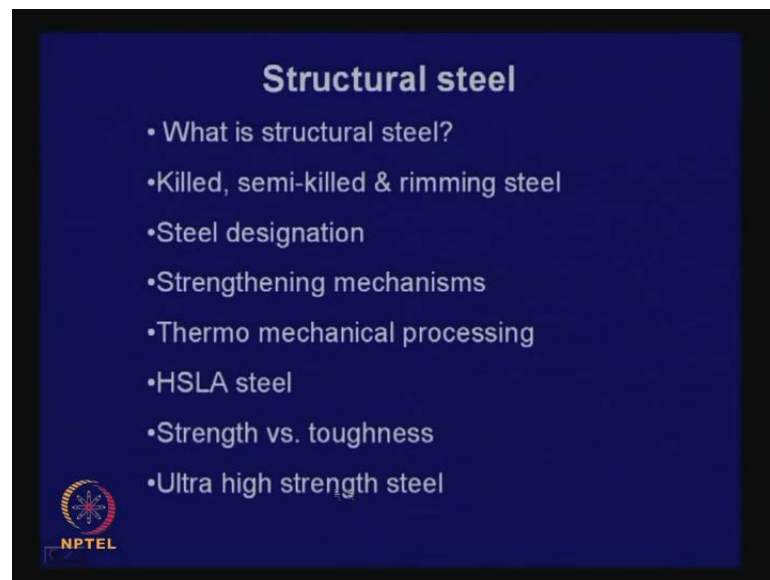


Principles of Physical Metallurgy
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Lecture No. # 39
Structural Steel (Contd.)

Good morning, we continue our lecture on structural steel, and we have seen in the last class that this is the bulk of steel, which is manufactured worldwide. It is primarily used for various structural applications, and there is an excellent way of if we can use or if we can cut down the use of steel, I mean the best way to use improve quality steel where its strength is higher, so you need less tonnage. So, that means more efficient use of steel there has been a lot of work has gone in on the last three decades to develop a range of structural steel, which have the best combination of strength and toughness.

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And we looked at the principles behind it, and what we talked about in the last class if we know we define structural steels and how steels are made; I think these are that important stages we must know about what is killed steel. And today bulk of steel which is produced by continuous casting rule they are all killed steel, so you also have in got root, you have semi killed and rimming steel also.

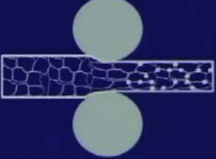
We looked at the differences we talked about steel designations, we talked about strengthening mechanisms, and we found that, the mechanisms most of the mechanisms I mean if you try and increase the strength, toughness goes down the ductility goes down. But for more reliable I mean most of these application the demand, best combination of strength and toughness and this is where grain refinement comes out to be quite handy. And most maximum emphasis has been given on grain refinement, and that is the very basis of thermo mechanical processing.

We shall talk about this thermo mechanical processing, how it has helped in producing a range of high strength low alloy steel, where alloy content may be extremely small. We will look also a little bit again on the strength toughness that relationship, and again and we will all talk about few again ultra high strength steel and which can be produce by controlling thermo mechanical processing. That means these are, we are not necessarily considering alloy steel even in plain carbon steel, you can get ultra high strength by controlling this composition and processing. We will see how.

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Hot / cold working


HW: instant re-crystallization on plastic deformation
 CW: $T <$ re-crystallization temperature



$$r^* = \frac{2\gamma}{\Delta G_v} \quad \& \quad \Delta G^* = \frac{16\pi\gamma^3}{3(\Delta G_v)^2}$$

$$\dot{N} \propto \exp\left(-\frac{\Delta G^*}{RT}\right)$$


Higher $\Delta G_v \sim$ lower T_{rcrys} . & finer grains. To get fine grains finish rolling done just above recrystallization temp & not allow time for grains to grow.

 NPTEL

And if you recollect your last lecture, we talked about thermo mechanical processing. If the working is done above re-crystallization temperature, we shared it is hot working and the bulk of the deformation from the continuously cast (()) is done through hot working. And cold working is often done in the finishing stage and often after cold working the steel may have to be given some amount of annealing to relieve the stresses or to get

crystallize structure to get a better ductility or best combination of strength and toughness.

Now, more technically if you define that hot working here, you have instant re-crystallization on plastic deformation, but this re-crystallization we will talk little bit about a re-crystallization temperature. This re-crystallization temperature it is fit it is not a definite fix temperature say, it also depends on a number of factors, it also depends on the amount of working that you put in amount of stored energy that goes in during plastic deformation, it also depends on the rate at which the deformation is given, it also depends on the amount of deformation.

So, it is not a fixed quantity and here, this is if we understand the factors that determine re-crystallization temperature, we will be able to design the thermo mechanical processing route by which you can get best combination of strength and toughness. Now, this is the schematical diagram which shows rolling say, hot working is a process you can see this is the initial structure, grains here you can see these are . And when you deform, the grains start to become elongated and this reduction in this grain thickness, this is the measure of the amount of reduction. And depending on that amount of reduction, then after it job comes out you know re-crystallization process can initiate; this is what has been represented here.

So, in its bulk of this deformation to steel is given in its austenitic state, say around the temperature let us say eleven 50000 around eleven 50000 degree centigrade may be that is the place where you give this large deformation. And after deformation you know either you cool it, if you want to these new grains which form, you know they will go with time and so the key to get a fine grain structure is to give.

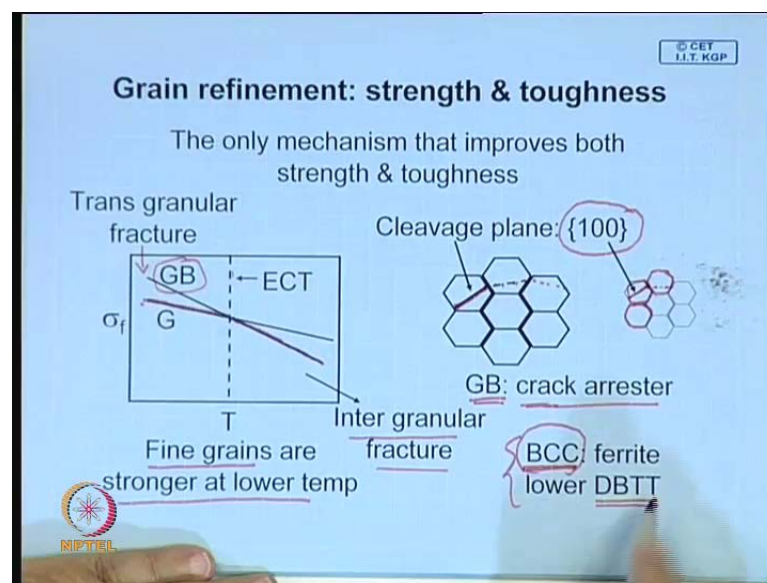
And if you recollect here it will be worthwhile to recollect the relationship, which were derived. That means whenever, new stress free grains develop they depend on certain factors it depends on that interface which is being created, that is the re-crystallized austenite and the cold worked austenite. This has the surface energy which is γ and this is proportional to the critical size of the nucleus is proportional to this surface energy γ and inversely proportional to the amount of energy that is get stored due to the deformation.

Now, this if you give large amount of deformation, you can see that the activation will go down this activation will in this goes down, then the nucleation rate here say that, this is the nucleation rate, we did not talk about this length. And the initial portion of the curve if this becomes less, you can see this is a negative sign. So therefore, this becomes quite large. So, higher cold work means higher is the nucleation rate so the key to get a fine grain structure is high amount of deformation (()) pass try to give as high deformation as possible.

And this will have low recrystallization temperature, so this recrystallization temperature is also depends on this activation help so you have you can say that recrystallization, because the nucleation rate becomes quite high. So, these also indirectly affect this recrystallization temperature and your critical nucleus radius decreases therefore, you have fine grain. So, to get fine grain finish rolling is done just above the recrystallization temperature and sees that, you do not allow time for grains to grow.

And here another important thing is after cool that is hot working the structure does not remain as austenitic, so it will undergo subsequent transformation. And in fact what it matters ultimately, factors that determine the ultimate property will be the ferrite grain size.

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And we will see now a quick before we go into that how do you control the ferrite grain size a quick look at the basic principles of the grain refinement, and why it improves

strength yet does not like all other strengthening mechanism it improves toughness as well and, so this is the only mechanism that improves both strength and toughness. Now, any polycrystalline material which is pictorially shown here, it is made up of say let us consider a single crystal I mean a single phase material these are the different polycrystalline different crystals which are arranged at random, and we have one picture over here so there say suppose this is the coarse grain structure.

And now you think about it is made up of two constituent one is the grain, another is the grain boundary and it is possible to visualize that strength of each separately, and it has been reported that, at temperature lower temperature the grains are stronger grain boundary is stronger than the grain. So, this is the line which represents strength of grain as a function of temperature. As temperature increases strength decreases this is true for both grain as well as grain boundary, but grain boundary loses strength. This slope is much steeper so there is particular temperature this temperature is called equi-cohesive temperature. This is the temperature, where both grain and grain boundary have same strength.

Beyond that the grain boundary is weaker so therefore, what you have in actuality you will see that normal temperature, we will have a Trans granular fracture occurs. Let us look at this sheet here so these are the different grains, and so what happens the strength of any poly crystalline material this will you can say this follows this is the lower boundary. So, below this temperature grain boundary is stronger, so the crack does not pass through the grain boundary it is the grain, through which the crack passes and you have transgranular fracture.

And if there are cleavage plain imagine say here, that crack is taking place this is the crack and when it reaches this grain boundary now for it to propagate, you need another cleavage plane over here and possibly this is the cleavage plane, and which may not be favorably oriented. So therefore, even if the crack propagates to grain which is favorably oriented for the cleavage crack to take place it does not automatically go to this.

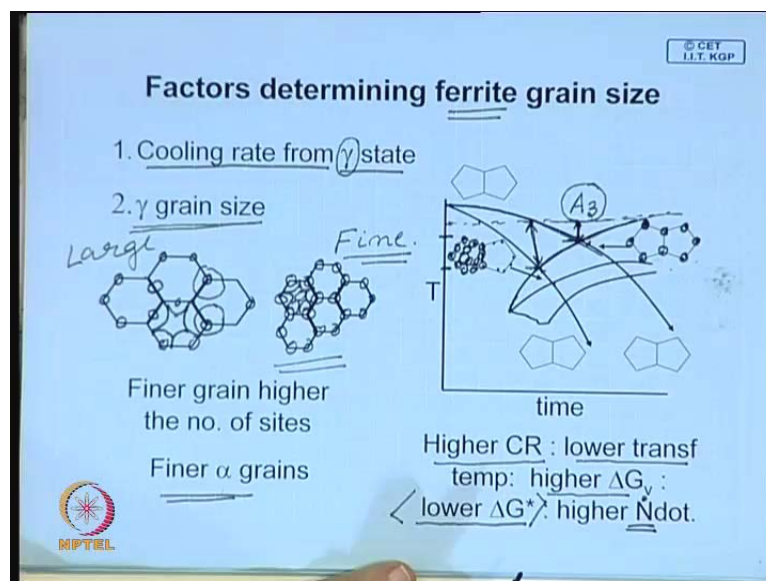
And at this temperature therefore, you know similarly these are paths so actually this is how the crack is likely to propagate and since but so therefore, at every grain boundary the direction has to change new grains the next grains neighboring grain may not be favorably oriented for the crack to grow. So therefore, the crack stops. So, this is why

you can see that, if you have this strength of a polycrystalline material will be influenced by grain size.

Fine grain structures, they are stronger at low temperature, which you see here whereas, and in fact and the fracture at higher temperature it takes place inter granular fracture because grain boundaries are weaker. So therefore, what you try to do since at low temperature, grain boundaries are stronger we try to have more grain boundary, so in the finer grain structures they will have these stronger which are shown over here. These are the fine grain structure. So, here a crack propagating cleavage crack only this small distance after that, it meets an obstacle and does not propagate either. So therefore, it has a greater resistance for the crack to grow.

So, the grain boundary they act as crack arrester so therefore, in this way what we can build upon it is if we make the grains finer, it will have much more or higher resistance towards crack growth it will not allow crack to grow, and it will therefore have high impact value, high toughness. And we also know it is particularly important for body centered cubic structure where you have cleavage plane. So, this is the plane on which crack can propagate easily, and it is also characterized by a ductile to brittle transition temperature we did not talk about it earlier, and if you can make the grain finer, you can lower the ductile to brittle transition temperature significantly.

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So therefore, the best way to improve strength without sacrificing strength ductility is to apply grainis to use the grain refinement technique for to improve the strength. Now, let us look at what are the factors that determine grain size of ferrite that phase which is present in most structural steel and this is shown over here. So, there are two important factors one we have seen is the cooling rate from austenitic state, because ferrite is a low temperature phase in steel it does not exist at a high temperature or this is not the crystalline structure, which exist during hot working it forms from high temperature phase austenite. And its grain size will depend on the cooling rate from austenitic state, it will also depend on prior austenite grain size.

Now, suppose you have one case you have two samples, one case the prior austenite grain size is large which is shown over here so this is large grain size and another case you have fine grain size. Now, what will happen we know that new grains that ferrite grains when it forms when you cool below the critical temperature ferrite grains will form and the most favoured nucleation sites are these, so ferrite grains form here. And most favoured sites are these grain edges so these edges these grains will form and they will try to grow and with time they will grow. So, you can clearly see when this grows ultimately they will impinge and what you will have, you may get a grain here **grain here** this will be ferrite grain another grain going here something like this.

Now, imagine something here the grain size is finer so therefore, you have more sites for this ferrite grain to nucleate. They all nucleate at these places let us say and again you go through the same exercise, it is assumed that they are even if you assume all these grains, which are nucleated grow at the same rate. In between also you may have some nucleation possible so in this particular case when they grow obviously you will find since, you have more nuclei when they grow, and ultimately they impinge grain size here is likely to be finer.

So, if you have the initial grain size austenite grain size is fine, the final ferrite grain size is expected to be finer. And then to understand the effect of cooling rate, we should look at the transformation diagram of the steel say let us say this is the transformation diagram of the steel. This is the temperature at which A₃ temperature where during cooling, let us say the ferrite nucleus begins, but here the cooling rate has to be very slow. So, this is the equilibrium temperature at which ferrite nucleus is likely to appear.

But in reality we have seen in the time temperature plot, this is the CCT diagram we have only plotted the upper relevant portion of the CCT diagram and this is the line, which represents initiation of ferrite precipitation.

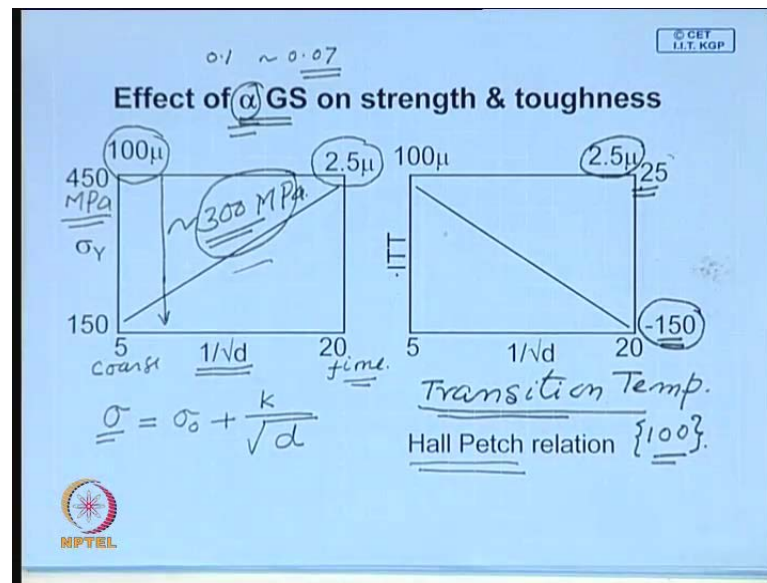
Now, we have super imposed two cooling rates one is relatively slow cooling rate another is fast cooling rate. Now, in the fast cooling rate you know this transformation takes place at this temperature, so let us see this temperature, whereas at slower cooling rate transformation takes place at this temperature. So, what you find over here the driving force we have seen is this degree of this super cooling or so, this is the temperature under cooling you have over here. Whereas, here this is the level of under cooling so the driving force for nucleation is higher over here. So, what it means higher the driving force, finer will be the nucleation size and faster will be the nucleation rate.

So, you can imagine so in these two cases the original austenite grains and here when this has just started you may think that here, you have a very fine grains at which have nucleated. Here also, let us see at these sides these grains have nucleated and these fine grains when they grow to diffusion control process. At high temperature, diffusion rate is faster, and also you can say here in this particular case; since driving force for nucleation is more this will be finer where this critical nucleus is larger so nucleus which forms here they will be larger to start with.

And secondly, here you will have more number of nucleus finer nucleus so we have some grains here. So, when they grow over here all of these large number of this are growing so you have so quickly all these gets filled up you have more nucleation taking place here. So, ultimately what happens in this particular case you will get a fine structure, so that means faster cooling rate higher cooling rate is the means lower transformation temperature therefore, higher driving force; therefore, the activation hill which has to be overcome for nucleation to take place is lower.

So, therefore and it has obviously it will have higher nucleation rate $N \cdot$, so therefore, we can say by controlling the cooling rate and prior austenite grain size, it is possible to control the grain size of ferrite and the final structure.

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Now, let us see what impact it is likely to have on the properties that is ferrite grain size, because ultimately at room temperature you have ferrite is the major phase. Because bulk of the steel percentage carbon will be extremely low say may be 0.1 there are many grades where it is even lower it could be 0.07, 0.08; these are the grades become quite popular so therefore, it will be this microstructure will be mostly ferritic. And here the diagram shows how this strength the yield strength which is in MPa mega pascals is likely to vary the grain size and this axis is one over root d.

We know we did talk about that the Hall Petch equation where the yield strength is given as, this is you can say lattice friction stress k over root over the grain diameter so clearly you can see if you plot this against one over root d, you expect a straight line. So, this end means it is a coarse grain, this end is fine grain and around say here, this side you have a around micron size and this size is very coarse may be 100 micron, and it can have significant effects say that means this increase in strength from here to here is around say three hundred mega pascal, which is a substantial increase in strength.

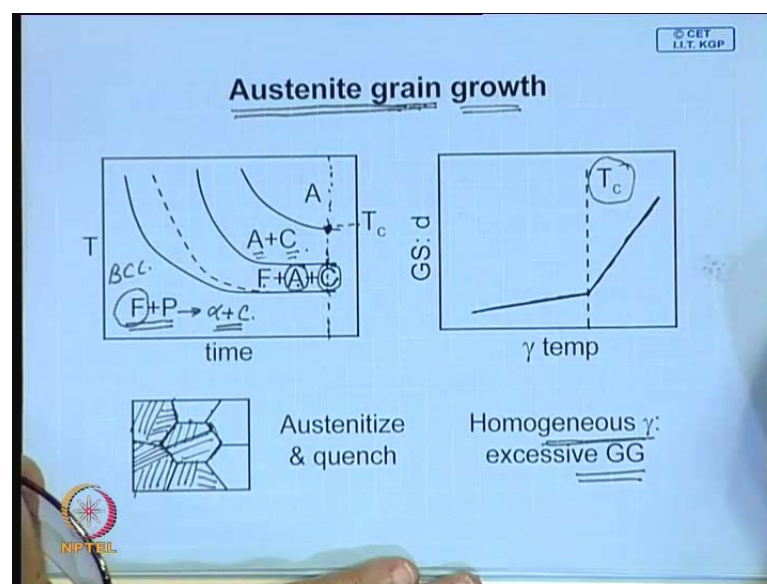
And we will see if you check up this solid solution strengthening, can never I mean can really approach such a high magnitude of strengthening most solid solution strengthening may be of the order of 50, 60 MPa are depending on the alloy element. And since the grains become finer, it will be more difficult for the crack to propagate; so therefore, we expect that this ferritic steel will have much higher toughness.

And one measure of this toughness is the transition temperature all particularly ferrite steel surface from this problem. At low temperature ferrite is brittle it has a cleavage plane that means crack propagate easily on 100 plane and you get a brittle fracture at a low temperature. And the temperature at which the fracture becomes brittle, that is known as fracture appearance or you can say that is the transition temperature.

And if you measure this impact and this is the best way to measure is by impact testing so ITT means impact transition temperature. And using p that is pre-cracked this r p pieces, you can find out impact transition temperature by conducting test at various temperatures and here the temperatures are noted here. So, look at it is also possible reported that you can have as low as minus transition temperature as low as minus 150 degree centigrade. If you can reduce the grain size to micron level whereas, normally if you have coarse grain structure this transition temperature at room temperature may be transition temperature may be close to room temperature.

And this is important and particularly important as we will see later that particularly, because these days one of the major fabrication technique for plate and sheet is welding. And when you weld, the problem comes up and you try to see after welding you do not deteriorate the fracture thickness. So, if you have the fine grain steel and after welding also, this should be fine grain, and that is why I think there is a major incentive loading the carbon content, and maintain the fine grain structure.

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Now, next we must look at see one of the factors that determines the fine ferrite grain size is the prior austenite grain size. And now let us see how do, we control the austenite grain size. So, primarily for all hot working processes this is done in austenitic state. So, if you have purchased say if these are say (C) continuously cast (C) ; if they are to be hot role, they must be austenitized. And if you austenitized, you have to do this process under a control conditions, so that you do not allow the grain to grow abnormally.

And how does this abnormal grain growth take place? Now we know the steel say it has the room temperature microstructure will be ferrite and pearlite. Ferrite was virtually this is a BCC structure and pearlite was made up of ferrite and carbide and when you heat it to a particular temperature say normally, we heat it at a usually most cases say soaking time is fixed may be few hours or one hour depending on the size of the stock. It can be even several hours long depending on the stock size that you have.

And when you heat it say suppose you are heating at this temperature, you will initially you know this austenite this temperature is definitely a function of time as well; say suppose, if you fix up the time see first when it crosses that low critical temperature this pearlite disappears it forms austenite in the pearlitic region. But some carbide may remain and dissolve, so you have a region where you will have a ferrite, austenite and carbide. As you increase the temperature, the amount of ferrite goes on decreasing and over here you will have all ferrite, this is the line which represents the conditions the time temperature conditions where ferrite disappears.

And here you have austenite, but still you may still have some of these carbides may not have dissolved in austenite. So you have a region where you have austenite plus carbide. Now, there is a temperature here where these carbides also dissolve, when these carbides dissolve there is nothing to clean this grain boundary. So therefore, once you exceed this temperature the grains starts growing at a very faster rate. Now, it is also possible to do some experiment and find out by giving heat treatment; that means heat to different temperature and quench, and then heat to austenite temperature say suppose you have heated here and quench.

And then what will happen? Here this is these are the austenite grains, so if you quench all these will converted into martensite. Here say depending on the carbon content the type of martensite it can be lath martensite or it can be a plate martensite, because

mostly we are talking about low carbon steel where you have the kind of martensite form. So, you have this kind of martensitic form, and which clearly reveal that austenite, prior austenite grain size. It is possible to determine this prior austenite grain size as a function of temperature which is shown over here.

Now, this is the temperature now let us say, and here you will find as long as you have carbides which can block the movement or which has pin the grain. The seaustenite grains do not grow that growth is slow, but once these carbides dissolve then the growth increases significantly. So, you can see here, so this is the critical temperature, when all carbides dissolve you have a homogeneous austenite and likely to have under such conditions excessive grain growth. So, to get fine austenite grain one important condition is to see that you do not have very coarse austenite grain in the structure.

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Austenite GS control during HW

- ↳ Micro alloy addition to get fine dispersion of ppts
total alloy addition, 0.2%
- ↳ Controlled re-crystallization $\langle \underline{TMP} \rangle$

Grain growth inhibitors: fine dispersions of
carbide, oxide / nitrides: \underline{Al} , \underline{V} , \underline{Ti} , \underline{Nb} , \underline{C} , \underline{N} , \underline{O}

Criteria: low solubility & high affinity for \underline{C} , \underline{N} , \underline{O}

$$\text{Nb} + \underline{\text{N}} = \underline{\text{NbN}} \rightarrow$$

NPTEL

And how do you do it and this is what we will cover in the next few slides. Now, how do you control this austenite grain size control during hot working? Now, this is where you can make some micro alloy additions say normal, if it is iron carbide it dissolves at a quite a low temperature therefore, this iron carbide or cementoid is not very effective in controlling or in suppressing the growth of austenitic grain.

And you we try to have certain strong carbide or nitrides, which have which are much more efficient in blocking or in pinning grain boundaries, and these alloy additions are called micro alloy additions they are called micro alloy, because total alloy additions

may not exceed more than may not exceed 0.2 percent, and these micro alloy additions form precipitates particularly nitride, carbide, oxides and they block the movement of austenite grain so this is one important. Second is you control the re-crystallization you have control; that means thermo mechanical processing you control in such a manner that you are able to control re-crystallization of austenite during hot working.

Now, these micro alloy addition we talked about these are the common additions we did mention that when you add that aluminium steels, you know you have likely to have fine aluminium usually aluminium steel they are inherently fine grain structure.

Now, each of these elements they have very high affinity for both carbon, nitrogen and as well as oxygen also, so to get these we must be and these are intentionally added element. This niobium pins the grain boundary very effectively, so also titanium nitride, niobium nitride, vanadium nitride block these grain boundary movements, so. And we if we want to use this to the maximum, we must ensure that steels should not have too much of oxygen, so aluminium is primarily added as a deoxidizer to control oxygen.

And balance that carbon, nitrogen to balance whatever in the steel they form nitrides or carbides with these micro alloy additions. And a criterion for selection of this is all these should be present as dispersion and this is possible only when each of them they have very low solubility. So that means solubility of each of these vanadium, titanium, and niobium should be low in steel and should have high affinity for these elements and the reaction that takes place which is written over here. Add niobium to the steel it reacts during steel making you know it will react with nitrogen and it can form niobium nitride.

Now, it is important to know which of these niobium nitride will form and can we control this formation of niobium nitride during hot working. Not only niobium there may be other alloy elements one or two vanadium, titanium so each of the carbon nitrides how can you control their formation during hot working is the key to thermo mechanical processing.

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Solubility product

$$\text{Nb} + \text{N} = \text{NbN}$$
$$\text{SP} = [\text{Nb}][\text{N}] = f(T)$$
$$\log(\text{SP}) \rightarrow A - \frac{B}{T}$$

If steel is heated above T_2 there is no precipitate to pin GB. Austenite grains grow rapidly

NIPTEL

Now, we talked about it is interesting this talk about this solubility product. We said that, these are soluble in steel in a very low amount so niobium which is dissolved in steel, then nitrogen which is dissolved in steel and the solubility product is the weight percentage niobium in steel, weight percentage nitrogen in steel which remaining equilibrium at a particular temperature.

So, this is a strong function of temperature and it is quite it is possible to show very easily here. So, if you consider for any chemical reaction like this, you have soluble niobium in steel, soluble nitrogen in steel. In solid state you see and they are forming they are in equilibrium with niobium nitride, so this is the equilibrium constant and these are you can see detectivity of these respective phases.

So, this is dissolved niobium dissolved nitrogen and this is the niobium precipitate we can assume that this activity to be one, and these are since they are present in very small amount. We can say that their activity is proportional to weight fractions of this respective element that is, with fraction niobium weight fraction nitrogen. And this we know this activation equilibrium constant is related to standard free energy for this particular reaction and with this it is possible to show log of this solubility product will be proportional to this.

So that means if you plot logarithmic of this solubility product, it is as this kind of a plot T is the temperature in degree Kelvin. So, this is the strong function of temperature and it

is quite important to see that how this solubility product changes with temperature and periodically, it is I mean typically it is shown over here.

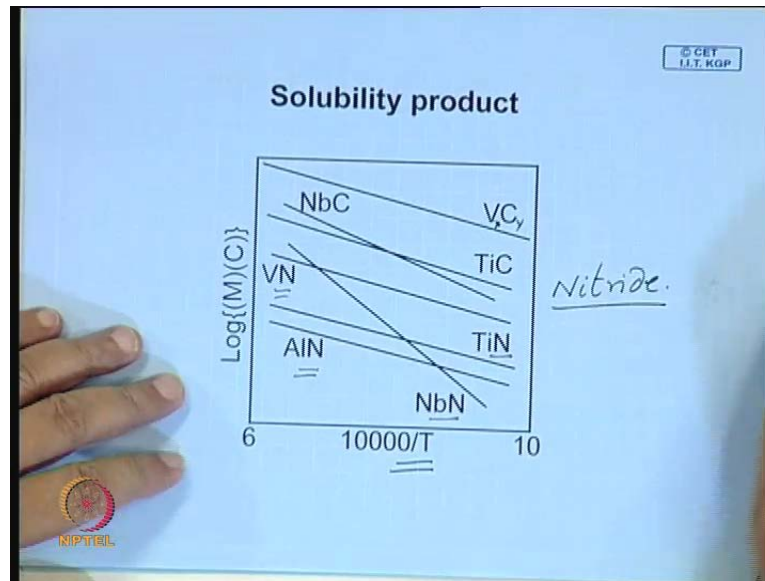
If you assume that this is the solubility product at particular temperature it is constant, then this represents a hyper polar so which is shown over here. This is the solubility line you can say so that means if you have this much of soluble niobium, this will be in equilibrium with this much of nitrogen, so what you can see if you have small amount of niobium this is amount of niobium, then amount of nitrogen in this steel can be high. Similarly, if you have high amount of niobium amount of nitrogen in steel is very low.

So, you have to maintain an optimum quantity of soluble nitrogen or niobium in steel so that, you get optimum amount of this dispersoid, and how do you get it now for this it will be interesting, to look at effect of temperature on this solubility line. If you increase the temperature, higher is the solubility say this is the line and if in a steel you have this much amount of niobium this much amount of nitrogen. So, if you are heating here, then all of these goes in solution, so if you go beyond you can say, this is the critical temperature roughly.

So, if you are austenitizing beyond this temperature the austenite will grow so if you are close to this, where some amount of niobium nitride is still there to depend on the boundary the grains will not grow significantly. And next is as you cool you know the temperature will go down say from T_1 it will come down to this, so you will have more and more amount of niobium nitrides precipitating out.

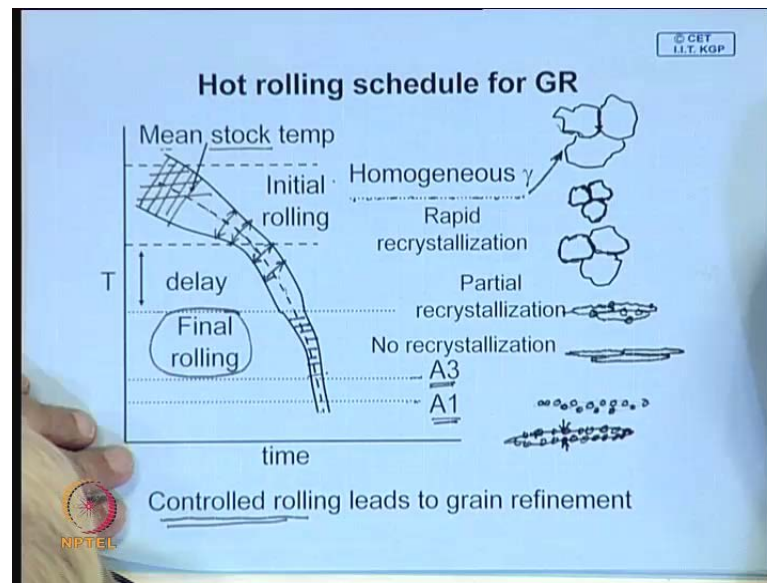
And it is possible to calculate that amount from this type of diagram what you need **you need** to know the stoichiometric if it is one to one, and that case you can plot the stoichiometry line something like this. So, you can draw this similar parallel line here and from this, it is possible to find out amount of vanadium and amount of see amount of this niobium nitride, which will form various temperature and it is essentially be a function of temperature.

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Now, next let us see what is the nature of the solubility product plots, so which is shown over here and we have seen the lower solubility products the better or more effective is the dispersoid. If you look at solubility products, you find these nitrides they are much more effective, because their solubility is less. Relatively, carbides; these are approximate composition you can say, this need not be exactly VC, it could be some numbers here. So, but nevertheless what it means these carbides and carbonitrides; these plots these solubility product plots, they are linear when plotted as against one over temperature. And nitrides are much more effective as dispersoid; these nitrides are more effective as destroyed than carbide.

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Now, the question comes how do we schedule or hot flow link and this here it is pictorially shown here. This is the time temperature plot, and let us say these are the temperature at which ferrite formation is possible, and this is the temperature at which pearlite may form in the steel so these are the equilibrium temperature. Now, suppose we are giving reduction to a stock and this dotted line this represents the mean stock temperature. And initially you know this stock size this length this represents the initial stock size this part and here, you are gradually this stock size this thickness is decreasing.

So, this is the temperature range where you give the initial rolling and here it is also shown here these are the critical temperature above which you have homogeneous austenite, so if you have homogeneous austenite these grains have shown typically which is shown here. Above this temperature you have this coarse austenite grain and when you are giving reduction, you try to give as high reduction as possible and high temperature the strength of the material is also low. So therefore, you can give high reduction and if you give high reduction there may be rapid re-crystallization also taking place here.

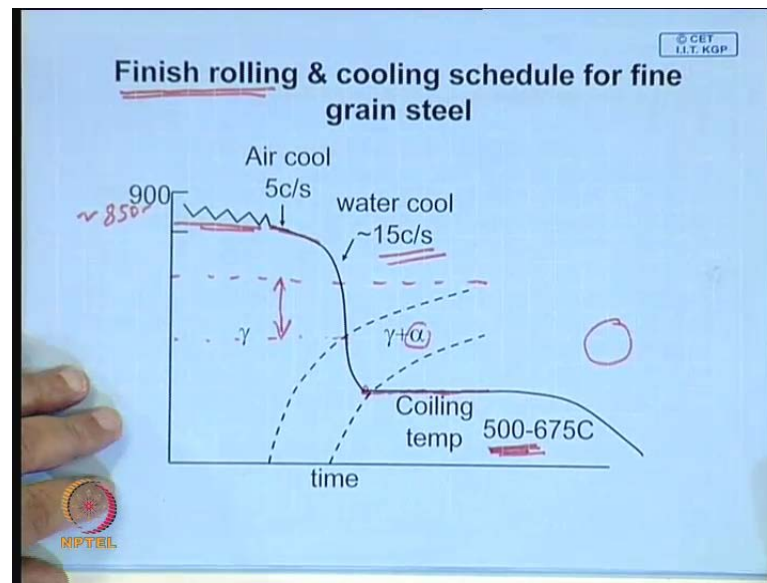
And because of this these grains they deform and fresh and replacement they get deformed and they get replaced by new strain free re-crystallize grains. And after that there is a delay you do not get so here this much reduction has been given, and after that since you are not giving any reduction these grains strain free grains they can grow also, this is how it has grown. And this is the temperature, where we see that we try to give over here.

Another rolling that is the final rolling and so here, you see this the thickness size is decreasing and if you give the final rolling here, so there is a stage here; these austenite grains which are the size they get elongated like this. And here that it is only that since you and you are giving only large reduction of the temperature also is substantially lower. So, we know that re-crystallization rate also will be low so here if at all re-crystallization is taking place, there will be very few re-crystallized austenite grains bulk of it still remains elongated.

And if you even continue this even further, it is also possible higher reduction it is also possible not to allow any nucleation to take place any I mean strain free grains that means, no re-crystallization is also possible and by the time you know the work is over and you allow it to cool. And that is the time the grains which form these are fine these are the grains, which will form the ferrite grains which will nucleate and it will nucleate particularly even it will, because these grains austenite grains which has been cold load here, it is very thin and it has very large surface area where grains can nucleate therefore, you have the large number of this ferrite grains forming.

So, if you have ferrite grains nucleating in such thin grains of austenite, the final ferritic grains of is expected to be extremely fine. So, this is the principle of control rolling you roll in such a way you control the temperature control the cooling rate, so that here you can delay that you may be able to cool it little faster or something, so that even this grain growth can be stopped. And finally, this is the stage where ferrite grains nucleated and later on we will see that, you can even control how it is actually done.

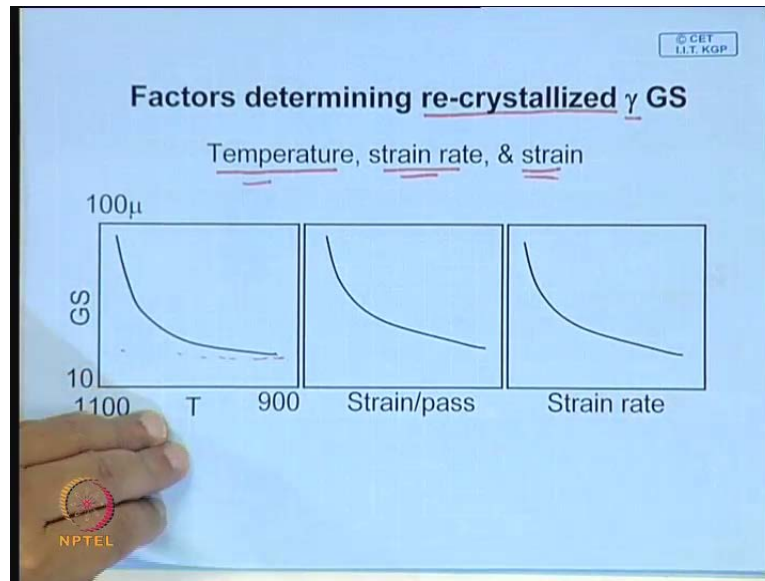
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In a rolling mill which is schematically shown over here, finish rolling which is done over here. And this finish rolling temperature is substantially low that is, may be depending on that carbon concentration, it could be around 850 to 900 degree centigrade you finish the rolling. And after that here the rolling is over, and then you cool it little rapidly, so that you cool it little rapidly this temperature cooling it rapidly.

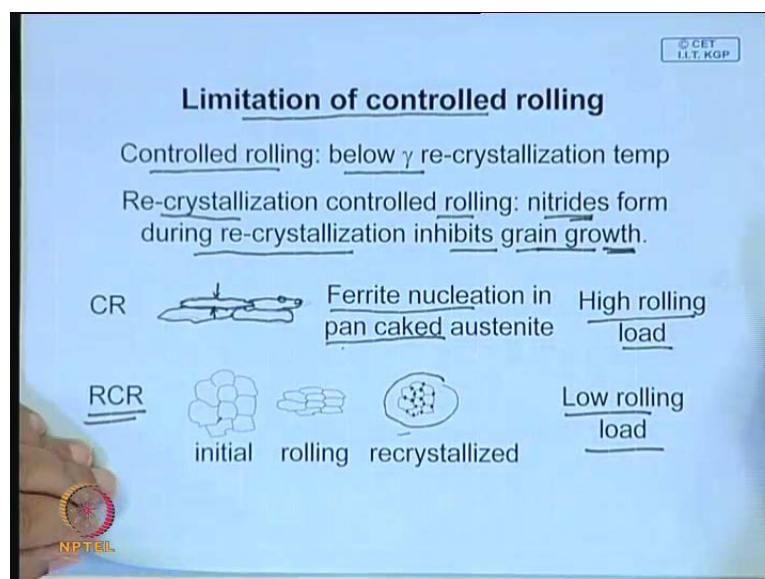
And then here the ferrite which starts forming forms at a much lower temperature if you are so this is the degree of super cooling and high the super cooling, finer will be the ferrite grain. And here, the ferrite grain formation is nearly complete and this where you take it out, and here you coil it and it is rolled into a coil. And when it becomes a coil, obviously cooling rate will be slow and the coiling temperature is around when the ferrite formation is nearly complete that is, the coiling temperature. So, this is how actually it is implemented in practice in steel plants.

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And then factors let us look at the factors, that determine final that re-crystallized austenite grain size it depends on several factors, it depends on temperature, strain rate and strain and which is shown here. So, that means during hot working itself, we finishing the working say around, let us say 900 degree centigrade. And that is the time you know if you finish here, you are likely to get a fine grain structure. And strain per pass higher the strain per pass finer is the grain, higher the strain rate finer is the grain.

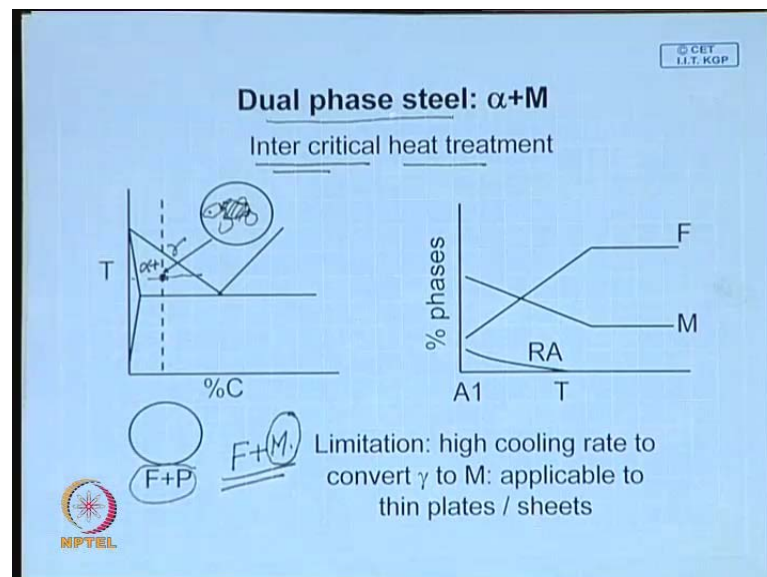
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But, there is a major limitation of this control rolling process. Now, one is the controlled rolling if you roll at a relatively low temperature that means here control rolling, you roll below austenite re-crystallization temperature do not allow the re-crystallization to take place so that you have this kind of a pan cake type of structure. So, here you have obviously if you do not allow to re-crystallize high strength, you need high rolling load so ferrite nucleation you do get extremely fine ferrite grains, because it nucleates in pan cake austenite, because these are very thin it has very large number of sides for nucleation of ferrite grains.

So, this is the major problem so by controlling the workings you can also possible by re-crystallization **re-crystallization** control rolling, where you allow the nitrites to form during re-crystallization, and inhibit the new re-crystallized grains you know do not allow them to grow. So, this is where you know this is the initial you roll, and then it is re-crystallized and that is the time if these precipitates form, they will form here and they will block; they will not allow these grains to grow. So that you will have fine re-crystallized austenite and here the rolling load is low, your finish temperature is little high finishing the rolling temperature is in the temperature zone, where you have this precipitation taking place.

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Now, a quick look at this we looked at by thermomechanical processing by controlling the transformations, how we can get **how we can get** extremely fine grain structure, and

which have **and which have** very good strength and toughness and as we will see later they also have very good weldability. Another important class of steel where you get good combination of strength and ductility is the dual phase steel.

Now, what happens? See in normally steels we process I mean what we do, we cool from that inter critical region given an inter critical heat treatment to steels say suppose, it is also possible to do online also say suppose if you quench from somewhere here this temperature, so what do you have here you will have ferrite and austenite ferrite plus austenite.

Now, here if you quench so over here so you will have these are this austenite grains and these are let us say ferrite grains, and these are let us say austenite grains and here if you quench it is possible, that room temperature it has a ferrite pearlite structure. But if you come over here, you get ferrite plus austenite here if you quench ultimately, it is possible to get ferrite plus martensite structure, so here and this martensite you have relatively higher carbon content. And this method is being exploited, this is the potential method which can be exploited to develop steel which has a good combination of strength and ductility, and so maybe I think to understand this, I think we have to spend a little more time we will talk about it in the little class.

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Summary

- Thermo mechanical processing
- Affect of micro alloy addition
- Effect of temp, strain & strain rate
- CR vs. RCR →
- Strength vs. toughness
- Dual phase steel ↓
- Patenting
- Ausforming

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So, today what we have looked at primarily is looked at thermo mechanical processing, and how by adding micro alloy addition it is possible to retain very fine austenite grain

size, in which fine ferrite size grains can develop. We looked at the effect of temperature, strain and strain rate austenite grain size. We talked about control rolling; that means, rolling at a lower temperature, but this has some problem; whereas, re-crystallization control rolling is become more popular, because here rolling is done at a little higher temperature where steel is still soft, so rolling load is less and by this technique, it is possible to get extremely fine grain ferrite steel primarily. And it will have some pearlite no doubt, but it will have definitely best combination of strength and toughness. And we also introduce the dual phase steel; I think, these three we could not cover I think before we proceed, we will cover in the next class. Thank you so much.