes that is utilised by forming carbides with strong Carbide formers like titanium, vanadium, zirconium, et cetera.

These are added and they form carbides which have high melting point much higher than that of aluminium and they act as heterogeneous nucleation sites for aluminium grains to nucleate alright. Then you can deform in the solid-state itself if you can deform a material you can deform it uhh do the cold working and then allow the (())(30:00) to take place. Do not allow the grain growth to occur you have to control your time and temperature so that there is no grain growth but there is only the re-crystallisation right you can define the grain size by that technique.

(Refer Slide Time: 30:21)



Now we shall talk about the thermo mechanical treatment. This is possible uhh particularly if you recall re-crystallisation is hindered by insoluble particle of the 2nd phase if they are present they will not allow the grain boundary to migrate and make very fine grains to form during recrystallization. So this Thermo mechanical treatment which we do for low carbon steels these are called high-strength low alloy steels, the Carbide formers are titanium in India we have lot of titanium available but we do not have vanadium and niobium this has provided good experience in American continent vanadium and niobium.

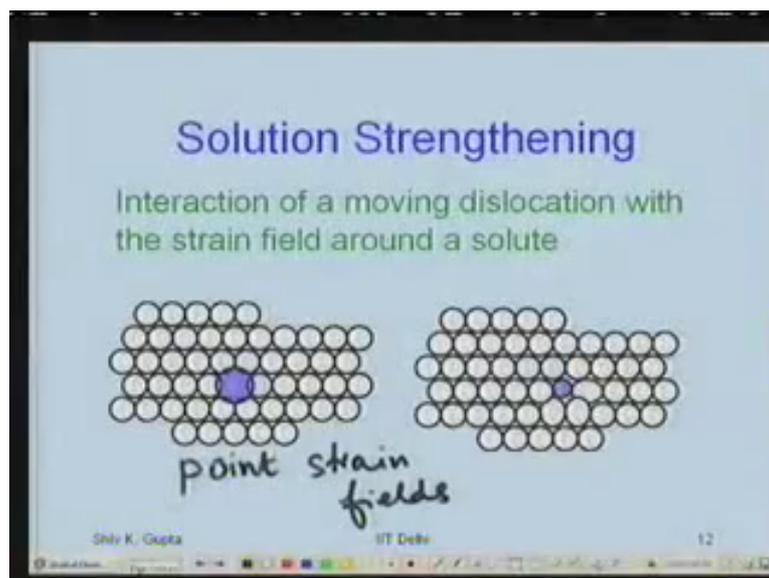
This the quantities you have to add of this alloying edition alloying elements is of the order of 0.05 percent by weight just half a KG in 1 ton of steel if you make an (())(32:12) of 1 ton you have to add half a KG it does not increase the strength of I mean the cost of the steel very much but what it provides is that this forms strong Carbides which become insoluble below 1100 degrees centigrade, below 1100 degrees centigrade these becomes insoluble carbides we do not dissolve in (())(32:42) and such and an (())(32:58) which is there and you are trying to form it to a shape of a rod or a channel or a I channel or anything you want to make the shape out of it whatever cross-section you are making pass it through the rolling mill in a temperature range of 950000 degrees centigrade. At that temperature this carbides are already there and that temperature is above the re-crystallisation temperature you are doing hard-working.

So simultaneously re-crystallisation takes place where the deformation is going on through the rolling mill it re-crystallises and these carbides which are present they do not allow the grain boundaries to migrate the grain growth does not take place and you add up with very

fine grain sizes and grain sizes grain diameters of the order of ASTM 13 it is possible you can get. You are in the range of 3 micron or less when you reach there very small grain sizes possible by the (())(34:14) and it is because of the pinning of the grain boundaries by the Carbide particles which are distributed all over the volume.

These carbides are distributed all over the volume of the matrix (())(34:29) they are not present only along the grain boundaries. Well some of those which are present in the grain boundaries are not going to help you these are the ones which are present all along the volume and do not allow the re-crystallize grain boundaries to migrate and therefore we end up with very fine grain size in the steel that is the treatment which is done and it does not add to processing cost of the steel only add addition of the cost is 0.05 percent of these alloying edition which are little more expensive elements than iron itself but that is only if the cost goes up in the proportion of 0.05 percent so that is a small quantity which you have to add.

(Refer Slide Time: 35:41)



Now next of this strengthening mechanism is called solution strengthening basically presence of the solute in the matrix. Solute can be interstitial could be substitutional, when it is substitution will it could be smaller in size than the parent metrics atoms or it could be bigger in size. What I have shown here is a biggest substitutional solute atom in the matrix and it causes a strain in the neighbouring grains here sorry in the neighbouring atoms and the electron clouds are strains in this region.

Similarly smaller one neighbouring grains uhh neighbouring sorry atoms you can see these electron clouds are strain they are stretching there to form the bound with the solute, so as a

result there are strain fields in the matrix around the solute where strain fields and the matrix around the solute and it is localised these point strain fields I can say that like they are the point effects I can call them point strain fields. Plastic deformation takes place by the slip motion of the dislocation, so it is moving dislocation. What is really moving dislocation in a solid or let us say crystal? What is a moving dislocation? It is a moving strain field because there is a strain field all along the length of the dislocation line be it the sheer strain be in the tensile strain or be the mixed dislocation the general kind of strain mixture of principle and sheer strength are there but this is a localised point strain field alright.

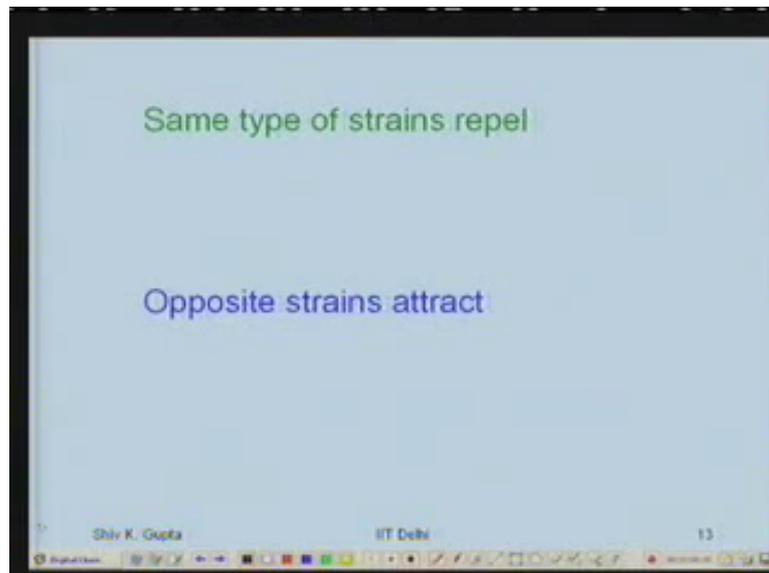
So when a moving dislocation comes near the strain field that is a moving strain field this is stationary strain field and when they come together close to each other there is an interaction between them. If the 2 strains stay in the dislocation and the strain around the solute are of the same kind there will be repulsion between them because when they come together strains will add up it will go as square of the sum, so in that region that localised region there shall be an increase in energy. So there will be repulsion between them to overcome that repulsion you will have to post the dislocation close to this you have to apply more stress that means that additional energy you will have to provide from the external source and the source is the one which is making the dislocation slip.

So applied stress will go up but once it has come close to it getting away from this will be easier because getting away means strains are separated and energy will be lowered at that stage energy will be lost in the form of heat but bringing the dislocation close to this itself is going to be difficult let us say I talk of a different situation. The 2 strains are of opposite in nature moving dislocation and the point field around the solute therefore once they come close they will be attracted because strains will be reduced opposite strains they will be reduced strain energy will be reduced and that energy which is lost goes waste as heat in the material and then gets disappeared in the atmosphere.

Now when you want to make the dislocation slip further because plastic deformation will be complete only when the dislocation gone out it has to move from this point it has to move away from there make it move away from here you will have to now apply more stress because energy you will have to increase that energy back, so therefore whether the interaction is attracted or the interaction is repulsive either way you have to at some stage apply more energy or provide more energy to the system is do more work means you will have to apply more stress and that increases in strength of the material because critical

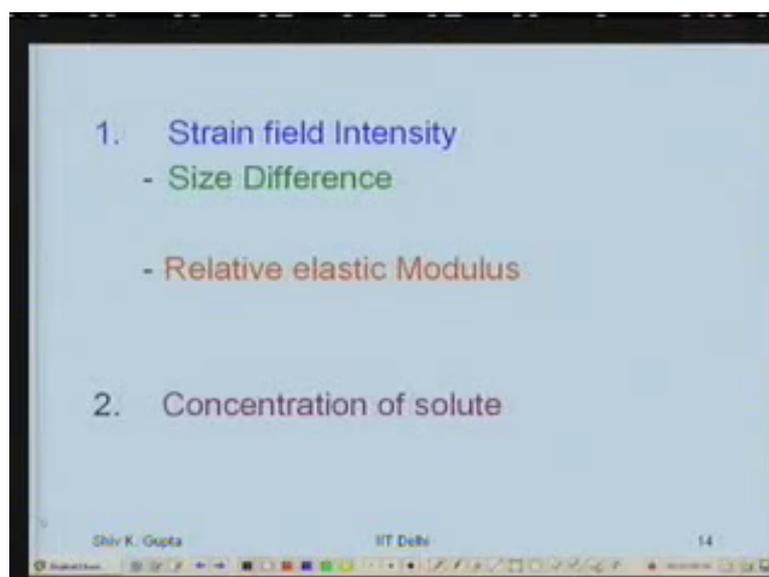
resolve shear stress goes up by that much amount and once you have reached that level of stress you do not decrease that stress, so you have to apply that stress and that is the increase in strength of the material. Now this increase in the strength depends upon well that is what I have already discussed the same type of strain they repel each other.

(Refer Slide Time: 40:48)



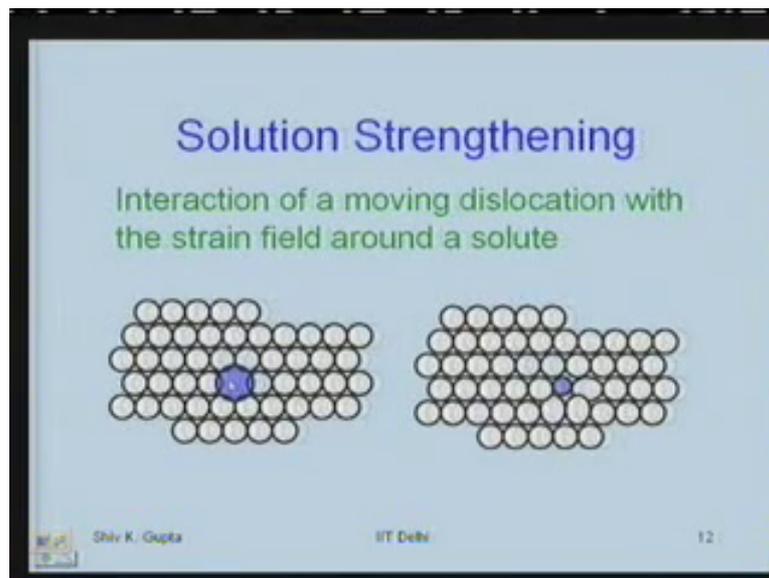
So bringing them closer is going to be more difficult and opposite strain attract each other taking it away will become more difficult they will be get attracted and then taking them or the dislocation taking away from the solute will become difficult. Now the point which I am trying to make is how much or what controls the amount of stress you need to apply.

(Refer Slide Time: 41:20)



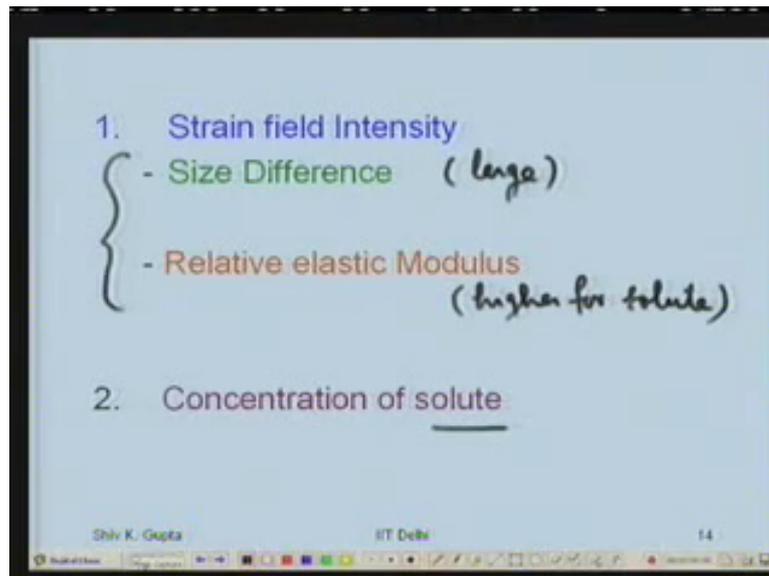
Well strain field intensity around the solute, if the strain field intensity is more interaction is going to be stronger and that is decided by the size difference of the solute and the matrix atom the solvent atoms. Solute atoms and the solvent atoms how much they differ in size or the radius will dictate the size difference and will cause this strain around the solute that maybe alright if I say modulus of elasticity of the 2 solute and the solvent at the same but if I say the modulus of the solute is very small negligible as compared to the modulus of the matrix, so what can happen is...

(Refer Slide Time: 42:26)



Let us go back then this electron cloud is more compressible when this uhh I say that this as a lower modulus that means this is compressible more compressible than these, so all this strains will be taken up by the electron clouds of the solute and it becomes of the same size as this parent atom that means all the strains are in the solute. If such a situation exists can a moving dislocation see that strain? It will not see the strain right and therefore I do not have any such material which has almost 0 modulus nothing is there, so therefore there will be some strain in the solute and some strain... On the other hand also it considers if these parent atoms has a very low modulus, if that is a very low modulus then all the strains will be in the matrix will be very high strain even that is normally not the situation but we are really looking at the relative modulus of the solute. If the solute radius uhh solute modulus is more definitely there will be more strain field right that is what we are worried about. Solute which is added as relatively higher modulus shall provide more strain field.

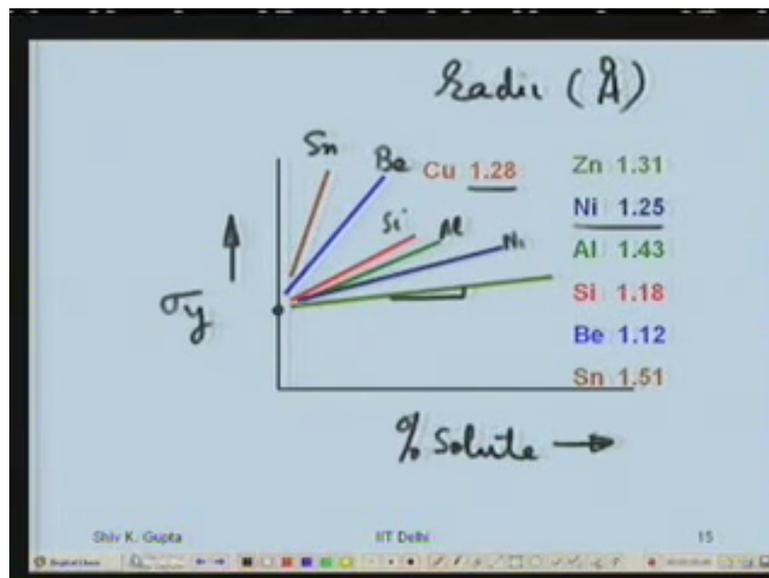
(Refer Slide Time: 44:16)



Alright so these are the 2 things, I need the size difference should be large for large strain field and relative elastic modulus should be higher for the solute and thirdly along the length of the dislocation line at how many places the interaction is taking place. If there is a small concentration of the solute that is 1 percent I mean in fewer places but if it is 10 percent large number of places the interaction would take place, so the concentration of solute is the next thing, so basically the strain field depends upon these 2 things this and the concentration solute depends upon how much solute you have added right but both these factors the size difference and the concentration are against each other.

What can go in solution should be less than 15 percent size difference if I want to extend the solubility but if the size difference is more than 15 percent I will have very limited solubility uhh we read the Hume-Rothery rules up to 15 percent possibly I can have extensive solubility and if it is more than 15 percent solubility will be restricted, so they work go against each other I want to add more concentration size difference should be smaller. When the size difference is smaller strain field will be smaller, so if I want to increase both I will have to make a compromise somewhere and this is what is shown here in the alloys of copper.

(Refer Slide Time: 46:09)



When I had different alloying elements what happens? This is I have here let us say yield strength and this is the percentage solute and that is let us say for the pure copper yield strength for the pure copper. When I add zinc to it the copper as a radius of 1.28 Angstrom these are the radii in Angstrom and the zinc is 1.31, when I add brass means from brass copper and zinc I can add up to almost 40 percent zinc to copper solute that can go on but the slope is smaller this slope is very small. For the same size difference nickel with 1.25 slope is larger than that for zinc this is nickel can see the color is the same as written here alright.

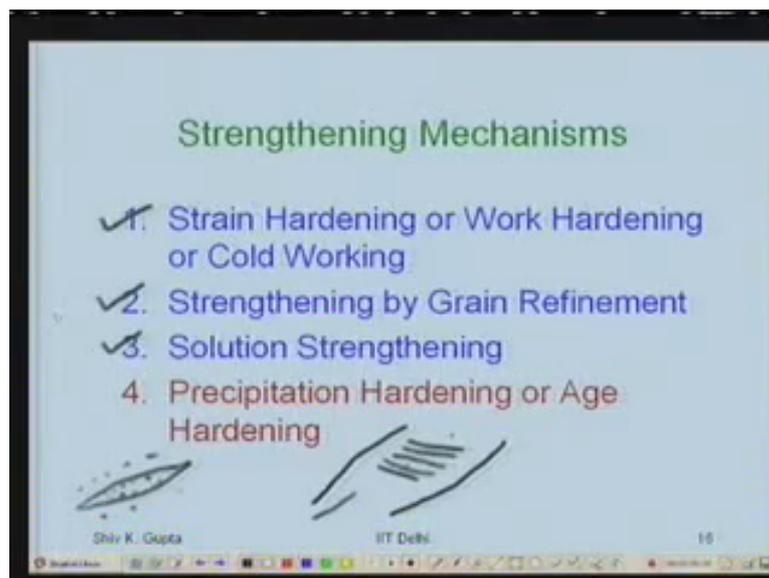
So with the same size difference nickel gives me more slope and I can dissolve nickel up to 100 percent right but 100 percent adding does not mean I have increased the strength or the modulus or the strength of the material it is the alloy which I am making about (47:48) is going up. While talking about the slope, why the slope for nickel is more than that for zinc? Size difference is small. Size difference is the same 1.31, 1.25, one is a smaller solute other is a bigger solute, smaller solute gives the tensile strength bigger solute gives the compressive strength strain field intensity is the same, is it?

Strain field intensity is not the same reason as elastic modulus when nickel is more than that of zinc and therefore it gives more slope than the zinc thus uhh zinc has a lower slope than the nickel. Similarly I put similar size difference kind of thing 1.43 and 1.18. 1.43 is aluminium and 1.18 is silicon, silicon has a higher modulus than aluminium. Similarly here this is beryllium and this is tin take the size difference is very large. Bronze are stronger much stronger than the brass is, copper tin alloy are much stronger but the amount of tin you add is not more than 5 percent it does not go in the solution that is also in the metastable

state, the equilibrium diagram says you cannot even dissolve that much amount of tin to copper with but below 400 degrees centigrade is not easy for tin to diffuse out and takes very long time.

So Bronze can remain uhh the tin can remain in solution up to about 5 percent and I cannot dissolve 40 percent like I can do that in zinc. I can add only small quantity but that increases that small quantity also increase the strength very much right. So that is the effect of these 3 things size difference and the modulus secondly the amount of concentration, more the concentration you add more is the increase in strength can see that and for a small amount of solute added it goes linearly or ultimately it would become a parabola because the other side also if as to go back you know somewhere in the middle the strength will be the highest then again it goes back to than the solute become solvent in that stage.

(Refer Slide Time: 50:28)



Alright these are the 3 strengthening mechanism which we have talked about strain hardening or work hardening that is the cold working. More you deform plastic (50:36) material more difficult it will be for the dislocation to slip I talked about the grain size. Finer that grain size hard will be the strength of the material and solution strengthening. Whole solute you can put uhh solvent or in the matrix more will be the strength and also the size difference is large will be more strength of the material. Well these are the 3 mechanism all 3 are working in one single material you have talked of martensite.

Martensite all these 3 are working 4th one we shall discuss in the next class will show you that also is working in the steel when I temper the martensite. Let us see how it is working strain

hardening in martensite. I told you martensite forms either the form of lath or in the form of plates. When it forms in the form of lath, lath are heavily dislocated there are high dislocation density means high strain hardened material and when it forms in the form of plates there is a high dislocation density in the (())(51:55) as well as inside the plate near the interface and there is a grain refinement and this particles are forming, lath are very small in size thickness of the order of 50 Angstrom 50 to 100 Angstrom lath have such small thicknesses and this plates are forming they are forming more interfaces and therefore providing for more presence of interface or the boundaries grain refinement is taking place. Also in the plates we have seen let me make a plate like this little bigger section in the mid rib this is the middle plane we find that there are presence of twins.

Each twin is again 50 to 100 Angstrom thick and thin boundaries also a grain boundary it also stops the motion of the dislocation like any other boundary orientation the other side is different I have to have enough resolved shear stress for the dislocation to move onto the next crystal, so therefore these act as grain refinement, grain boundaries are added by these and then all the 0.8 percent I consider the case of (())(53:17) all the 0.8 percent carbon is in solution in martensite it is not able to diffuse out no Carbide has formed as everything is in the solution though the solubility at room temperature of carbon in iron is only 0.002 percent what I have 0.8 percent all of it in solution, so solution strengthening is also taking place so all these 3 mechanisms are working there and therefore the strength of the martensite or its hardness is very high alright we shall look at the next one in the next class.