Failure Analysis & Prevention
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Lecture – 40
General Procedure of Failure Analysis:
Embrittlement of steels

Hello I welcome you all in this presentation related with the subject Failure Analysis and Prevention and this is the very last presentation or related with this subject, we have talked about the various aspects related with the failures like the fundamental sources of the failures and how to investigate. So, the general procedure of the failure analysis also we have talked apart from the few examples.

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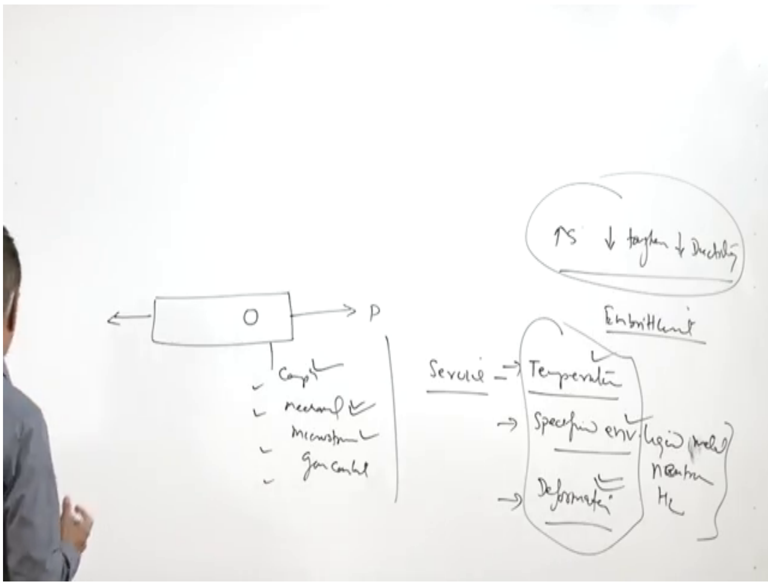

Now, we will see sometimes the failure of the some of the components take place under very unique conditions, like the component is subjected to the certain loading conditions. Even if it is having some of the notches the composition mechanical properties microstructure the gaseous content everything is fine, but when we put in service say this the new component when it is put in service having everything in perfect form, this kind sometimes the component during the service when it is; when it is exposed to the a particular kind of environment like, when it is subjected to the high temperature or when it is subjected to the some specific environment like liquid nitrogen like liq sorry liquid metal neutrons the hydrogen.

So, these are the specific environmental these are the temperature related or when the component is subjected to the deformation. So, under these unique set of the conditions sometimes the same component which was perfect in the beginning sometimes shows the increase in strength, reduction in toughness you know impact resistance reduction in ductility.

So, this variation in the properties of the material when it is exposed or of steel when it is exposed to the unique range of the temperature, unique environment or subjected to some kind of the deformation; then this kind of the change in the mechanical properties of the steel is known as embrittlement and if we see it is just the environmental exposure which is given otherwise there is no change composition is same there may be minor modification in the mechanic micro structural aspects which is governing the mechanical properties.

So, but most of the time we are not able to understand what is the cause of the failure, because otherwise there is no there is no unique observation or there is no unique finding as far as the failure analysis is concerned for some kind some of the components.

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So, like the component fracture is taking place in very brittle manner, well the component which was the metal of the component which was used for making it had a sufficient the ductility, it had sufficient toughness. But when it had sufficient mechanical properties in terms of toughness ductility hardness strength etcetera and a required the micro structure required chemical composition everything was fine, but when it was put in service it filled in brittle manner.

So, the component which was ductile which was tough and subsequently failing in the brittle manner, really encourages us to see what kind of changes in the material are taking place due to which it is changing it is a behavior. So, for that for that we need to really study the kind of the things which change the behavior of the material during the service, either due to the exposure at high temperature due to the deformation or due to the particular kind of the environmental condition and that is why we need to see what are the factors lead to the embrittlement of the steels.

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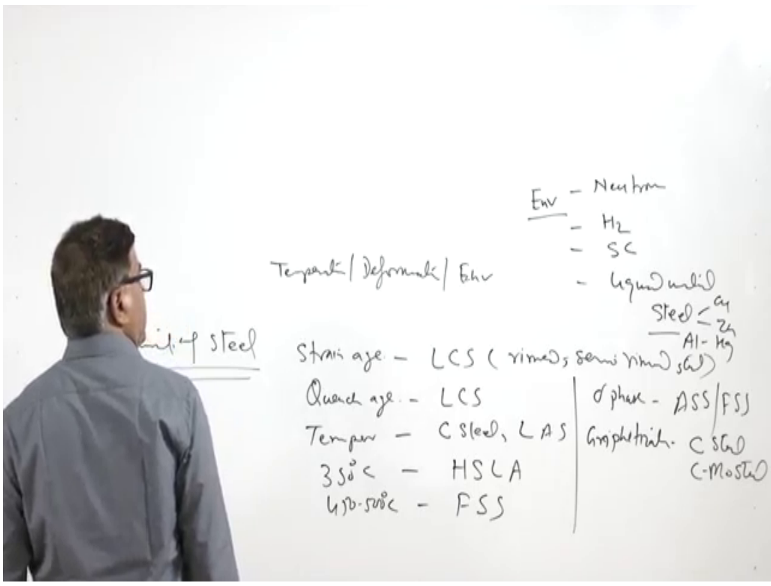

So, there are different grades of the steels which are sensitive for the different kinds of the embrittlements. So, here what we will see like there are 3 factors, one is temperature as I have said then there is a deformation and there is environment in which the exposure is being given accordingly. The different kinds of the embrittlements I will be mentioning first like the strain age embrittlement and the low carbon steel is sensitive for this kind of embrittlement. Mostly these are the rimmed or semi rimmed steels, which have the oxygen and nitrogen content then quench H embrittlement and low carbon steel is also sensitive for this kind of embrittlement then there is a temper embrittlement.

Temper embrittlement is observed in case of the carbon steels um, then low alloy steels then we have the 350 degree centigrade embrittlement which is observed in case of the high strength low alloy steels, then there is a 450 to 500 degree centigrade embrittlement.

This is observed in case of the ferritic stainless steel then we have the sigma phase embrittlement this is typically observed in case of the austenitic and the ferritic stainless steels, which are high chromium means the high chromium steels, then there is one more embrittlement which is called graphitization this is observed in carbon steels as well as carbon molybdenum steels and then there is then there is there are few environment assisted then there are few environment assisted embrittlements environment assisted embrittlement, these are neutron embrittlement are mainly observed in case of the nuclear power plants, where there is a absorption of the neutron of the components which are being used.

Then there is a hydrogen embrittlement due to the excessive concentration of the hydrogen in the steel either absorbed or in dissolved condition, then there is a stress corrosion embrittlement and the liquid metal embrittlement.

So, liquid metal embrittlement like steel is sensitive for the embrittlement by the liquid copper or the liquid zinc, similarly aluminum is sensitive for the hg or a mercury. So, these are the various kinds of the embrittlement which are experienced by the steel under the different conditions of the temperature environment and the deformation. Now, I will be taking up one by one these embrittlements and also we will see that how do these affect the performance of the steel in terms of the mechanical properties.

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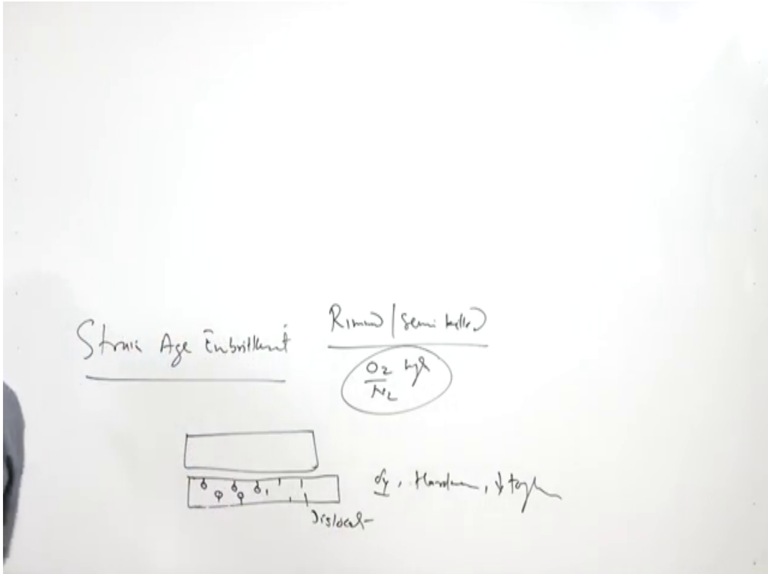

So, we will be starting with the strain age embrittlement strain age, as I have said this kind of the embrittlement is experienced in case of the rimmed or semi killed steel. In these both these steels the oxygen concentration is oxygen and the nitrogen concentration is more.

So, in this case what happens that when the component is deformed by a certain amount and then the component is left. So, the differ left in under the ambient conditions or at a high temperature for some time then it leads to the increase in yield strength and sometimes reduction in the ductility. So, basically increase in strength and the hardness is accompanied with this increase in yield strength and the hardness is observed may be some kind of the loss in toughness may take place.

So, what happens when we deform a component, it produ deformation leads to the plastic deformation leads to the generation of the dislocations in the material due to the deformation and the dissolved gases like oxygen and nitrogen this they occupy or the lock the dislocations being created through the diffusion and so the locking of these dislocations will reduce that dislocations movement and which is necessary for the plastic deformation.

So, in case of their semi kill or the rimmed steel where these gases are present they easily diffuse at the edge of these dislocations and they tend to lock them in order to facilitate um, in order restrict the movement of the dislocations which in turn increases the yield strength, but this kind of the this kind of since here the diffusion of the oxygen and the nitrogen is involved.

So, it is the process is slow at room temperature and it may take like a few hours to the few days in order to have the effect of the strain aging, but when it is done mean the after deformation if the component is exposed at a high temperature. So, it immediately causes the strain aging effect within 1 minute of the exposure at a high temperature.

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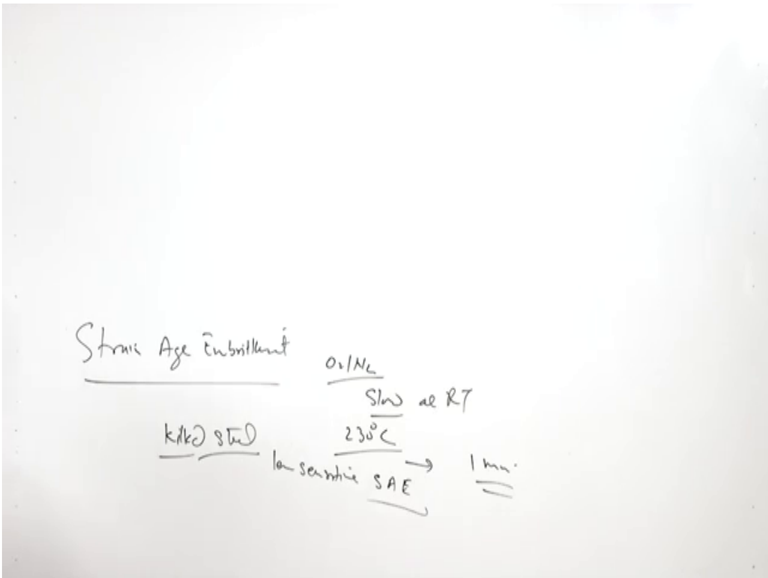

So, at a high temperature the strain aging effect is very fa faster than that at the room temperature and the killed steels which have the deficiency of the oxygen they are less sensitive for the strained age embrittlement. So, this is the one type of the embrittlement then another one is the quench edge embrittlement and carbon steel is also sensitive for this kind of the embrittlement and this is caused by the 2 situations one is in case of the quench age embrittlement, like we know that the steels having a very limited carbon at the room, can dissolve the limited carb very limited carbon at room temperature this is 727 degree centigrade, and this is 910 degree centigrade this is alpha and this is eutectoid and here this is eutectoid point.

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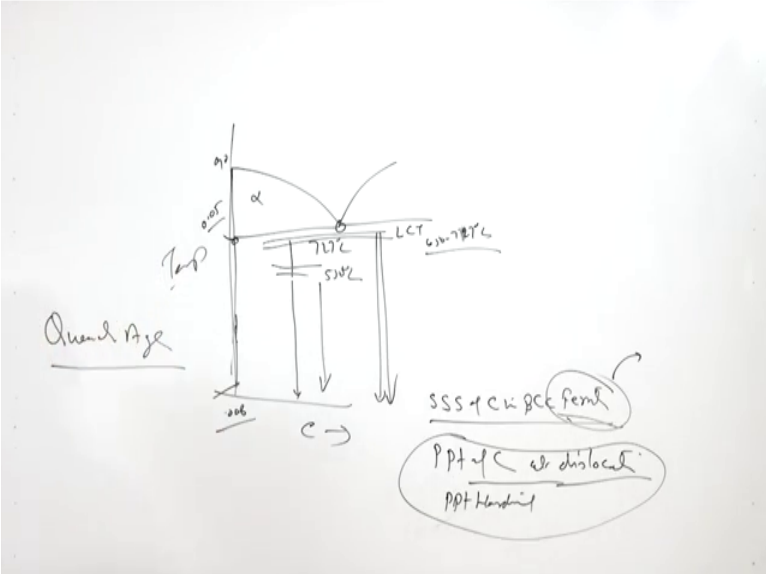

So, so this is the lower critical temperature in iron carbon diagram here this is the carbon content and here this side we have temperature. So, when the steel of steel is quenched rapidly from the lower critical temperature from below the lower critical temperature. So, whatever carbon content which is high like it is 0.05 and here at room temperature it is point this is 0.8.

So, the rapid cooling or the quenching from the lower critical temperature leads to the supersaturated solid solution of carbon in BCC alpha iron that is ferrite. So, this one the which is the this ferrite which is supersaturated of the carbon, this starts this starts rejecting the excess carbon gradually under the room temperature conditions and which leads to the 2 effects, one is the one is like the precipitation of carbon at the dislocations and once the dislocations are blocked due to the precipitation of the carbon. So, it will be resisting the movement of dislocations and thereby increasing the yield strength and then another one is the precipitation hardening due to the rejection of the carbon.

So, these are the 2 regions which are attributed to the increase in yield strength increase in hardness and some loss of the toughness due to the due to the rejection of carbon from the ferrite, this kind of the effect is especially observed when the quenching is taking place quenching of the low carbon steel is taking place from the low higher low critical temperature like say 650 to 727 degree centigrade.

But if the quenching is taking place from say 550 degree centigrade or less, then the effect of the quench ageing is negligible because it reduces the carbon which is available with the ferrite content. So, the extent of the super saturation of the ferrite with the carbon is reduced, if the fast cooling is if the fast cooling or the quenching is taking place from the lower temperatures. So, to and there is another aspect about the carbon content, the steels with the carbon in the range of the 0.042, now 0.12 they are more sensitive for this kind of the embrittlement 0.04 to 0.12 percent of the carbon.

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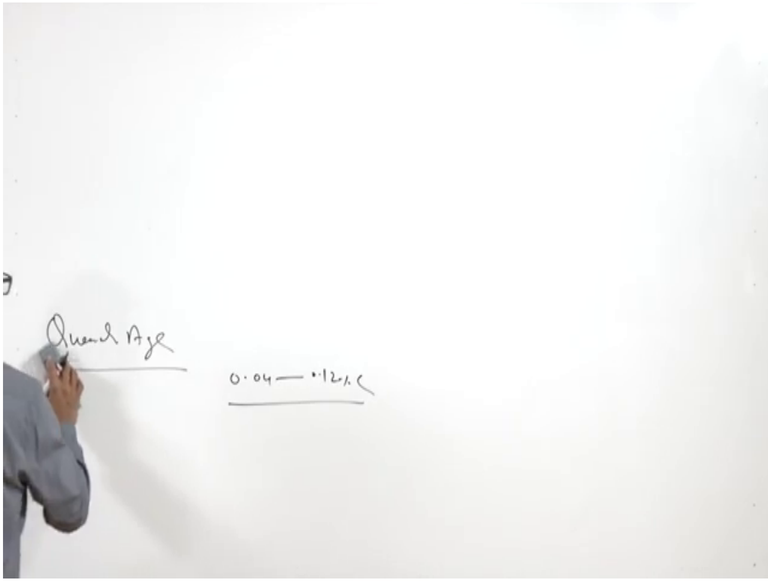

They are sensitive for this kind of the aging, if the carbon content is greater than 0.1 then the extent of sensitivity reduces for the quench edge embrittlement.

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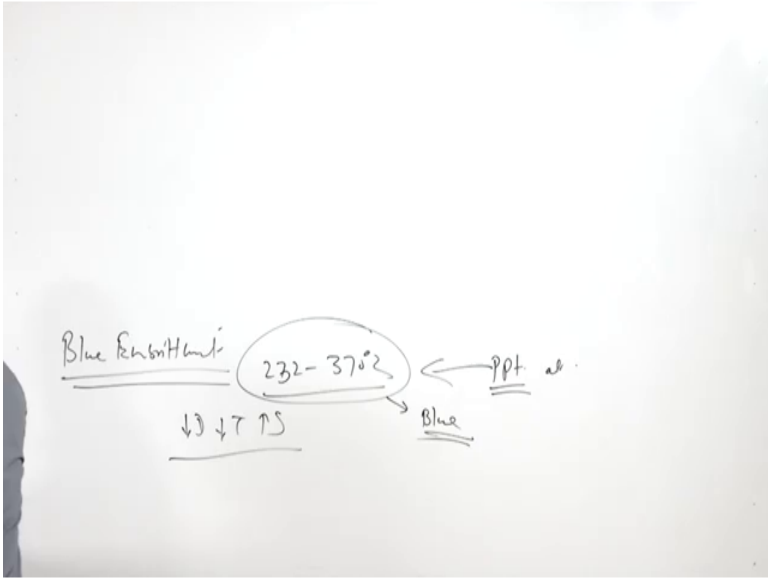

The next one is the blue embrittlement blue embrittlement, the blue embrittlement is just like the accelerated strained aging in case of the accelerated strained aging at a high temperature. So, straining will be developing the dislocations and at a high temperature in the range of like say 232 to 371 degree centigrade the faster movement of the of the faster movement of the solute impurities in the steel, will be leading to the locking of the dislocations at much of higher rate and thereby it will be decreasing the ductility decreasing the toughness and increasing the strength.

Since this at this temperature range the still appears to be of the blue in color and that is why it is called the blue embrittlement and this is a attributed to the precipitation of some of the compounds at the grain boundaries and this critical temperature range of 232 to 371 degree centigrade. Then we have the temper embrittlement, so blue embrittlement will be happening over a range of 232 to 371 degree centigrade probably primarily due to the precipitation of some hard constituents and now this will be experienced by both low carbon steels as well as the low alloy steels, then we have that temper embrittlement.

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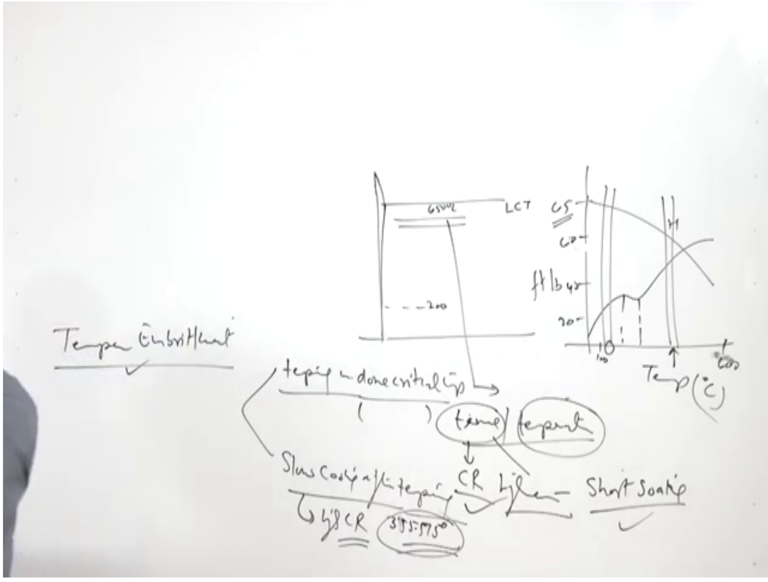

The temper embrittlement happens in the 2 ways you know like this is typically observed in case of the tampering heat treatment and the tempering heat treatment is typically carried out below the lower critical temperature this is a iron carbon diagram, so this is the lower critical temperature.

So, like say it can be carried out from 200 degree centigrade to almost about 650 degree centigrade, this is a range of normal tempering temperature and so as per the requirement of the properties the tempering temperature is selected suitably, because the variation in the toughness and the hardness goes in like this is the hardness variation and this is the tempering temperature say varying from the 100 degree centigrade to 600 degree centigrade and this is say for any medium carbon steel or high carbon steel is starting from 65 HRC for the hardness and fit pound is the unit say for the toughness if we mentioned from like say 20 40 60 and 65.

So, there is a sharp drop in the hardness and a increase in toughness, over a range of the like say 100 to 200 degrees 200 to 300 degree centigrade, there is some drop in the toughness thereafter a it increases. So, as per the choice of the properties with regard to the hardness or toughness if we need higher hardness we will be selecting the lower tempering temperature if we want the higher toughness and so somewhat lesser hardness will be also then we will be choosing the higher tempering temperature.

So, as per the requirement say if this is the tempering temperature chosen, from this tampering temperature now embrittlement can take place in some of the steels and during the tempering due to the 2 regions, 1 is like the tempering is done in the critical temperature like some of the steels are sensitive for embrittlement, if they are tempered over a certain range of the temperature and so how long means the time of holding at that temperature and the temperature. So, basically temperature and time both effects the extent of embrittlement.

If the tempering is being done in that sensitive temperature in your critical temperature range which is leading to the embrittlement, then it will be leading to the embrittlement of the steel, but again it is affected by the 2 aspects. How long we are holding at that temperature and after holding that what cooling rate is being adopted.

So, if the tempering is being done in the critical temperature range in that critical temperature range which causes the embrittlement, then high cooling rate after holding at that critical temperature and shorter soaking period in that critical temperature shorter soaking period in that critical temperature, both these aspects will be reducing the extent of embrittlement due to the tempering embrittlement.

So, the one thing is that the tempering embrittlement can happen in 2 ways one when tampering is done critical temperature, then followed by slow cooling leads to that a temper embrittlement and if the soaking time is less or the cooling rate is high then the ex effect of the tamper embrittlement will be somewhat lower.

The another type of the embrittle another reason for another way by which embrittlement of the steel in during the tampering, which can happen is like slow cooling after tempering; even if it is not in the sensitive temperature range but if it is a if it is cooled slowly then this also leads to the embrittlement. So, here and the high cooling rate it is the cooling it only that affects the extent of embrittlement, in general higher cooling rate reduces the effect of the embrittlement.

As far as the effect is concerned so in this case basically the cooling rate especially with re 375, 350 to 355.575 degree centigrade this is a temperature range in which cooling rate is crucial. If the cooling rate is done fast in this temperature band then the extent of effect of embrittlement during the tempering can be reduced.

Now, the primary reason for the embrittlement means the tempering embrittlement is attributed to the this is actually abutted to the formation of the undesirable precipitates. So, so the main reason behind the embrittlement is due to the whatever carbon is rejected from the tempering of the martensite, it leads to the formation of unfavorable precipitates unfavorable precipitates. So, this may be in form of the carbides or other intermetallic compounds.

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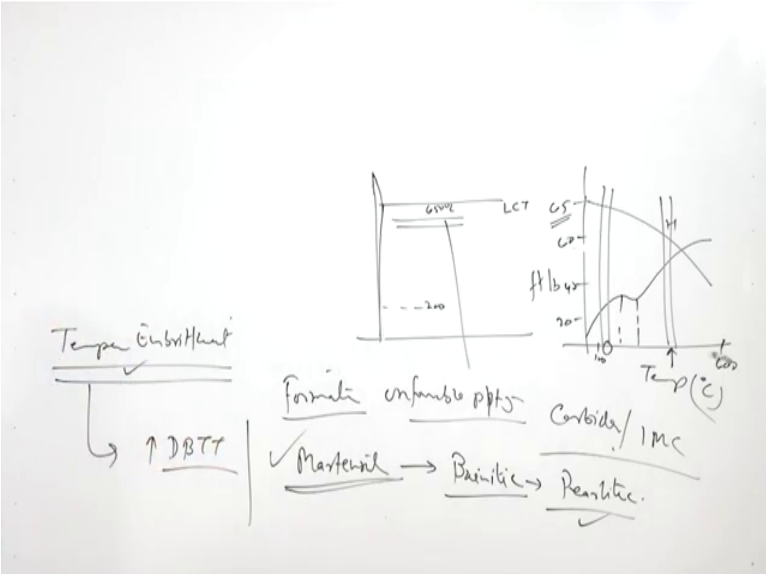

So, whenever the temper embrittlement takes place it increases the ductile to brittle transition temperature also and the extent of the sensitivity for the temper and embrittlement with regard to the microstructure is concerned, the maximum sensitivity existed during the tampering when we are having the martensitic structure and the extent of sensitivity is somewhat lower when we have bainitic structure. So, the temper embrittlement when structure is bainitic is somewhat less and further lower when the structure is perlitic. So, the temper embrittlement sensitivity will be maximum when the martensite is tempered thereafter bainite, bainite is tempered and after tempering when tempering is done and the structure is primarily the perlitic then the possibility for the temporary embrittlement is somewhat lower.

Now, we will see the another type of the embrittlement which is a 350 degree centigrade embrittlement and this kind of the embrittlement so 350 degree centigrade embrittlement, this happens especially in case of the HSLA steels and it is due to the tempering of the tempering of martensite and it leads to the precipitation or when so damping of the martensite will be leading to the rejection of the carbon and the carbon leads to the precipitation of the Fe 3 C and if these precipitates at the grain boundary then this causes the embrittlement of the steel.

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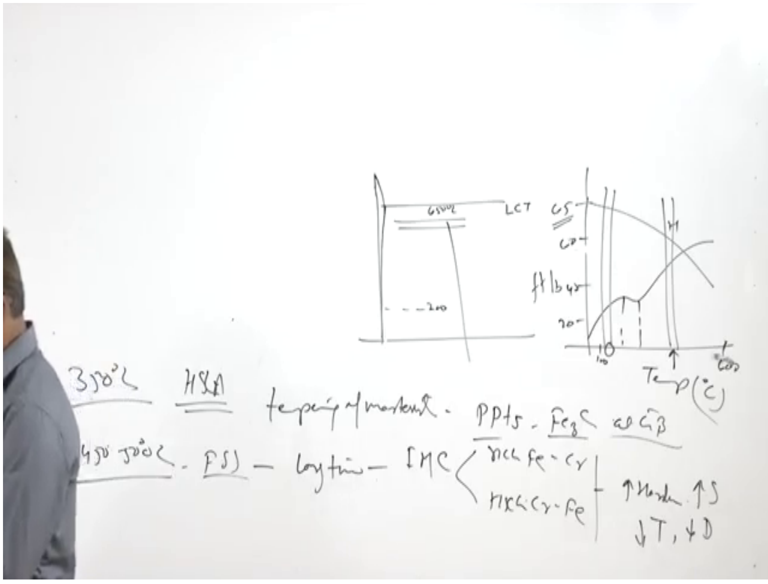

Ah then there is 450 to 500 degree centigrade embrittlement this is mainly observed in case of the ferritic stainless steel and when the steel this kind of this steel is exposed in this sensitive temperature range for longer period, it forms the 2 types of the intermetallic compounds 2 types of the intermetallic compounds IMC one is which is rich in Fe with chromium and another is rich in chromium with iron. So, both these will be leading to the increase in hardness, increase in strength reduction in toughness reduction ductility of the steel.

Now, the another one the next embrittlement is the sigma phase embrittlement, sigma phase embrittlement is primarily observed in high chromium steels like austenitic stainless steel and the ferritic stainless steel, the chromium content has to be greater than the 18 percent. So, which under the favorable conditions forms the sigma phase and the sigma phase is an intermetallic compound, which will have the higher concentration of the iron and chromium both and the hardness is also high.

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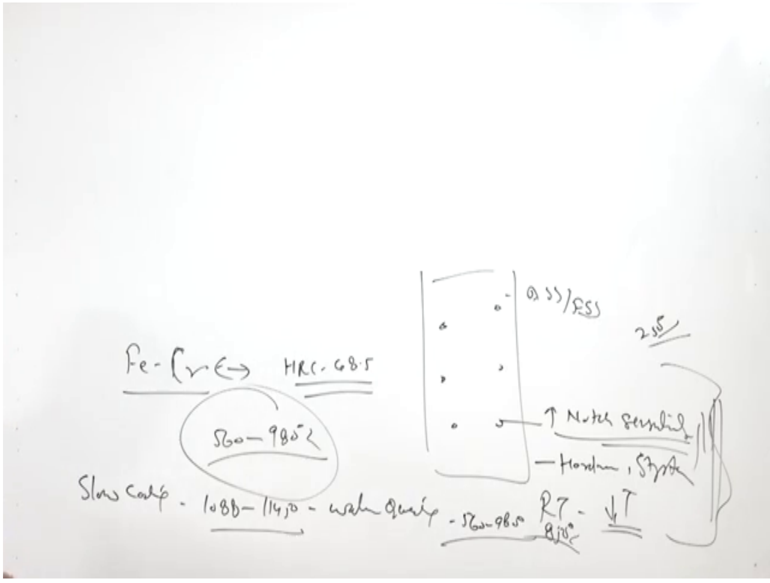

So, sigma phase is basically the iron chromium compound, which will have the carbon also and this will have the hardness HRC is the 68.5. So, it is quite hard but now since in the in the stainless steel whether it is ASS or FSS, if it precipitates under the favorable temperature conditions of exposure, then the precipitation of this 1 basically the sigma phase.

This increases the notch sensitivity, notch sensitivity means this will facilitate the nucleation of the cracks and their growth at the same time, but it does not affect the hardness there is no effect on the hardness there is no effect on the strength, but the notch toughness or the notch sensitivity is high in the sigma phases present and it is formed under the favorable conditions of exposure like sensitive temperature range for this is 560 to the 980 degree centigrade and it can be formed and this kind of the effect is in the effect on the no sensitivity is especially at the room temperature.

At the room temperature ma we may find the reduction in toughness, but other properties are not much affected. If the exposure of the stainless steel is above the 250 degree centigrade and the sigma phase formation does not adversely effect the performance of the steels, there are 2 conditions under which it is formed this is the sensitive temperature range in which it is a formed and when the steel is cooled slowly slow cooling in the temperature range of 1088 to 1145 degree centigrade, followed by the water quenching and then reheating in the temperature range of the 560 to 980 degree centigrade more precisely 850 degree centigrade, then it is it is a formation is encouraged.

So, this is how we can see that there are various aspects there are various unfavorable metallurgical transformations which will be taking place, in the steels when they are given exposure under the different kind of the conditions. So, basically now will I will summarize this presentation basically in this presentation, we have talked about that there are 3 aspects that leads to the increase in strength and hardness at the same time reduction in toughness and ductility takes place and these are will be there in form of exposure of the steel in the unfavorable range of the temperature, either during the manufacturing like heat treatment or during the service or steel is subjected to the deformation then under the unfavorable composition of the steel condition it can lead to the embrittlement.

Similarly, when the steel is given the exposure of unfavorable environments like stress corrosion unlike hydrogen like liquid metal or the neutron exposure in the neutron environment, then all these will also be leading to the embrittlement of the steels and eventually during the service these may be causing the brittle fracture of the component. So, for failure analysis we need also to see, if there is an there has been any modification in properties of the steels due to such kind of the embrittlements.

Thank you for your attention.