Welding Metallurgy
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Lecture - 17
Hardening and Hardenability

Welcome to the lecture on Hardening and Hardenability. So in the last lecture, we had some overview of the heat treatment processes and we discussed about the annealing processes, a variety of non the annealing processes, then we also discussed about the normalizing process. In this lecture, we are going to typically talk about the hardenability in metals, especially we will talk about the steels and also the hardening processes or you can say the quenching process.

And then also we will talk about, so first we will talk about the quenching and then tempering processes, which is required to induce some softness in the martensite, which is obtained because of quenching and then also we will talk about the hardenability, how hardenability is defined, how harden ability is measured. So about it will discuss. So coming first about the hardening or when we talk about the hardening, then certainly there are many hardening methods.

But as we discussed about others like normalizing or so, so we will talk about the quenching method.

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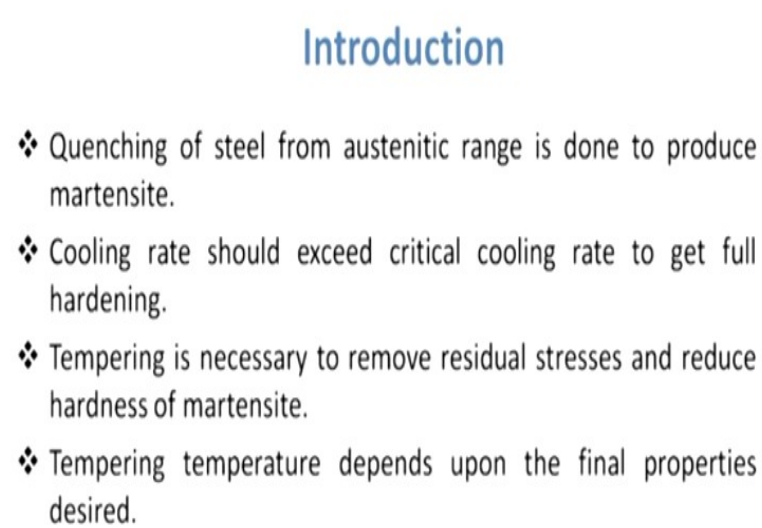

You know that is the most widely used method for the hardening of steel, when we have to make the steel hard. So what we do is normally, we go into the austenitic zone and from there we are quenching, you know into either water or salt or you know the oil, so that we discussed even in the last class and quenching of you know for that what is important is that normally you go to the temperature above the upper critical temperature and then you are quenching.

So the cooling rate has to exceed the critical cooling rate to get full hardening. So what happens that you know we are always thinking of having the martensite in the full structure, all along the cross section we want the hardening to occur. So certainly at the surface the normally you are most likely to get the hardened phase that is martensite and you know then maybe inside the core it may be less so that these issues, we will talk later. Now when we you know do this hardening, then as we know that there is formation of martensite.

And because of the formation of martensite, martensite is an extremely hard phase and because you have the transformation of austenite to martensite, which you know is by this year mechanism. So lot of stresses are developed also you have the cooling you know, differential cooling at the surface as well as at the center. So that develops a lot of temperature gradient and stresses.

So that is one thing, but the formation of martensite basically you know because of the extremely you know high level of stresses. So we need basically you know to temper you know to reduce this hardness, extreme hardness and induce certain toughness. So basically we use this process known as tempering, which is necessary to remove the residual stresses and reduce the hardness of martensite. So in the tempering process, what we do is we further heat to a certain temperature range.

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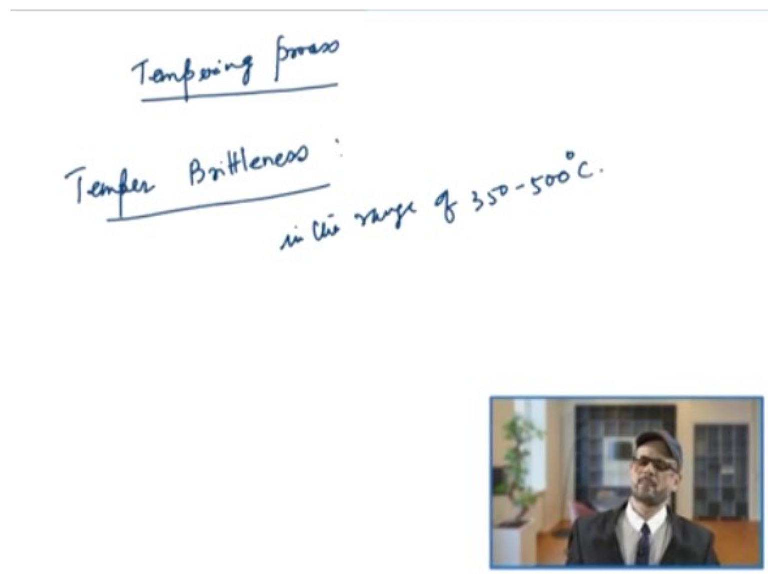

So if you talk about the tempering process, so you know you have to choose a temperature to which you have to further you know heat the specimen and then you have to hold for some time so as to ensure that the residual stresses are you know becoming lesser and lesser and correspondingly basically the softness is induced or toughness is increased. Now depending upon the you know degree of toughness you want or degree of you know ductility you want or depending upon the degree of softness you want to induce you have to take the temperature.

The thing is that if you take a higher temperature zone, in that case your toughness will be more and if you go to a lower temperature zone in that case you will have hardened you know material. So like you may have different kind of you know materials based on its use like you we may have the use of material in terms of spring or you may have the shock resistance tool where we require the high amount of toughness.

So accordingly you have to choose you know temperature you know, so that the hardness as well as toughness can be maintained. Now apart from you know the tempering, while we do the tempering basically there is one more phenomena which comes into the picture that is your temper, brittleness. So basically there is one temperature range where this once if it is held in that period in that case the brittleness you know is you know observed.

So that is known as temper brittleness. So that is the embrittling phenomena, which is observed and it is you know in the range of 350-500 ^{0}C. So it occurs while also cooling you know during this critical temperature range and once you do after tempering at high temperature, so while you cooling also if you come to this temperature range, then also you can get it and the reason for you know this temper brittleness is you know there are certain reasons.

Like there are certain elements like you know chromium, manganese or nickel. So they will be interacting with some elements like you know a Pb, Sn, Sb, so you know or As. So if these materials are present, so they will be reacting with that and that leads to the temporary embrittlement. So basically these elements if they are not there like Pb, Sn, or As or so, you know like P that is phosphorus, tin, lead and you know arsenic or As.

So in those cases if they are absent then temper brittleness is not observed. So basically in this case you get the embrittle steel. So basically you get the inter granular type of fracture is observed you know along the grain boundaries. So that is what the phenomena of temper brittleness, which is observed. Now many a times, we also what we do is we take the protective atmosphere inside the you know furnace where we are doing the heat treatment.

And in those cases we may have you know inert gas atmosphere or we may have some other gases atmosphere. So normally whenever we have the heating or cooling in the normal atmosphere, then there will be chances of the you know oxide formation because oxygen will react and so there are two things which are very much you know common, that is one is oxidation another these decarburization.

So the oxygen may react and there may be formation of oxides or the carbon depletion may be there from the surface because carbon may react with oxygen and then that will lead to the product and so carbon will be depleted from the surface. So for that normally, we also go for the inert atmospheres. We can have inert gases as you know medium, but that normally you know is quite costly.

So unless otherwise required, if you have you are going for some titanium type of materials is very, very oxidizable. You go for the use of these you know type of gases, which are you know you know we used for avoiding any kind of oxidation. Nitrogen is also used to provide the inert atmosphere. So this is about you know use of the inert atmosphere. We already discussed about the kind of bath we provide. We may provide water; we may provide the brine solution.

So it may be agitated or non-agitated. We may have oils also. So that you know this is about the bath, you know. So now we will discuss about you know concept of hardenability. So what is hardenability? Now we know that our intention is to have the hardened structure. So as we know hardness achieving is normally by the formation of the martensite. So if you are able to get the martensitic structure with relative ease, with more ease, then we say that the material has quite a good amount of hardenability.

And if we are not getting, in that case we say that it has poor hardenability. So hardenability of steel if we talk about the steel.

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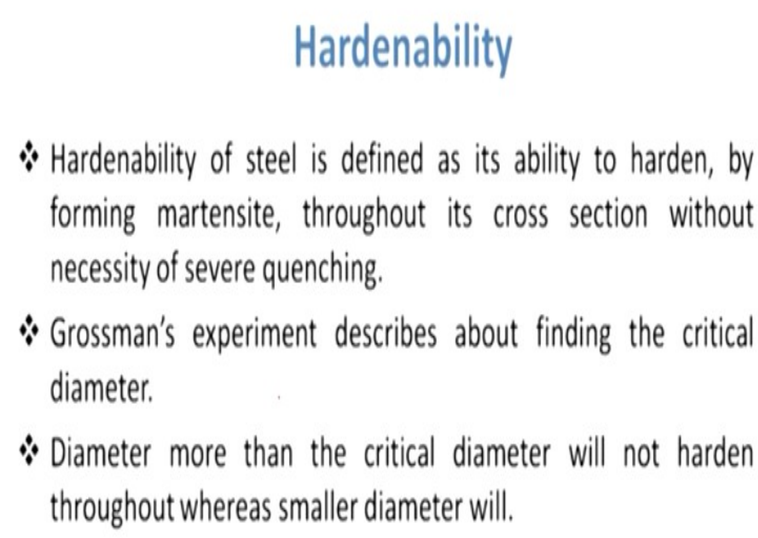

So it is defined as its ability to harden by forming martensite, certainly because martensite is the hard phase. So throughout its cross section without necessity of severe quenching, so you know so with even the mild cooling also medium with not very drastic quenching methods also you can have the formation of martensite. So the material is said to be having very good hardenability. So in many cases you have to go for drastic quenching.

And in many cases even if you go for you know, you do not go for drastic quenching, if you are quenching relatively in an open way, if you use the normal fluid only at normal temperature. So in that case without much of agitation, so in that case also you will get martensite. So the thing is that in that case you say that it is more hardenable. Now the thing is that for you know for finding the hardenability that how you can quantify what is hardenability?

So for that there is a concept of the critical diameter you know, so diameter that diameter is basically critical diameter is the diameter more than the critical diameter will not harden throughout whereas the smaller diameter will. So the Grossman experiment is dealing about it. So what he did that he took the diameter you know of steel rods, so he has taken the number of steel rods of different diameters and then he did the experiment.

And after the experiment you know he has used the quenching process and what he has seen that you know with the different diameters what he tried to see that how you know the fraction of the martensite you know is there in that rod. So based on that basically, he has defined this critical diameter. So he in that experiment basically the 4 steel rods were taken of different diameter, one is smaller than one is more than that so the in the increasing diameter size 4 rods were taken.

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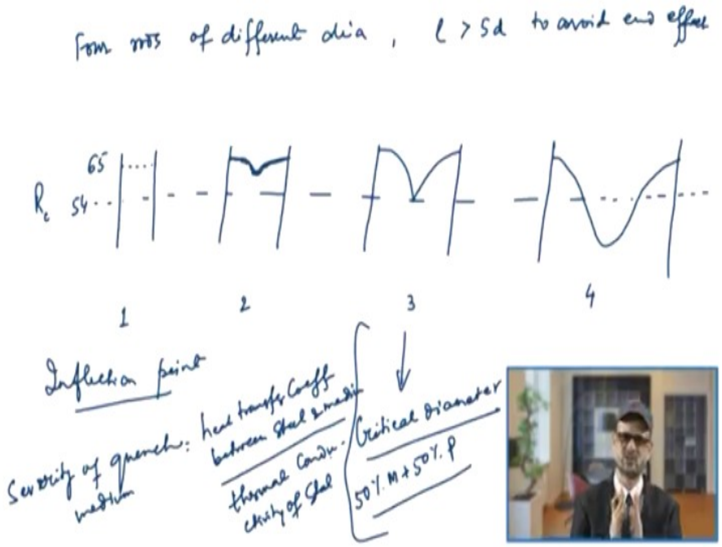

And the length of rod it was ensured that so you have 4 you know rods of different dia and then it was also seen that the length of rod, it must exceed 5 times the diameter. So length should be more than 5D, so that you know to avoid the end effect. So basically if you know otherwise there may be end effect also. So to avoid the end effect, it was ensured that the length should be taken, so that you have the length is more than 5 times the diameter. So you have 4 diameter.

One is smaller one, another one is bigger than this, then third one is even bigger than this and fourth one is even large. So that way you know just you can say that this is first, this is second, this is third, and this is fourth rod. So you have you are taking for steel rods of different diameter. Now you know what happened that you tried to measure the hardness so basically and then they are quenched you know and once you quench, then you know the hardness was measured.

And what we saw that you know in the case of the rod, which is the slimmest one, you are getting, at the center you are getting completely martensitic structure. So if you take this as you know the 54 Rockwell hardness. So Rockwell$_C$ on C scale if your hardness is 54 is there and now at, so what we see in this case that you are getting you know complete you know right through you get the martensitic structure.

Whereas if you go to the second rod, now you know the cooling rate at the center will decrease. So in this rod basically cooling rate at the center will be quite fast, because it is thinner. As it will become thicker and thicker, then cooling rate at the center will be basically smaller and smaller. So what will happen that you know hardness, which is achieved at the center it will go on decreasing, so towards the center on from both the sides what you see?

That you have you are getting some you know hardness, but then it is decreasing and at the center it is even less. Now if you go on increasing the diameter, then you will come to a certain diameter where you see that at the you know center you have 50% martensite and 50% pearlite. So in this case this diameter will be known as the critical diameter and if you go for the largest diameter this 4.

In this what you see that your structure becomes you know hardness pattern is you know seen at the you know in this fashion. So in this case, you have 50% hardness you know pearlite and 50% martensite, whereas if you go for this structure in this case, you get the only fine pearlitic structure at the center. So this size is said to be more than the critical diameter. So basically you are getting one inflection point and so this inflection point.

Basically the inflection point which you get, so it is the transition between the hardened and non hardened parts of the cross section. So you know so for this diameter what you see for this diameter what you see that the microstructure is 50% martensite and 50% pearlite and pearlite has the hardness of 54 and this diameter basically, you are calling it as the critical diameter. So the diameter at which you know, they said at the center when you see you have the 50% martensite and 50% pearlite.

So this diameter is known as the critical diameter and if you are taking you know the diameter more than this in that case you must know that it will you know you cannot, it cannot harden throughout. So if your diameter is more than this critical diameter, then it will not harden throughout. That is you know the concept of measuring the hardenability of steel, which is given by the Grossman. Now you know you have used the quenching media.

And quenching media as we have discussed that we can have different type of quenching media. So your severity of quenching media also is different and you know so the critical diameter, which we are defining you know in this experiment, which we have got suppose you know in this case here. Now it depends upon the composition as well as the austenitizing temperature of the steel and also there will be effect of the quenching medium.

So you know for the so grossman again defined these quenching medium and you know and also the ideal you know critical diameter, so corresponding to that quench in the medium. So for the quenching medium the another parameter which is defined is the severity, severity of the quench medium. Now severity of quench medium will be basically the ratio of the heat transfer coefficient between steel and medium.

So this will be heat transfer coefficient between steel and medium and that divided by so the thermal conductivity of steel. So you will have you know the severity of quench medium becoming different you know for the different material you know for the different quench or so, because it will be depending upon what is the heat transfer coefficient between the specimen that is steel and the medium and then you are going to divide it with the thermal conductivity of steel.

So the ideal medium basically will be the one which will be converting the surface of the steel instantly you know so and also the bath temperature will be maintained you know so at that temperature. So that is basically the definition of the ideal you know quenching medium, although this is theoretical you know concept that will be hypothetical, because that cannot occur because once your cooling starts.

Then certainly once you go towards the inner zone then certainly your cooling rate will be changed. So for such medium basically parameter H will be infinite and you know the ideal medium will be bringing that temperature of the bath temperature instantly still the temperature of the steel surface temperature of the steel instantly to the bath temperature. So you know and also it is not feasible because there will be flow of heat taking place so from the center to these towards the surface at a finite rate.

So and also that is determined by the conductivity of steel. So basically the two ratio is defined as the severity of the quench medium. Now as we know that this is simply a hypothetical case that is the ideal medium, but in actual what happens that when we talk about the quenching medium like water. So what happens that in that case you know when we do the quenching with water, then there will be a vapor blanket, which will be you know observed in between the steel.

And so vapor is formed, so because of the vaporization and that will reduce the heat transfer, which will be taking place. So the heat transfer rate becomes less. Then another factor which is you know affecting that heat transfer will be the viscosity of the liquid and you know certainly more viscous liquid will certainly decrease the you know heat transfer rate. So you will have oil as less efficient than water or brine. Now also the brain is said to be more fast than water.

Now it's concept is that when we use the you know brine solution, in that case the salt particles which are there in the brine solution they basically explode near the surface and they will be you know. So near the vapor blanket and they will be puncturing that vapor blanket. So the vapor blanket, which is formed near the surface that is being punctured by you know this salt particles. So that way your degree of you know heat transfers that is increased.

So that is why the NOH is said to be more effective you know quenching medium. We also have learnt that when we agitate the liquid in that case also you know the vapor blanket, which is formed that will be broken and your heat transfer will be increasing. So that will increase the efficiency of the you know heat transfer. So efficiency of the quench medium, so this severity of quench medium is known as H and this H has the different values.

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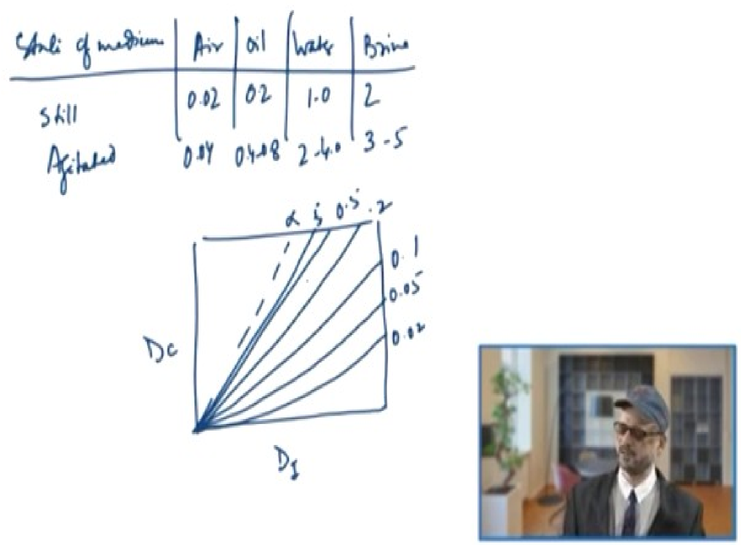

And different value of H if you look at so if you have the suppose medium state, if you talk about the state of medium and value of H, so you know you may have air as the medium, you may have the oil as the medium, water as the medium or brine solution as the medium. Now in this case if you look at still you know if a still condition is there, if there is no movement, you are not agitating, in that case you see that you have this value 0.02 and this becomes 0.2.

This is 1 & 2 and for the agitated conditions this goes on increasing, so this becomes 0.4. This is 0.4 to 0.8 and this becomes 2-4 and this becomes 3-5. So that way what we see is that when we are agitating the liquid in that case you have the value of H, that is your severity of quenching medium that is defined that goes on increasing. So this is about the severity of quenching medium. Now the Grossman basically also he has correlated this, constructed this graph.

Where he correlated this critical diameter you know 2H, so of known H, you know if you have a known H value of any medium, so the critical diameter for that what will be the ideal critical diameter, for that he has found the graph and the graph looks like this. So in the graph if this is your critical diameter on this axis and this is the ideal critical diameter and for different value of you know the H, so you will have H value if it is less so it will go like this.

You may the H value may, so H value in this case will be something like 0.02 and in this case it may be 0.5, so for 0.1 it goes like this, for 0.2 it goes like this and for 0.5 say suppose like this.

So it will go on increasing you know it will be 5 and this way for ideal one, you will have the infinity. So this is your you know the ideal critical diameter and against that you know critical diameter, your this concept this graph goes like that.

Now for Grossman basically you know determining the hardenability, this method was little you know cumbersome. So there was another method also to find the hardenability and that was the Jominy end-quench test. So in that test basically what we have, that is we have a you know rod of particular dimension like a rod shows you have Jominy end-quench test.

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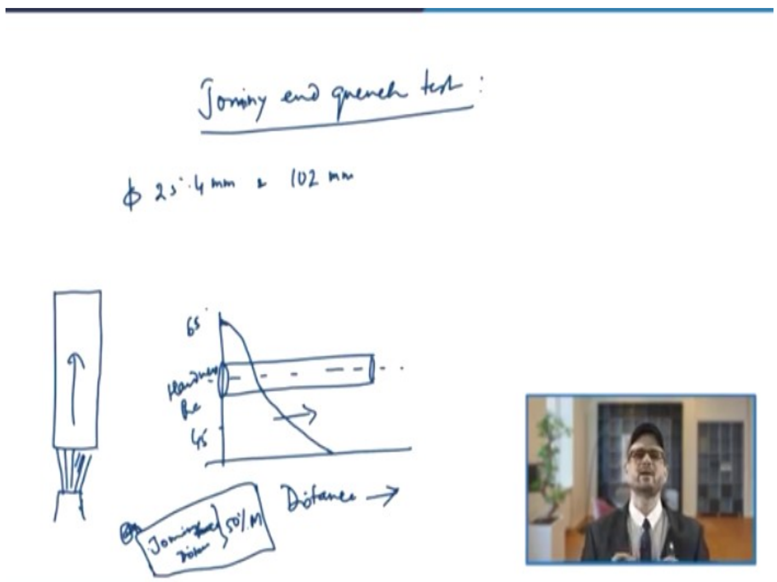

So these tests is also you know to find you know it also details that how the variation is there in the hardness. If you take a you know rod, so you are taking a steel rod of you know diameter 25.4 mm. So that is like 1 inch and then you have 102 mm long, so something like 4 inch long. So in that you have a standard set up and in that what you do is you are with a standard you know apparatus. Things are standardized, so you are quenching from one end so you are you have if this is the rod. So basically you are quenching you know through a nozzle.

So from here the water will go, so you have certain diameter of that nozzle also water pipe will be about 12.7 mm diameter jet height is frigid height a 64.7. So that is one standard values through that basically it is giving the quench and then what happens that the hardness is measured. So what was seen that and the hardness measured also and it was seen that how the microstructure basically is changing.

So certainly is similar to the test which is conducted by you know the Grossman's experiment, here also you try to have the you know graph and what you see that you have the hardness that is R_C and then with distance you know the hardness you know change was measured. So if your rod is suppose going like this, so what was seen that we as you go across this distance, so what will happen the hardness will, so from here it will have 65 R_C and if suppose this is 45 R_C .

So what you see is that you have at certain distance so say you have 50% of you know martensite and 50% pearlitic structure and this variation, which is observed you know will be like that. So what was seen that you know this way you know this hardness was seen to decrease as we move, I mean in distance in this dimension and this distance you know at which your microstructure was 50% martensite that distance was known as the Jominy distance.

So at this point you know you have 50% martensite. So and then you have other related graphs also talking about the critical distance from the coincident and the critical diameter. So you have different graphs. So ultimately it talks about you know the hardenability of the material, how much it will be hardenable, and basically hardenability depends upon many factors like as you discussed, it depends upon the carbon content.

It also depends upon you know grain size of the material. So that way also you know hardenability will be changing. So if you are you know ideal critical diameter, which is to be calculated you have for the carbon percentage also as you know that when the carbon percentage will be more, you will have more hardenability and also for the grain size also you have another variation, which it talks about the hardenability of the material.

So this is you know about hardenability and we will have more discussion on you know features related to hardening of the material in our coming lectures. Thank you very much.