Principles of Physical Metallurgy

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Lecture No. # 38

Structural Steel

Good morning. Today we begin a new chapter; here we will talk about structural steel. And in fact this is an area where principle of physical metallurgy has been very effectively utilized to improve the strength of structural steel. And in fact the automotive industries most of the automobiles bulk of it made up of structural steels and major driving force to cut down or to improve the quality of structural steel came from that oil crisis. And main aim was to cut down the weight of vehicles and this has been possible by improving the strength of structural steel of which these vehicles are made and so, that they are lighter they are more fuel efficient.

We will see how the principle of physical metallurgy has been used in this particular case will improve its strength very effectively. And in fact since 1980s very large numbers of newer grades of structural steels have been used and this had found application in many other areas as well.

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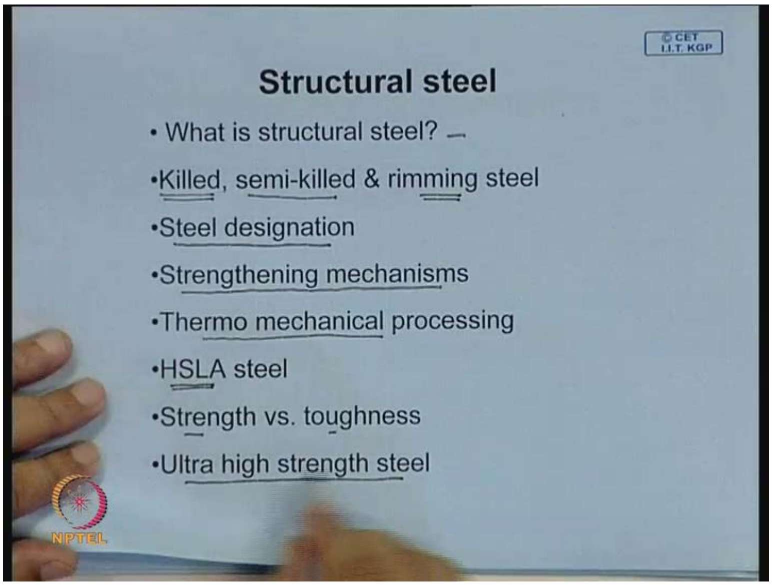

Structural steel

- What is structural steel?
- Killed, semi-killed & rimming steel
- Steel designation
- Strengthening mechanisms
- Thermo mechanical processing
- HSLA steel
- Strength vs. toughness
- Ultra high strength steel

And here we will take up; we will first know what is structural steel? Then, we will talk about so few important points. See there are steels which we used they are put under these three categories; killed steels, semi killed steels and rimming steel. What they are and how they are produced we will know about the little bit of steel designation we will talk about strengthening mechanisms we find out which of this mechanisms will be most applicable to improve the quality of structural steel. We will talk about thermo mechanical processing by which this is achieved. We will talk about few high strength low alive steels this is also known as micro alloy steel.

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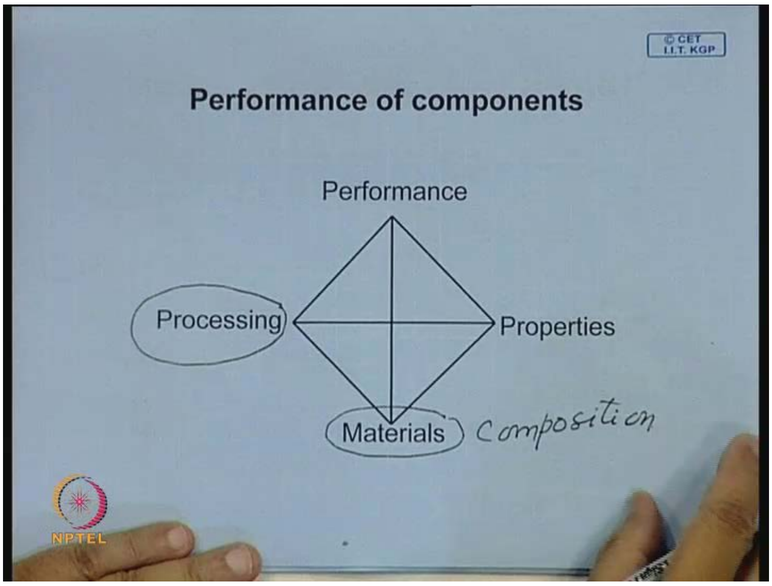

Performance of components

We will talk about the relationship between the strength and toughness and we also know about what is the ultimate nor is it pass what do you mean by ultra high strength steel and how are they produced or what goes into making improving a strength of steel. In fact we talked about this concept is tetra hydra, where we say that properties are material depends on composition. That means material that is a chemical composition the property depends on this. Similarly, that is which property also depends on how you process? So, the fine doing structure will have higher strength so, how do you produce fine grain? So, that will effort the properties and in fact all this together affect the performance.

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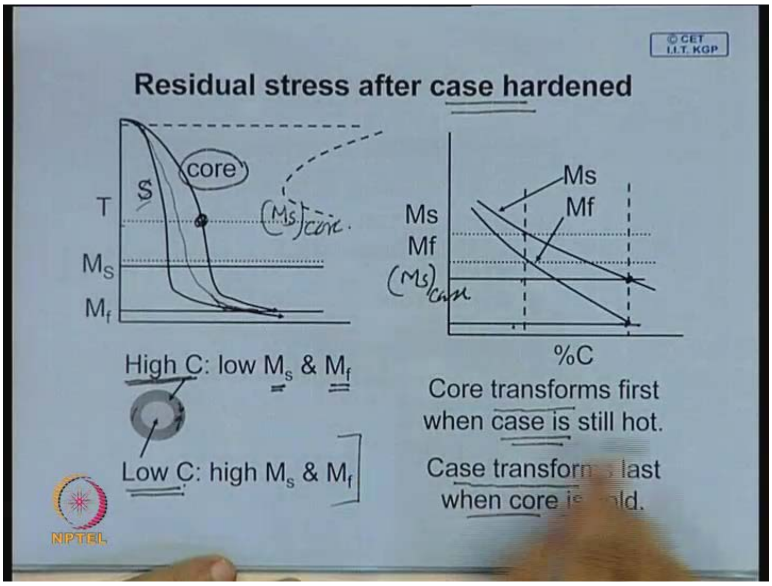

Residual stress after case hardened

High C: low M_s & M_f

Low C: high M_s & M_f

Core transforms first when case is still hot.

Case transforms last when core is cold.

Last class we talked about the limitation of hardening a steel, because this is totally dependent on the sets and size and in many cases defects and size is large it cannot be harden. Because we have seen by quenching the strength of steel can be increased many fold. So, this obviously will be the most obvious choice for strengthening, but it cannot be yet now, because of it can be attain the full mark ends of the structure can be attain only through over a very limited thickness depending on the type of steel that we use. In fact this has been used effectively to find out cases, I mean to utilize this by modify the composition and we talked about case hardening. We talk about case hardening I am projecting this here, because I just realize there has been some mistake, which I will explain here.

Here, when you have a large section here you want a tough core to be tough. So, one would prefer a low carbon steel. And since, it cannot be harden through and through attempt is made to enrich the carbon content of the surface by difference the carbonizing process like black carburizing or gas carburizing. You increase the carbon content of the case core remains low carbon content. When you made this modification there M s and M f temperature decreases so, you will find that case will have this is the M s temperature of case, because case has high carbon content case has high carbon content. So, here this is M s temperature this is M f temperature case has lower M s and M f temperature than the core.

When you cool this, when you quench this job try to cool it fast always core, which is the inner portion will cool slowly than the surface. But inspite of this you would see the core crosses this M s temperature for core, this is the M s for core before transformation begins. In case although the case temperature is lower at any instant so, here you will find that this temperature. Therefore, what happens at any instant this before this starts this is not to scale that is possible by controlling the cool event to allow the transformation.

To begin first case here and before this start this line should be I think this side. So, trick is the core transforms first when the case is still hot therefore, when the core tries to expand. So, it case can be form and accommodate the strain and later on. When case transforms lost when the core is cold therefore, the core will not allow this to expand therefore, residual compressive stress will develop on the surface. So, this is the reason why you get, because of this difference in M s and M f temperature by modifying the composition. It was possible to introduce by case hardening a favorable residual stress, that is compressive residual stress at the surface and by that you input the performance of this component.

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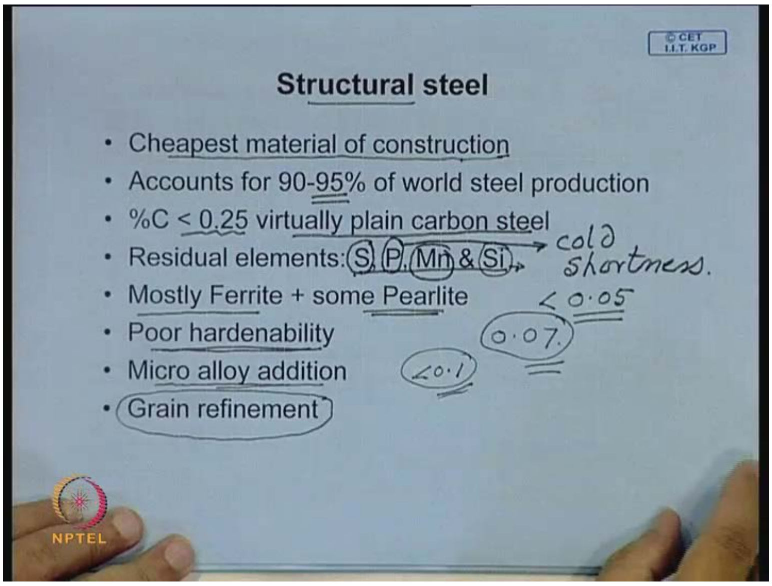

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Structural steel

- Cheapest material of construction
- Accounts for 90-95% of world steel production
- %C < 0.25 virtually plain carbon steel
- Residual elements: S, P, Mn & Si
- Mostly Ferrite + some Pearlite
- Poor hardenability
- Micro alloy addition
- Grain refinement

cold shortness.

< 0.05

0.07.

<0.1

Same concept similar that this type of principle basic principles have been used in case of structural steel as well and we will see how this is turn? Now what is mean by structural steel? That is the cheapest material of construction bulk of construction is made of structural steel and it is a cost wise it is possible it is only cement concrete structure as possible with cheapest. The next cheapest material of construction is structural steel it accounts for bulk of world steel production may be 1995 bulk of this production actually is for structural steel. We call least carbon steel less than a 0.25 rather relatively low and this virtually plain carbon steel it has some residual elements.

Which are not intensively added, which are listed here sulfur, undesirable it gives hot sharpness makes that hard working difficult and to overcome the same amount of manganese is added to steel. Phosphors is also detrimental it has a very high hardening coefficient, it increases strength of a right significantly it input the solution. It is a very important solid solution strengthener for if you write, but it segregates to bring boundary and max the steel it is actually gives cold shortness cold shortness. It is brittle at low temperature and manganese is often use as a that to overcome bad effect of sulfur, it forms manganese sulfide which has high melting point and therefore, it does not allow. I mean it is distributed uniformly in the steel.

So, it may it overcomes the problem associated with hot shortness and silicon is often use as a deoxidizer and it also has some beneficial efforts as well. But they are not I mean, we to amount they which they are present is very less like sulfur, phosphorous. You will never have more than a vary to have than 0.05 of these or even better quality these days has even less sulfur and phosphorous. This micro structured structural steel is mostly ferrites. We have some pearlite depending on the carbon content many of this grades have has lower carbon content as a 0.07. So, virtually it will be made up of mostly ferrite am I made and very little amount of pearlite, because it has low alloy element it has poor hardenability.

So, the marten setting strengthening will not be applicable strengthening by hardening cannot be done over here. Often you may have some micro alloy addition is very small amount even less than 0.1 or 0.05 and certain elements. If they are added in set small amount and by combining the thermo mechanical processing it is actually possible to refine the structure to make that mean size very fine and thus improve the strength of steel. Now, let us see what are the factors I think this was done, but to recapitulate?

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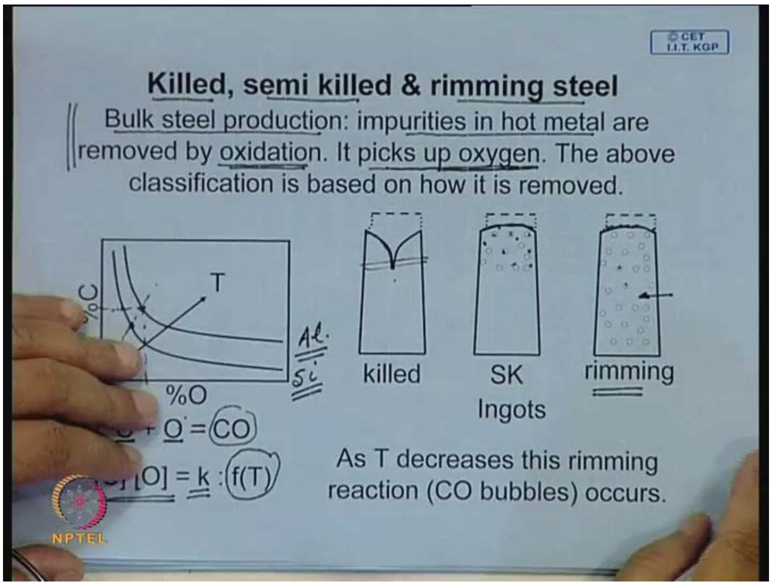

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Killed, semi killed & rimming steel

Bulk steel production: impurities in hot metal are removed by oxidation. It picks up oxygen. The above classification is based on how it is removed.

$+ \underline{O} = CO$

$[O] = \underline{k} : f(T)$

As T decreases this rimming reaction (CO bubbles) occurs.

Let us see that a few lines about the three major classification of steel are based on the way the steel is deoxidized. If you look at bulk steel production technique so, it is produce from hot metal, which comes from let us say blast furness hot metal. Which is actually a cast harden it has very high carbon contain may be around four percent. It has silicon also and these impurities it also has sulfur, phosphorus and they must be remove to make it steel. Because such high carbon material is extremely brittle they cannot be formed. Therefore, these impurities have to be removed and this removal is done by oxidation process. So, in basic oxygen furness is oxygen burn from top and then this oxygen reacts with this impurity and these impurities are observed in slag and in the process.

Since, the atmospheric air atmosphere that is maintained in the furness is oxidizing. Atmosphere steel also picks up oxygen, this oxygen is in dissolve state liquid harden and this above and this has to be removed. Because as you cool down you will find under you remove that stream. If you do not do any special treatment you have full find that this steel, when it solidifies there is vigorous reaction taking place and this is primarily. Because steel dissolubility of oxygen in molten iron depend also on other alloy element and particularly carbon. You are trying to remove carbon by oxygen and this is and they will be soluble amount of carbon and oxygen that can remain in solution in iron was given by plus equilibrium reaction and the product of concentration of carbon.

And oxygen steel is called the solubility product and this product; it is a function of temperature and is content. Therefore, if you plot a graph percentage soluble carbon in harden and soluble oxygen in harden. You will get this kind of hyperbola you get this equation is that of a hyperbola and therefore, higher the temperature higher is the solubility product. So, higher temperature this temperature is increasing it can keep say, if it has this much amount of oxygen. It will have this much amount of carbon, but when you cool the steel. When you pour the molten metal in an invert like this, what will happen as the temperature goes down?

So, it becomes it has higher amount of carbon and that carbon has to now come down so, carbon will come down. Let us say some line so, it has to come down if carbon come down oxygen also will come down solubility of oxygen also decreases. So, if it happens it comes down from here, then what happens to that excess carbon that will react and form C O bobble? These bobbles trying and form and this are a vigorous reaction this gas bobble trying and form and what happen the reaction is extremely vigorous. You have to control properly and often you know normally if molten metal solidifies. They should be contraction and usually get this kind of shrinkage.

Whereas, in this particular case, if this vigorous reaction takes place with at this reaction called rimming reaction and that these are the some of the C O bobble, which are not able to escape. Because if it forms a plastically not be able to escape and in that case we had a steel, which is full have the C O bubbles and it combine sets the shrinkage cavity. It has one page you have higher in, but it has a problem you have some amount of dissolve oxygen in the steel and oxygen makes the steel brittle. So, rimming steel although it can be a wearing subsequent rolling this are the pores to steel up and all that, because that some amount of soluble oxygen in the steel.

It has relatively poor ductility and it has higher transition temperature other extreme. If you add a deoxidizer and one of perfect deoxidizer is aluminum either which has a very strong affinity for oxygen. In that case this oxygen will be used up by aluminum or silicon and depending on what you adding the steel? It can stop this rimming reaction completely and in that case you get you kill this particular lapsing, that means you kill the steel, which is very reactive you kill it. And therefore, you get a large shrinkage cavity and when you arrive here of course, the yield is low. Because later on you have to crops a certain part of it, which cannot be the sure tempo, say flat product or the section in between also it is possible, you have console amount of this.

Deoxidizer and that you can control this rimming action that you denote allow this shrinkage to take place. Some amount of C O bubbles allow to form and here by this yield can be increased.

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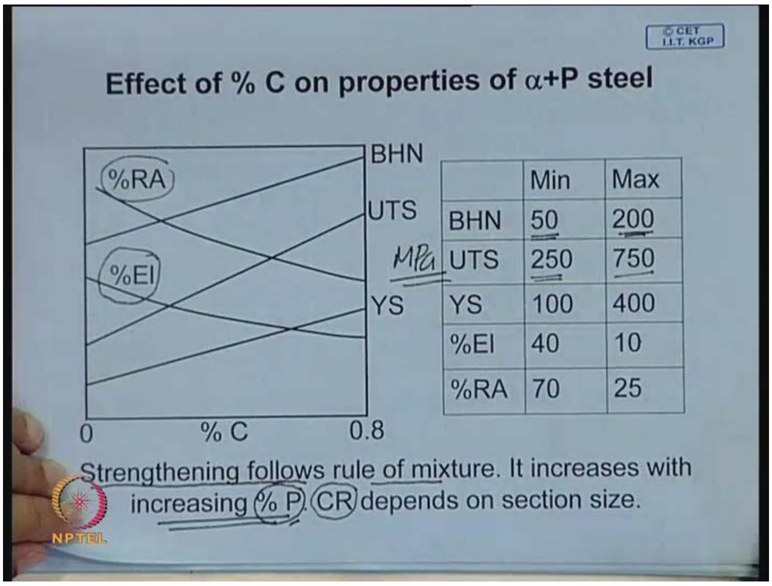

Effect of % C on properties of α+P steel

	Min	Max
BHN	50	200
UTS	250	750
YS	100	400
%El	40	10
%RA	70	25

Strengthening follows rule of mixture. It increases with increasing % P. CR depends on section size.

Now, we are quick look up the effect of carbon content on the properties of steel. I think this was mentioned earlier that with carbon contain yield strength UTS hotness. They all decrease, but the ductility which was represented by reduction in area decreases with increasing strength or increasing carbon content ductility. If express in terms of percentage elongation also decreases and these are the values of that waving your properties that you can get, which are listed here. The brindle hardness numbers that minimum you get particularly when you have virtually low carbon.

So, if you have pointed you get something like this, UTS ultimate tensile strength is of disordered MP a this is make up Pascal’s. Similarly, this also you know some values are there is ductility. So, strengthening in this particular it is types of growth it follows rule of mixture, if you increase the amount of power light it is strength will increase and by cooling rate, it is also possible to control the fineness of power light. If you increase the cool rate all light, if it is finer then also responsible increase.

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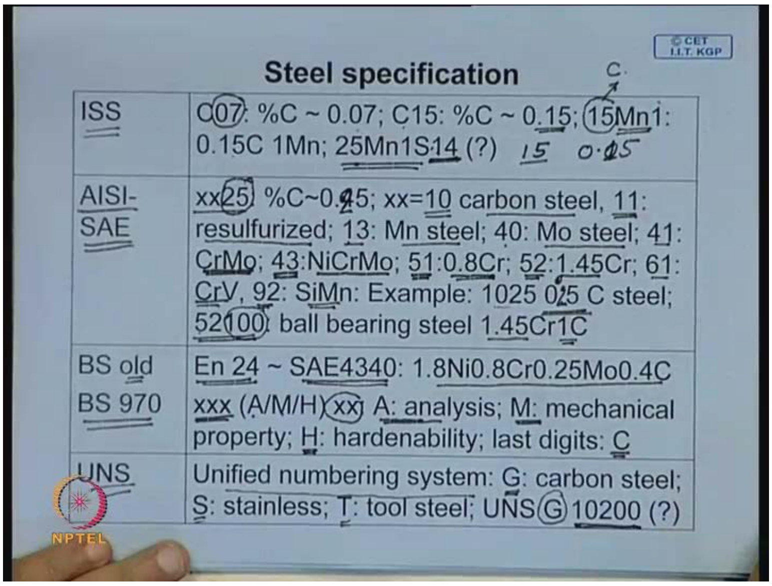

Steel specification

ISS	C07: %C ~ 0.07; C15: %C ~ 0.15; 15Mn1: 0.15C 1Mn; 25Mn1S14 (?) 15 0·05
AISI-SAE	xx25 %C~0.25; xx=10 carbon steel, 11: resulfurized; 13: Mn steel; 40: Mo steel; 41: CrMo; 43:NiCrMo; 51:0.8Cr; 52:1.45Cr; 61: CrV, 92: SiMn: Example: 1025 0.25 C steel; 52100: ball bearing steel 1.45Cr1C
BS old BS 970	En 24 ~ SAE4340: 1.8Ni0.8Cr0.25Mo0.4C xxx (A/M/H) xx: A: analysis; M: mechanical property; H: hardenability; last digits: C
UNS	Unified numbering system: G: carbon steel; S: stainless; T: tool steel; UNS G 10200 (?)

Now, few line points about steel specifications so, obviously most of the specification are based on the compositions. Now, different confide follow different Indian standard specification, which is listed here. Say suppose carbon steel, if it is plain carbon one way of representing is C 07, here this number represents percentage carbon. So, percentage carbon means here you divide by 100. So, 0.07 percent carbon this steel C 07 represent this C 15 minus carbon content is 0.15. Sometime you have certain other alloy element though you do not write C you write that mean alloying element, which is present you say that 15 M n 1. You meant first two numbers so, it represents carbon content. So, that is 0.15 is the carbon and the second one gives the manganese content 1 percent manganese, sometime this elements you have more elements like there are certain grades.

We mention that where you know normally sulfur is undesirable, but there are certain grids where you add sulfur. This is particularly where you know good much inability, there you need a little bit of inclusions made of manganese sulfide, which improves the massing ability of steel. So, this is one such steel here 0.25 was the carbon content manganese is 1 and sulfur is 0.14 and in fact some time you use underline to show that this is 0.14, it is not 1.4 or 14. It is our which are unexpected unheard of so, that means it is underline means, if any number is underline say if is 5 underline that means, it mean 0.05 or 15 underline is 0.15.

Now, many of these have been derived a systems see from system followed by American hardening steel institute or society of automotive industries enterprises automotive engineering. So, these are AISI specification is this we use four digit the first two digit, which can be represents the type of steel in the last two digit this represents carbon content like x x 25. This 25 means this carbon content is 0.25, it say there is a mistake here this should be 0.25 is the carbon content and this x x. If it is 0 means it is plain carbon steel, this first two digits, if it is 1 0 means plain carbon steel first two digit. If it is 1 1, this is resulfurized steel 1 3 means manganese steel 4 0 means mollies steel 4.

One this is the convention there is no bases, but sometime if you follow this convention that is possible to guess. What is the composition? And what are they allow major alloying element four? One means you have chromium mallon, this are alloy content amount may not be much larger, may be 1 percent or 2 percent around that. So, 4 3 means nickel, if you have first two digit as 43 nickel chromalloy, first two digit 5 1 in that case this means it says 0.8 chromium steel 52. Then, it is chromium steel there are bear in steel 1.45 chromium 61 means chromes domatium steel 92 silicon manganese steel. So, one example which is given here 1025, this is actually the carbon content is point there is a mistake here 0.25 carbon steel this is a ball bearing steel here 5 2 1 0 0.

So, this has 1.45chromium and these last three digits represent carbon content and carbon is 1 percent. Now, better specifications that old specification there is no like these are some certain number engineering steels E n 24, which is equivalent to SAE 4340 and this is the composition that steel and the new bear spec they use digit. Like this first three digit they signify composition alloy element, last two digit gives that last two digits gives the carbon content and it also uses certain letters a m h, which means that specification is by analysis by mechanical property or whether it is a harden ability. In fact this specification varies from country to country and attempts have been made to use unified numbering system and here UNS system and here the g they use a letter grade to represent G for carbon steel, S for stainless steel, T for tool steel and you can see this is a simply a plain carbon steel. You find out this should be a 0.2 percent carbon steel.

Now let us see, we have talk about some steel specification. We also learn that structural steel what is structural steel is basically plain carbon steel. Let us see what type of strengthening mechanism will be applicable here. Because here since the sets and size depending, sometime it can be very large and sometime and it has very low carbon content low alloy element.

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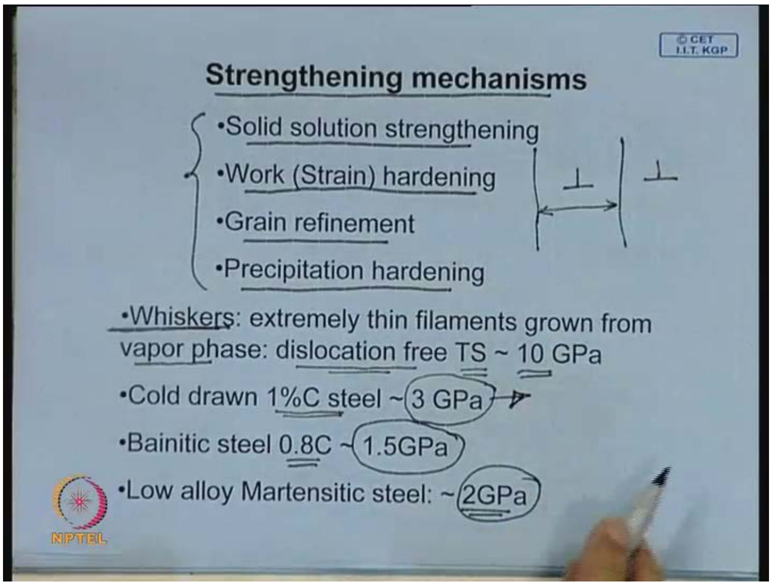

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Strengthening mechanisms

- Solid solution strengthening
- Work (Strain) hardening
- Grain refinement
- Precipitation hardening

- Whiskers: extremely thin filaments grown from vapor phase: dislocation free TS ~ 10 GPa
- Cold drawn 1%C steel ~ 3 GPa
- Bainitic steel 0.8C ~ 1.5GPa
- Low alloy Martensitic steel: ~ 2GPa

Therefore, it has little harden ability therefore, the strengthening mechanism, which are normally applicable in steel which are listed, but all may not be applicable. We will see, which will be most preferable. So, one is the solid solution strengthening we learn this about this earlier then strain hardening or work hardening grain refinement precipitation hardening, these are the common strengthening mechanism, which are use to improve the strength of steel and you feel or any metal and alloy these are the basic strengthening mechanism just.

To give an idea say what is the strength of steel iron can be made in the form of whiskers these are very fine pheromones, which are grown from vapor phase and these are so, fine that means dist normally. We have seen the dislocations they have a stress field to dislocations cannot stay very close via. So, if it is possible to find out or make a material to add the two dislocations. You know it is impossible to accommodate at this location if the dimension is very small. It is quite lightly that this material will be defect free and this whiskers are very thin filament crystal and these are virtually dislocation free it is tensile strength is of the order of 10 GP a by cold drawn 1 percent carbon steel.

We will see how it is very special deformation process by which you can achieve this in a actual practice. Bainite steel having at carbon strength will obviously depend on amount of carbon that is there if it is pointed. You can get this level of 0.15 giga pascal strength whereas, low alloy mortensitic steel. We can get strength of this order, but very often the structural steel that we use there are neither there are not mortensitic.

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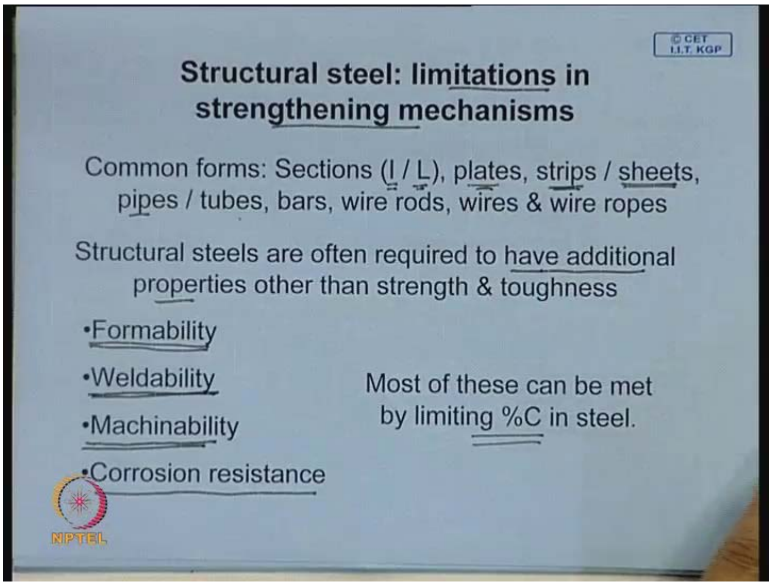

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Structural steel: limitations in strengthening mechanisms

Common forms: Sections (I / L), plates, strips / sheets, pipes / tubes, bars, wire rods, wires & wire ropes

Structural steels are often required to have additional properties other than strength & toughness

- Formability
- Weldability
- Machinability
- Corrosion resistance

Most of these can be met by limiting %C in steel.

Let us see how we can strengthen them and in structural steel there is a limitation in strengthening mechanism what are they? Now, there are common forms of structural steel say very common say it could be I plain it could be l section it could be plates, it could be strips or it could be cold role sheets, it could be pipe tubes bars wire rods wire rope. So, there are so many and when the structural steels are made you know they are often require to have not only strength and toughness, but certain order additional properties this depends on what is the downstream application of these. So, suppose you want to form our automotive body you, which is made up of steel say thin steel sheet. So, in that case property that will look for this formability and often just formability is also not enough, sometime you have to join or give a proper sheet that is should be amenable to certain fabrication process.

Like welding was one second fabrication process you have to look at the weldability. Sometime certain application machinability is important and many applications, you will also look for the material. Should we able to withstand corrosion should be corrosion resistance and many of these we will see can be made by limiting percentage carbon in steel, but the problem comes up. If you decrease percentage carbon in steel it is strength will go down and how do we make it up.

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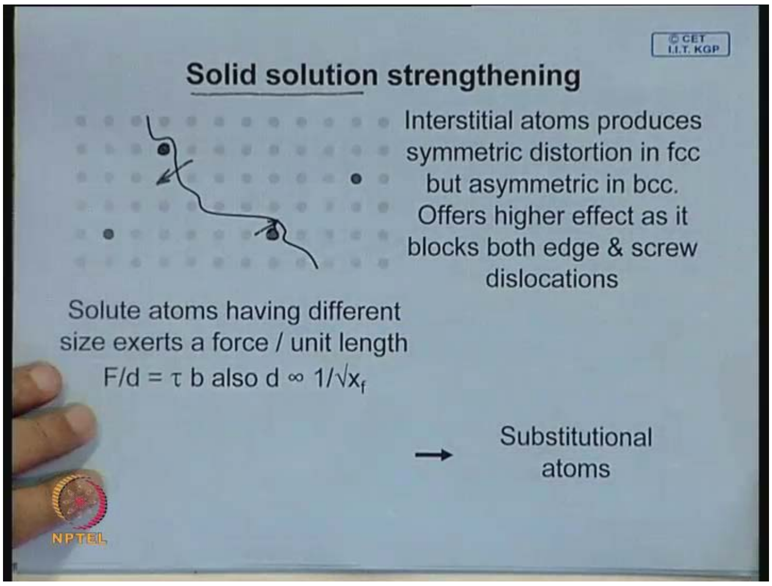

Solid solution strengthening

Interstitial atoms produces symmetric distortion in fcc but asymmetric in bcc. Offers higher effect as it blocks both edge & screw dislocations

Solute atoms having different size exerts a force / unit length $F/d = \tau b$ also $d \propto 1/\sqrt{x_f}$

→ Substitutional atoms

That is let us see, how this is possible my quick look at the strengthening solid solution strengthening. If you add solute atom this atom like, here you add it will have a different dimension. So, there will be some elastic distortion it will have a stress free and we know that deformation takes place through movement of this location of course, this dislocation is moving in this direction. This is a stress field not free to move so, this dislocations movements hindered by the stress field of this solute atom and overall effort will depend on how closely they are spaced. So, if and therefore, say proper it is more than number of atom node will be the strengthening and people have it has been possible to work this out.

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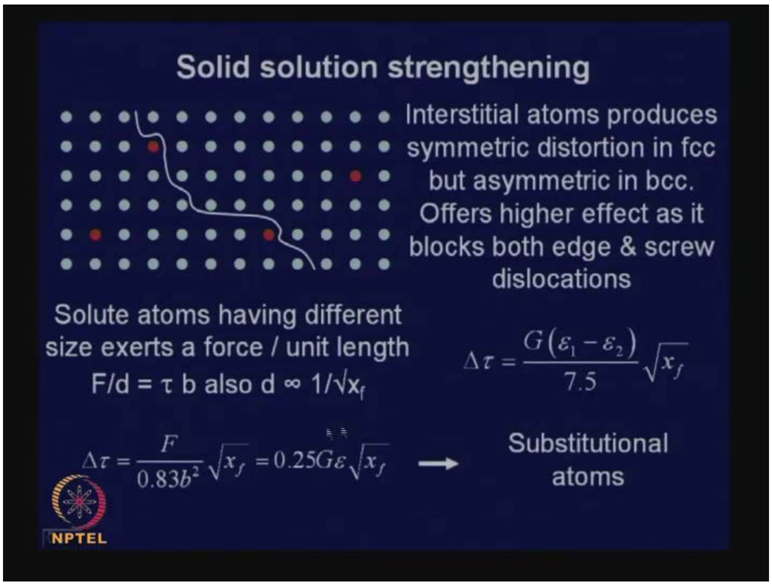

Solid solution strengthening

Interstitial atoms produces symmetric distortion in fcc but asymmetric in bcc. Offers higher effect as it blocks both edge & screw dislocations

Solute atoms having different size exerts a force / unit length

$F/d = \tau b$ also $d \propto 1/\sqrt{x_f}$

$$\Delta\tau = \frac{G(\varepsilon_1 - \varepsilon_2)}{7.5}\sqrt{x_f}$$

$$\Delta\tau = \frac{F}{0.83b^2}\sqrt{x_f} = 0.25G\varepsilon\sqrt{x_f} \rightarrow$$

Substitutional atoms

We will see quickly here does now it is possible to find out that how much force is exhorted by the solute atom on the dislocation and this force will depend on. You know if you have more number of atoms so, what is more important? What is the force, which is permanent length of the dislocation exhorted by the solute atom? If d is the spacing between two solute atom then you can say this is the force permanent length and to move the dislocation. We apply here a stress a tau in that case force on the dislocation will be tau b and both have to be equated, if you equate the both that is possible to find out a relationship between thus it is also possible to find out

If you know the atom fraction of solute present it is possible to show that the distance between two atoms will goofily equal to 1 over root, over atom fraction of the solute element atom fraction of the solute element. And therefore, if you make just substitute over here then you will find that increment in tau merciless strength will be proportional to square root of the solute content. This is a case where solute atom is the substitutional solute atom and same thing can be extended to cases in the interstitial atom also, but interstitial atom. We know that in free centered cubic in f c c, that means in carbon occupies octahedral site and these sides are symmetrical.

So, in f c c both whenever you have a carbon atom distortion that it produces is uniform in all directions whereas, in b c c lattes note even. If the carbon atom whether it is tetrahedral or octahedral and more lightly chance. I mean people have seen by experiment that carbons are preferred sides of octahedral, these octahedral sides in b c c. They are not symmetry in direction it is large and another direction it is short the gap interstitial gap is shorter. When carbon atom goes into the interstitial is produces expansion in one axis and that axis is c and this introduces a tetragonal distortion in the lattes and this distortion is called large and that is more important factor for strengthening and therefore, in substitutional atom summarized here.

In symmetric distortion in f c c, but asymmetric in b c c and therefore, in asymmetric distortion are more effective in blocking dislocation movement. Because uniform stress can block only edge this location movement whereas, asymmetric distortion will have shear stress. And therefore, it can block screw dislocation motion as well therefore, they are much more effective barrier to dislocation motion and they have a good high amount of strengthening effect. And this also will be never the less proportional to the number of atoms that you have that is also proportional to square root of atom fraction. So, this is applicable for interstitial and this is the relationship for substitutional atom.

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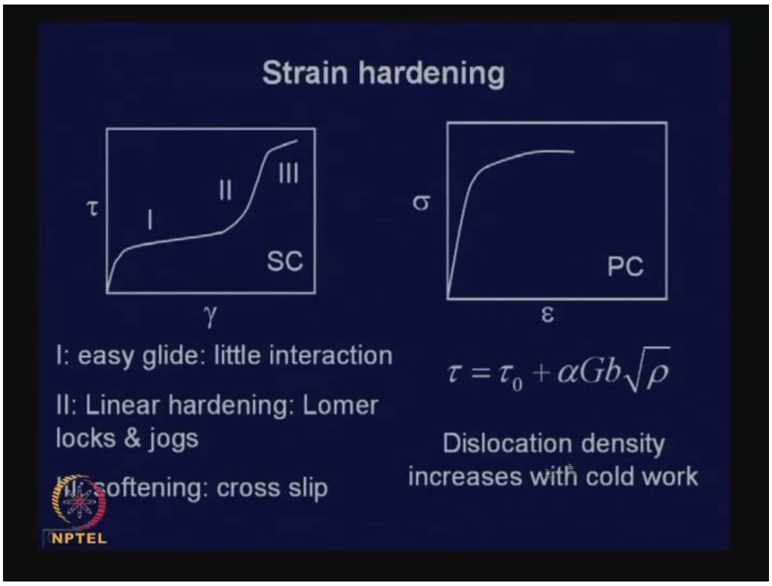

Strain hardening

I: easy glide: little interaction

II: Linear hardening: Lomer locks & jogs

III: softening: cross slip

$$\tau = \tau_0 + \alpha G b \sqrt{\rho}$$

Dislocation density increases with cold work

Stain hardening we have seen that is, this is the typical deformation behavior of a single crystal. We talked about three stages easy glide where there is a little dislocation interactions whereas, in the stage two it is aid two period of linear hardening. Where dislocation interaction takes place control lomer locks are forms the jogs are also formed on the dislocation and this makes the movement of dislocation difficult. Therefore, there is high amount of stain hardening and then when the stress increases significantly here again another node of deformation, which is a responsible lead to little bit of softening that is crossly. So, this is the stud stage and in general this is the behavior in a single crystal, but poly crystal you have large number of grains.

So, burn through this three distance stages what you see this is a typical stress verses strain plot in case of poly crystal alloying material and here the total strength of the material will be determined by the dislocation density however dislocation density means you have no dislocations in the slip line and dislocations because of the dislocation interaction it form strangest of dislocation and what is more important is if the dislocation? Density is increase the distance between two dislocation also will decrease the dislocation between the dislocation rude will decrease. It is possible to show that the strength as it is shown here that is the strengthening is proportional to square root of dislocation density here G is a clear normal us b is purchase vector. So, the dislocation density it main strain hardening mechanism was primarily increase in dislocation density and it is dislocation network becomes very fine dislocation distance becomes smaller and the strength increases.

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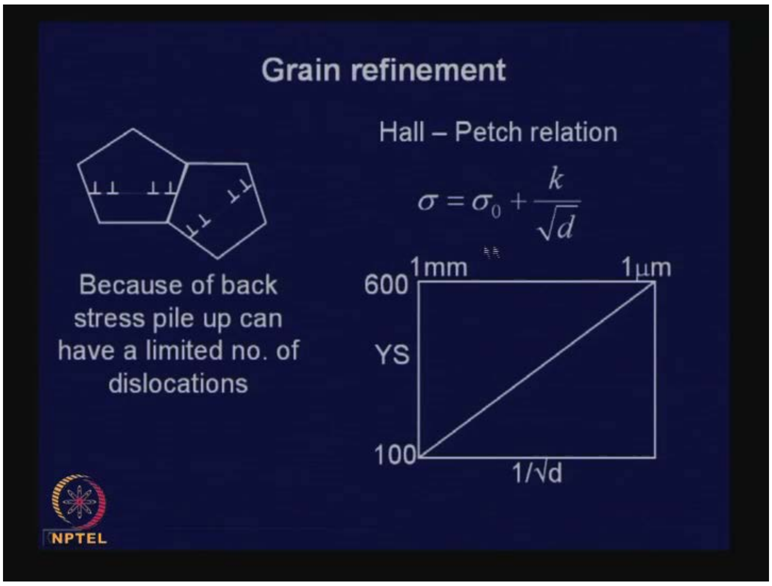

Grain refinement

Hall – Petch relation

$$\sigma = \sigma_0 + \frac{k}{\sqrt{d}}$$

Because of back stress pile up can have a limited no. of dislocations

Another important strengthening mechanism is grain refinement when dislocation source acts on this are the two grains. Let us assume if a dislocation source is operating it will generate dislocation and when it moves through the slip plain it causes, it deforms the grain and in doing. So, you mean it is that is possible it can come across the barrier and here this dislocation. It stops and pile up develops and this also loosed stain hardening it depending on the size of the grain. It has a limited capacity it can accommodate only a limited number of dislocation and this grain boundary also has a and if this number of dislocation increases stress on the brain boundary local stress gets intensified.

It can move into the dislocation and this area brain boundary or it can move from here to next boundary it is possible? And therefore, the grain size is an important factor it determines how many dislocations can accommodate and it is possible, if you recollect your earlier lecture. It has been shown that strength of the crystal can polycrystal alloying material is inversely proportional to square root of the grain size d is the average grain size and in fact this is the plot.

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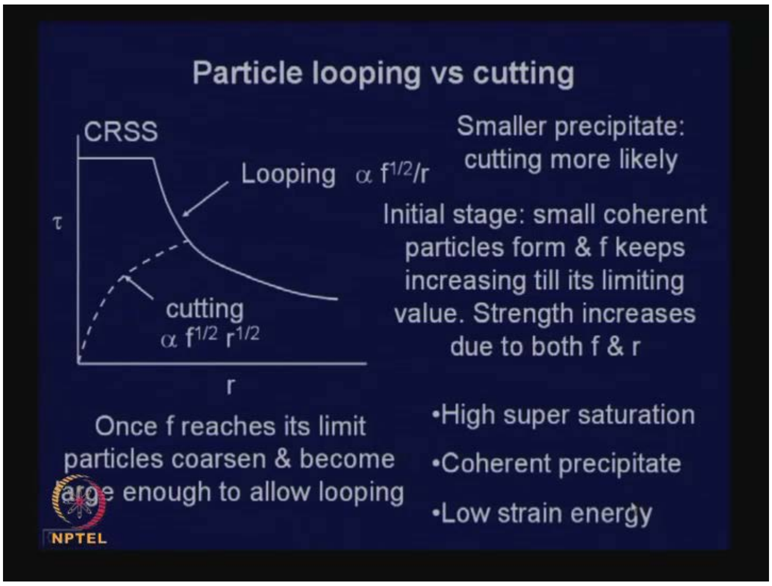

Particle looping vs cutting

Smaller precipitate: cutting more likely

Initial stage: small coherent particles form & f keeps increasing till its limiting value. Strength increases due to both f & r

Once f reaches its limit particles coarsen & become large enough to allow looping

- High super saturation
- Coherent precipitate
- Low strain energy

Which diagrammatic representation, if you plot yield strength against 1 over root d, you will get a linear line and in fact from this you can find out sigma 0 and k. We also talked about precipitation strengthening at length; in fact there are two mechanisms, which are important. One is particle looping another is a particle cutting and we derived we said that this is the limiting strength a critical resolve stress or critical strength of the material. And here this is the looping stress and this is directly determined by you know it is it will be particle distance and for a given volume fraction are precipitate. It can be related to the particle size also and this has this kind of a relationship and the mean time. You also have the particles initially; you do not have any precipitate as the precipitate grows the volume.

Fraction of precipitate increases and the precipitate also grows in size or also increases. The stress require to cut a fine precipitate is given by this volume fraction of precipitate raise to the power of a radius of the precipitate race to the power half. So, this plot looks like this. So, this is the optimum strength that you expect after that if the precipitates coarsen. You know then the strength drops so, to get ideal strength maximum strength. What you need is you need high degree of super saturation. So, you need a super saturated solid solution and then we knew age the precipitate that forms must be coherent precipitate and the coherent precipitate is always associated with some lattes strain. We talked about this lattes strain, if there is too much of lattes strain; you know the precipitate is trying to form.

So, this will oppose the driving force therefore, too much of lattes strain is also harmful. You may have some amount of lattes strain coherence strain it can accommodate. So, basically some low strain energy not too much and then coherent precipitate and high super saturation by controlling this you can control the extend of precipitation strengthening.

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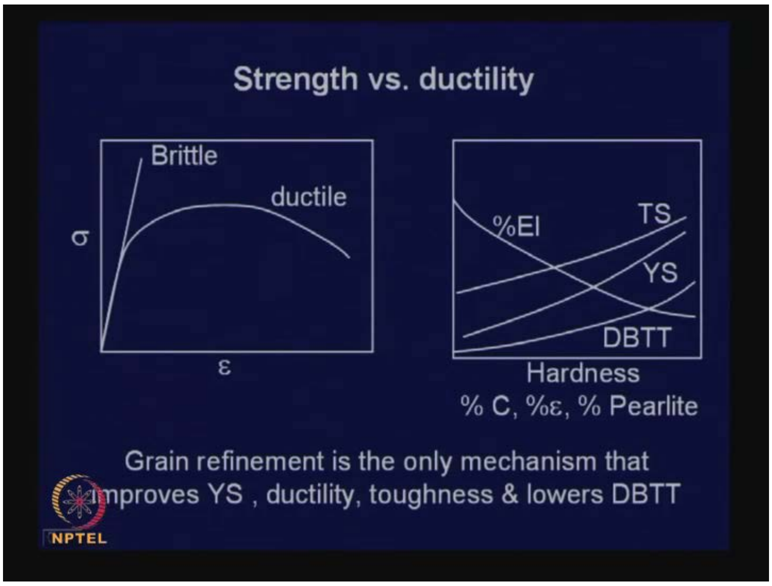
Strength vs. ductility

Grain refinement is the only mechanism that improves YS , ductility, toughness & lowers DBTT

Now, by most of these strengthening mechanisms if you try to increase the strength of crystal, what happens? What effect does it have on the ductility? If you recall it out that initial plots of the stress strain plot normally the brittle material are those, which is brittle even before elastic deformation occurs. So, a brittle material says a stress strain plotter virtually linear and here it breaks. In fact marten sites if you have fully harden say wires steel wire each have been marten to harden to marten site fully harden. If you try to find out a stress strain diagram refine it is before it deforms it break, but the same steel wire. If you were need you make a ductile it that case you will find it exhibit this kind of a stress strain behavior.

So, before it fails it grows passes through a necking region and you have a very large percentage elongation in reduction area. So, in fact it has been seen that if you try and improve the strength of the material. Whether it is by cold water so, if you take a wire and try and bend it reputedly. Each time you bend you are deforming causing some deformation in the material and it is strength increases and in the process it reaches. It is limiting strength and later on you find that it breaks you try to deform it breaks. So, that means, if you increase the hardness or strength of the material yield strength or tensile strength of the material then it is elongation ductility decreases and there is also another term we talked about ductile to brittle transition temperature which is quite important.

For structural steel many of the structure, which are made of satiate plates, you know say particularly ships. Which go in to regions in the see where see is cold and this plates one of the main fabrication technique is welding? When you weld a tick plates you have to see by welding you do not the property in the welded region and you do not increase the strength and adversely affect the toughness of the material and one mechanism. So, one problem that comes up where, many of these fabrication process or alloy elements. When you improve the strength ductile to brittle transition temperature increase. So, certain steel, which is normally ductile at room temperature, but if you test it at a low temperature you will find it is brittle so temperature at which this transition takes place brittle to ductile.

It is called ductile to brittle transition temperature and high ductile to brittle transition. Temperature means that material is acceptable to brittle failure at low temperature. So, normally if you strength increases means ductile to brittle transition temperature also increases. Now most of the strengthening mechanisms, which increases the adversely effort ductility toughness and the ductile to brittle transition temperature there is one mechanism. Which is grain refinement this is the only mechanism that improves yield strength at the same time there is not adversely effort ductility or toughness. In fact some cases that is reported to have lower to have ductile to brittle transition temperature normally, when a fracture takes place. We will see that whenever fracture takes place there are certain crack parts, which are favorable.

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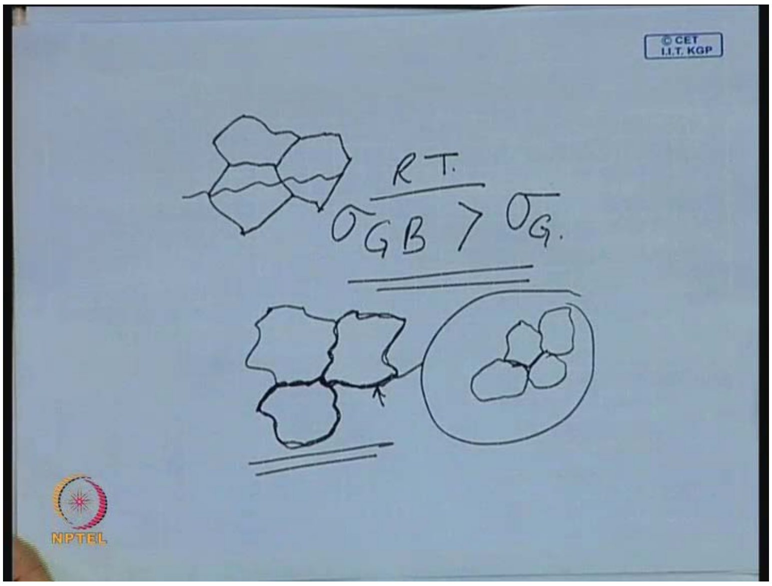

Now, usually at a room temperature we find these green boundaries are stronger. Normally at room temperature green boundary strength or green boundary is greater than strength of green. So, if a fracture takes place at a room temperature is more likely that fracture takes place through this. Now in certain cases it is possible that because of certain if the green boundary is say. In certain cases some solute element the segregate to the green boundary makes the green boundary brittle, in that case what happens; because of the segregation cold shorten this green boundary. So, these are green boundary some segregation has taken place and this is brittle. So, one amount of segregation we talked about is a thin network of cemented brittle cemented.

Network or some mono layer kinds of precipitate or monolayer suppose phosphors segregates here. It makes the steel brittle, because this provides say low, I mean easy fracture path crack can propagate like this inter granular fracture. So, in that case you have a material becomes brittle it has inter granular fracture. Now what happens, if you make these green boundaries finer you reduce the chance of the segregation? Because you have more amount of green boundary so, chance of this kind of brittle network forming is reduced. So, this is one reason which makes fine grain steel more resistance to crack root. So, this is a mechanism which helps improve the strength without sacrificing ductility or toughness.

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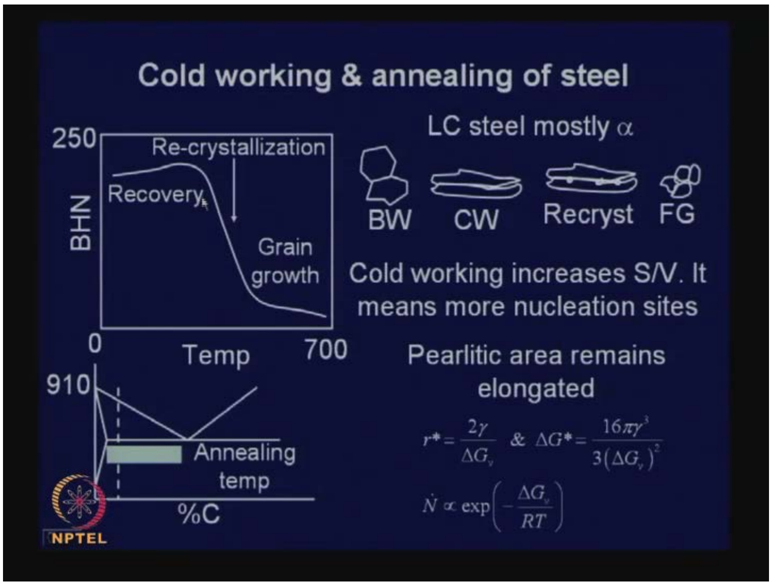

Cold working & annealing of steel

LC steel mostly α

Cold working increases S/V. It means more nucleation sites

Pearlitic area remains elongated

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

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

Now, quick look about how do you control the grain size and steel. So, one method is by cold working and annealing you can by this process. We did talk about it by cold work and annealing it is possible to get very cold stale structure as well as very fine grain structure and how do you do this is typical annealing when you anneal. If you have a cold work material it has a very high hardness. Let us consider it is a low carbon steel it is have very low carbon contain it is mostly ferities and what happens and the recovery stage there may be little increase in hardness.

This is a strain aging sometime the solute atom particularly this interstitial carbon and nitrogen they can precipitate and block the grain boundaries. And this can increase a little bit of strength, but it helps in removing the residual stresses micro stresses by through rearrangement of dislocations and after certain temperature that is a rapid drop in strength. So, here what happens the new grains? Form new re-crystallized grains are form and these grains are strain free.

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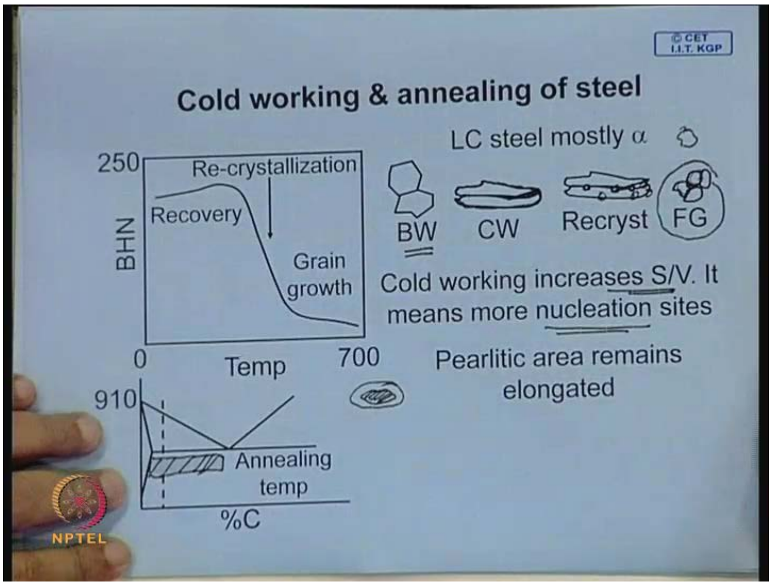

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Cold working & annealing of steel

LC steel mostly α

Cold working increases S/V. It means more nucleation sites

Pearlitic area remains elongated

So, like which is shown ever here, these are the grain structure before working and when you cool work this grains get elongated and you have large grain boundary area. When you heat here during annealing what happens? You know this it has a high elastic stored energy and it will try to come to it is position of lower energy. So, there is a driving force existing, but first grain cannot nucleate, because to nucleate new grain. New area is to be created. So, this is the main, this is one has to overcome the barrier that surface energy barrier has to be overcome and this grain boundaries provides, such heterogeneous location varies can easily overcome.

So, these are the new creation sides and when these grains grow and finally, all of this they are replaced by these types of fine grains. Now, cold working in fact it increases surface area to volume ratio. So, you provide more sides from nucleation of strain free grain. It means it is more nucleation side and high other cold work finer will be the grain and by controlling the amount of cold work it is possible to control the grain size. Usually the annealing temperature for cold working, after cold working of low carbon steel is in this region. You do not go to the austenitic region so; definitely the pearlite effect all is there the pearlite area. If it gets deform it will remain like this, they do not undergo any re-crystallization, but ferrite region will undergo re-crystallization.

You will recall that these are the critical nuclear size; this grain size will be determined by this critical nuclear, which is inversely proportional to the cold work. So, higher the cold work finer will be the grain and also higher the cold work much lower is the activation hill, which is to be overcome. So, the nucleation rate will be faster a nucleation rate means finer grain.

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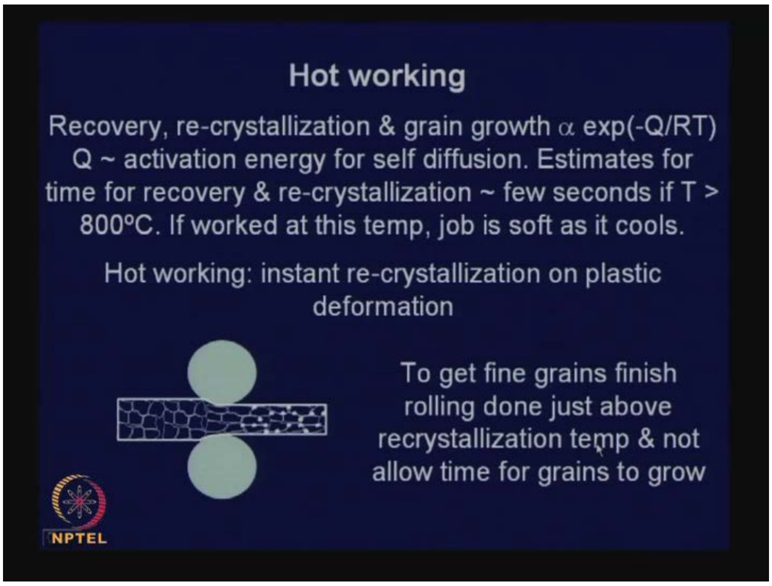

Hot working

Recovery, re-crystallization & grain growth α exp(-Q/RT) Q ~ activation energy for self diffusion. Estimates for time for recovery & re-crystallization ~ few seconds if T > 800°C. If worked at this temp, job is soft as it cools.

Hot working: instant re-crystallization on plastic deformation

To get fine grains finish rolling done just above recrystallization temp & not allow time for grains to grow

Now hot working is a process where re-crystallization plastic deformation virtually takes place simultaneously. It is possible to calculate the time one takes for a re-crystallization to take place. Because there crystallization process will be determined by the movement of iron atom sodium the lattes. So, self deficient of iron it is possible that you the self deficient co-efficient are given by the exponential minus Q by R T, where Q is the activation energy. So, if you know the activation energy for self diffusion it is possible to calculate the time for recovery and re-crystallization. Often say if you do it for 800 degree centigrade you will find thus time will be order of 2 seconds. So, that times by the time the job cold.

If you are working at this temperature the time it takes for the job to cold to room temperature is enough for re-crystallization to take place. So, when the job cools infinitive soft so, hot working is actually you can say that there is an instant re-crystallization on plastic deformation. Which is pictorially shown here so, if you have these are the initial that course do in structure and here in rolling this grains get elongated and these are the nucleation sites and after this also temperature is high. The face grains are forming and to get fine grain. What you can do you have to increase the decrease the diffusivity and how can you do that means you finish that rolling to a temperature just about the re-crystallization temperature. So, that atom move into we can rested hat means you finish rolling is done closer to the re-crystallization temperature and do not allow enough time for grain to grow.

So, the key to fine grain structure, if you were doing by hot working you give all that here reduction major reduction bulk of it may be at high temperature. Where you need low rolling load, but give a finish rolling temperature should be low. The finish temperature rolling also the reduction should be little high so, that critical nuclear size is less and that and you do not allow and finish rolling temperature is close to re-crystallization temperature. So, as it comes out the rolling mill it does not get enough time for the re-crystallize grain to grow.

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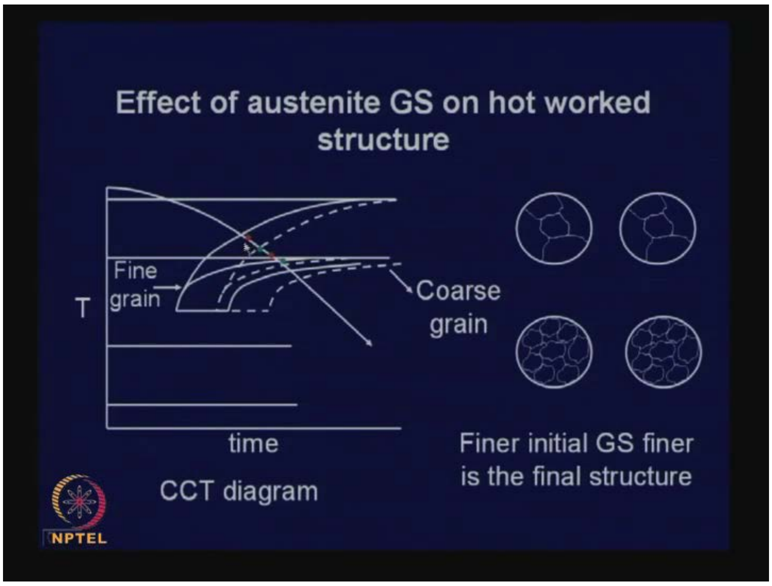

Effect of austenite GS on hot worked structure

CCT diagram

Finer initial GS finer is the final structure

The austenite grain size also determines that finer structure initial grain size, if it is groups and if you deform at finer structure is likely to be grows. If initial grain size austenite grain sizes finer will deforming it further you make it more fine and the champs have getting a fine grain is higher. This also knows that austenite grain size does affect this CCT diagram and which is pictorially shown here. So, in this case if the grain size is fine the transformation starts at higher temperature, if grain size is grow transformation will take place a little lower temperature?

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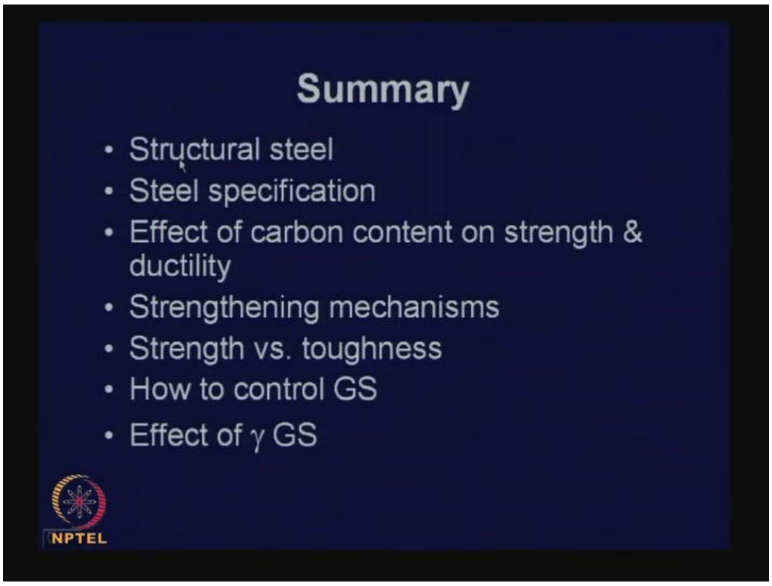

Summary

- Structural steel
- Steel specification
- Effect of carbon content on strength & ductility
- Strengthening mechanisms
- Strength vs. toughness
- How to control GS
- Effect of γ GS

So, by playing with this is possible to control the fine house structure of steel and to some of whatever that we have covered today. We talked about structural steel specification. Here we again emphasize the effect of carbon content on strength and ductility. We talked about strengthening mechanism which had been applied or which can be applied. We talk about strength relationship between strength and toughness and we have seen how by controlling grain size. It is possible to increase both strength and toughness. We also talked about how to control grain size by controlling degree of working and the re-crystallization temperature. We will see in the next class little more about it. Thank you.