Introduction to Materials Science and Engineering
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Lecture - 95
Heat treatment of steels

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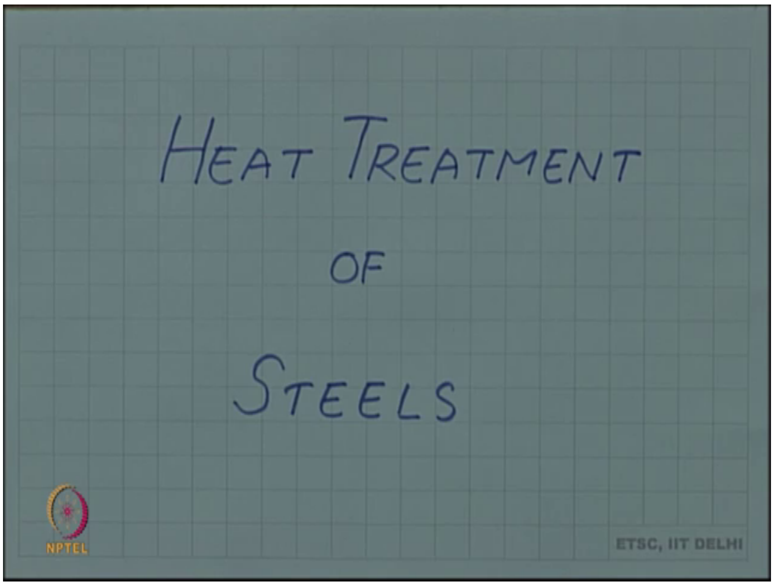

HEAT TREATMENT

OF

STEELS

A very important topic in engineering is the heat treatment of steels. We have looked at steels, let us look at now what is meant by heat treatment. To motivate our topic, let us look at 5 different suppose we are supplied with 5 different samples of a steel.

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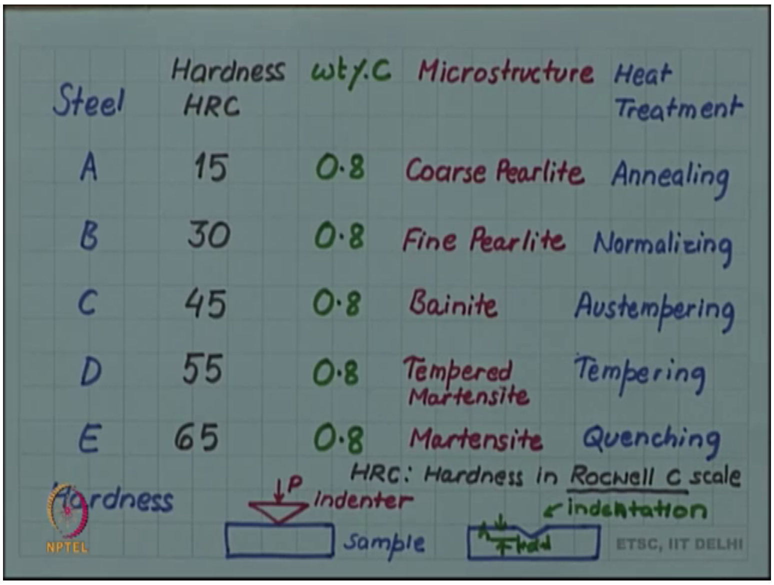

Steel	Hardness HRC	wt%C	Microstructure	Heat Treatment
A	15	0.8	Coarse Pearlite	Annealing
B	30	0.8	Fine Pearlite	Normalizing
C	45	0.8	Bainite	Austempering
D	55	0.8	Tempered Martensite	Tempering
E	65	0.8	Martensite	Quenching

HRC: Hardness in Rocwell C scale

Hardness

So, let us and let us just call them steel A B C D and E. Now suppose these steels are supplied to us, and we want to test their property. One simple property one simple mechanical property of any given steel is what is called the hardness. And hardness is a simple test in which all you have to do is to prepare a nice flat surface of your specimen. And in that you then press some sort of indenter, some sort of hard indented made of diamond or hardened steel, and you press the indenter through some load. So, this is an indenter, this is your sample.

An inductor is pressed into the sample through the load the resulting after if there is sufficient load to press it hard such that there an depression or indentation is created in the specimen that a specimen is plastically deformed. So, even after the specimen is removed, even after the indenter is removed there will be a depression left that is called an indentation.

And either the depth or the diameter so, let us say depth h or the diameter D of the specimen of the indentation that is the size of the indentation, then gives us the idea of the hardness of the specimen. You can intuitively see that if the specimen is harder the indentation left for a given load and indenter will be smaller. So, is smaller the in indentation harder is the specimen. And depending on what shape of indenter we use we can use conical indenter, or pyramidal indenter, or spherical indenter and so on.

So, depending on what kind of indenter we use, and what load we use different kind of hardness scales have been developed. So, suppose we send our steels A 2 E to laboratory and test them in some scale. So, let us say that we are measuring their hardness in a Rockwell C scale. So, hardness and our hardness scale is hardness in Rockwell C.

So, that is one of the scales of hardness HRC hardness in Rockwell hardness in C scale. So, let us not worry at the moment, that exactly what load and indenter is used, but for a given Rockwell C means a specific kind of load is being used and a specific indenter is being used and that is same for all these steels.

So, that is kept constant, but then the impression left in the different steels may be different and that will indicate their different hardness. So, you get a number which is called the Rockwell hardness. Now if we do that, we find that a has a Rockwell hardness of 15, B has a Rockwell hardness of 30, C 45, D 55 and E 65.

I am just making up these numbers, essentially, I want to say that the hardness is continuously increasing as we go down in this table. So, that E is more than 4 times harder than A. So, suppose we make this measurement and we find these harnesses, what can we guess about these 5 steels. So, if we go by if you remember for the moment our iron carbon diagram.

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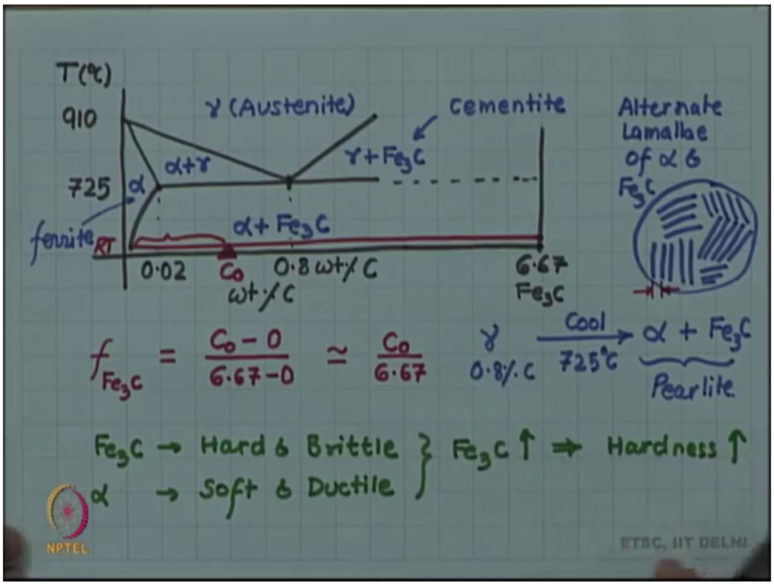

$$f_{Fe_3C} = \frac{C_0 - 0}{6.67 - 0} \simeq \frac{C_0}{6.67}$$

$$\underset{0.8\%C}{\gamma} \xrightarrow[725°C]{Cool} \underbrace{\alpha + Fe_3C}_{Pearlite}$$

Fe_3C → Hard & Brittle
α → Soft & Ductile
} Fe_3C ↑ ⇒ Hardness ↑

So, recall that we studied the iron carbon diagram in detail, and we said that it was the lower portion of the iron carbon diagram which was of interest to us. The y axis is temperature axis, this is 910, this is 725 and the x axis is weight percent carbon.

So, this is 0.02 very low carbon, and this is the so-called eutectoid composition with 0.8 weight percent carbon. So, this was our iron carbon diagram the phases were gamma or austenite, then alpha which is ferrite and this region is alpha plus gamma, recall the one to one rule, this region is gamma plus Fe 3 C, because it is 6.67 percent on this side Fe 3 C forms which is cementite. And this region is alpha plus Fe 3 C.

So, this was our iron carbon diagram, and let me take it all the way to cementite, let me say that this is 6.67, that is Fe 3 C. So, if we have a steel at room temperature, then depending on so, this will be our tie line, let us say at room temperature. So, depending upon the carbon concentration so, if this is if whatever is the carbon concentration of my steel, let us say this is C not, then depending on the carbon concentration of my steel, the fraction of ferrite and cementite can be found using the lever rule, and we have seen that that is fraction of Fe 3 C, Fe 3 C one is on my right-hand side.

So, the lever arm, relative liver arm, relevant lever arm will be on the left-hand side. So, that would be Fe 3 C will be C naught minus, look at that that this point is 0.02 and the curve is reducing in carbon concentration.

So, we will have much less than 0.02 at room temperature. We can approximate it to 0, or if you service your 0.02. So, easier to approximate it to 0 so, this arm becomes C naught minus 0, the overall arm is 6.67 minus 0. So, approximate to the fraction of ferrite is simply C naught by 6.67. So, it is directly proportional to the carbon concentration, if I have 2 times more carbon concentration, I will have 2 times more Fe 3 C as fraction in my alloy. And Fe 3 C is the phase which is hard and brittle, Fe 3 C hard and brittle, and alpha the ferrite ion a soft and ductile.

So, you can see that since I have a mixture of alpha and Fe 3 C, hardness will depend upon the ratio of these 2. So, more is Fe 3 C more will be the hardness of the steel. So, if Fe 3 C goes up this will imply hardness goes up. So, coming back to our table now, we are seeing that the hardness is increasing. So, one guess will be that they may be of steels of different carbon concentration. So, let us look at that so, we send our samples to laboratory for determining their carbon concentration.

So, let us now have the third column weight percent carbon. But to our surprise, we find that all of them are 0.8 percent carbon, the carbon concentration is not changing. So, then how do we here? If the carbon concentration was changing, we could have explained the difference in hardness because of the carbon concentration that higher carbon leads to higher Fe 3 C and leads to higher hardness.

However, now we find that although hardness is increasing by a factor of 4 going from A to E, the carbon concentration is seen in all of them, and all of them have been chosen to have a carbon concentration 0.8; that is all of them are eutectoid steel remember 0.8 percent carbon, we call a eutectoid steel so, all of them are eutectoid steel. So, then, this interesting question comes, that how can how are we able to get hardness varying by a factor of 4 in a steel of the same carbon concentration. And the answer to this question is very, very interesting, and this answer comes through difference in the microstructure of a steel.

So, these different if we look at the microstructure, we find that they have different microstructures. So, for example, steel a has coarse pearlite from the phase diagram chapter when we saw the iron carbon phase diagram, you remember, we met with pearlite, pearlite was nothing but a mixture of alpha and Fe 3 C produced by cooling of austenite.

So, when austenite cooled when gamma of 0.08 percent carbon was cooled through this eutectoid temperature which is 725 degrees Celsius. We have got a mixture of alpha and Fe 3 C, this mixture was named pearlite. And the microstructure of pearlite we said was alternate lamallae of alpha and Fe 3 C.

So, alternate lamellae of alpha and Fe 3 C is what is called pearlite. So, and when we say coarse pearlite, we mean the spacing of these pearlite plates; so, this is spacing from 1 plate to the next plate, that is called the pearlite spacing and depending on the coarse is of coarse a relative term, but depending on whether these this is spacing is very large we will call it coarse pearlite, if this is very less, we will call it fine pearlite. So, A which is having the lowest hardness we are saying that in the microstructure we are seeing coarse pearlite.

Then in B we see that it is still pearlite, but it is fine pearlite so, this is quite interesting. So, both are giving us pearlite, but in one case the pearlite lamallae are thinner and finer in one case they are coarser. And this itself is capable of giving us a hardness value change by a factor of 2, this is an extremely interesting thing, and this is in some sense central to entire material science, that in the same composition, you can have different properties depending on the control of the microstructure by different microstructures.

In C, you have a microstructure which we call bainite. Now you have not met it as yet we will have time to discuss this for the moment I am just writing this the name bainite. So, this is a different micro structure from pearlite all together, we will discuss that as we go along. Then in D there is a still more still a newer microstructure which we call tempered martensite. And finally, E is martensite, now you can see in the phase diagram, we never came across any such phase named bainite or martensite or tempered martensite.

So, phase diagram will not be able to help us in identifying these microstructures. And this is because in the phase diagram, we are only able to show the micro structures which are obtainable by equilibrium cooling, which means very slow cooling because phase diagram are equilibrium diagram. So, they show only equilibrium or near equilibrium micro structures. So, if we cool fast or if we take the system away from equilibrium transition, then we expect to get different micro structures and the this is the result by which we get bainite tempered martensite and martensite.

How are we able to produce these different microstructures? So, that is the process which is given the name heat treatment. So, in the same steel of 0.8 percent carbon, we are able to produce different microstructures and get different properties different hardnesses, because we have given different heat treatments. So, coarse pearlite is obtained by heat treatment called annealing. Fine pearlite by heat treatment called normalizing. Bainite by a heat treatment called austempering, temper tempered martensite by a process called tempering. And finally, martensite by a heat treatment called quenching.

We will discuss all these heat treatments as we go along. So, do not worry you are not familiar with these names already. So, annealing, normalizing, austempering, tempering and quenching are different heat treatments which can produce different microstructures in the same steel of 0.8 percent carbon with hardness value going from 15 to 65.

This is indeed extremely dramatic this effect is very, very dramatic because the property the hardness the mechanical property is highly sensitive to structure. And usually we feel that a certain composition will give a certain property, but in this case, the hardness the mechanical property of hardness is very, very sensitive not only to the composition, but also to the microstructure produced.

So, the micro structure property dependence is central to material science and in this sense this slide is very, very important which is telling you it is not only the composition, but also the treatment and the microstructure which is produced by the treatment is very, very important in determining the final property. And you can see that hardness is a very structure sensitive property, there are properties for example, if we talk about the density, densities of these steels will not be very different.

So, density will is more or less dependent on the composition of material. But here is a property they make particularly mechanical property, even electrical property some of these properties are highly structure sensitive. And they will depend on the microstructure which have produced, and thus will depend upon the processing history.

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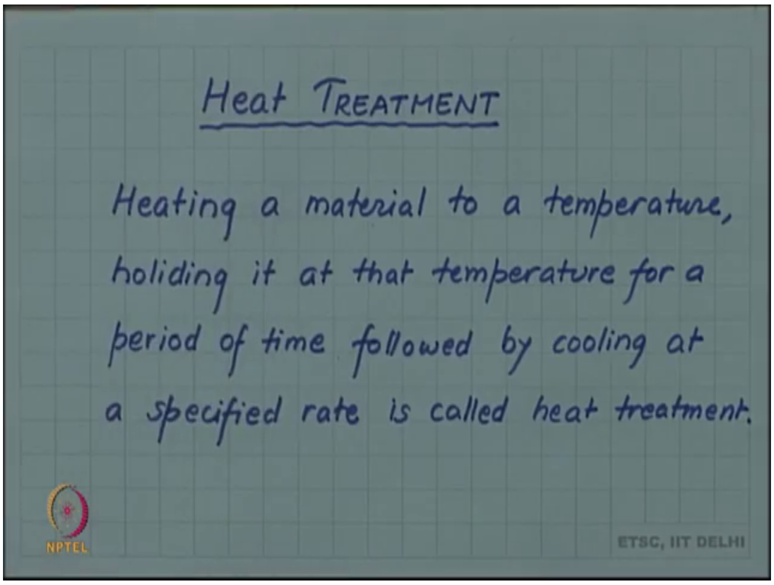

Heat TREATMENT

Heating a material to a temperature, holiding it at that temperature for a period of time followed by cooling at a specified rate is called heat treatment.

So, let us look at what exactly is meant by this term heat treatment. In fact, heat treatment is a very, very simple process. It is simply so heating a material as the name suggests to a temperature holding it at that temperature for a period of time followed by cooling at a specified rate is called heat treatment. So, it is nothing more than what the name suggests it is heating a material, and then keeping it at that temperature for some time and then cooling it back and this.

So, all these processes are essentially that heating holding and cooling. So, you can see, but that is just by the simple treatment of heating holding, and cooling we can produce different microstructures and different properties.

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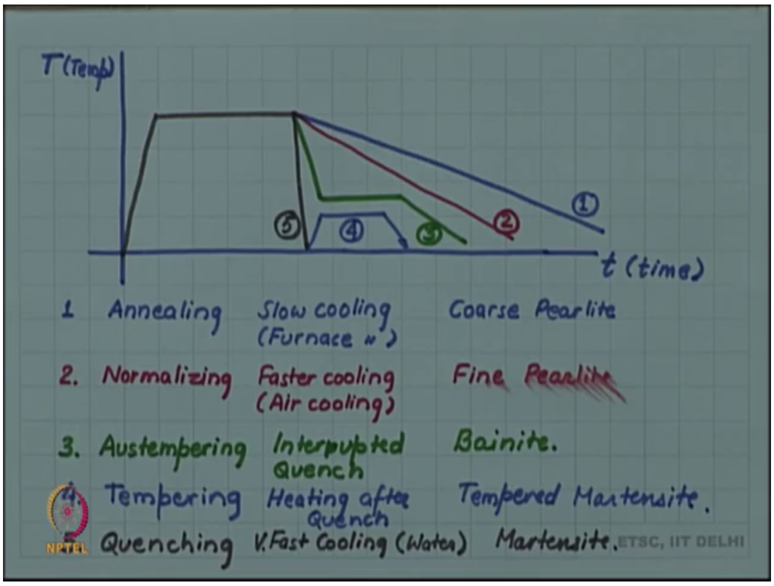

1	Annealing	Slow cooling (Furnace ")	Coarse Pearlite
2.	Normalizing	Faster cooling (Air cooling)	Fine Pearlite
3.	Austempering	Interpupted Quench	Bainite.
4.	Tempering	Heating after Quench	Tempered Martensite.
	Quenching	V. Fast Cooling (Water)	Martensite.

So, let us try to see how we put these different heat treatments in the temperature time diagram. So, I keep the y axis as the temperature, and the x axis as time. And so, let us initially steel is heated to some temperature and then cooled. So, for steel the heating and the holding is same for all these different treatments which we named here annealing normalizing austempering tempering and quenching.

But essentially how you cool, that is what controls these different heat treatment. So, if the cooling is very slow, let me show a slow cooling. So, it is a slow cooling, and that is what is called annealing with slow cooling. In fact, it is so slow that it is called furnace cooling, which means you simply switch off the furnace and do not take out your sample from the furnace.

So, it will cool along with the furnace and the cooling will be very, very slow. This is what the heat treatment which gives you coarse pearlite. Then you have normalizing, which is faster cooling, let us call this air cooling, which means we take the sample out of the furnace, and leave it in the air. So, because of the air cooling will be faster.

This is what gives you fine pearlite. So now, the cooling rate is faster. So, it with a curve with higher slow. Now let us do a very fast cooling, or let us do what is called an interrupted quenching. So, austempering, here we cool it very fast, but then hold it at a certain temperature. And then again, we cool further. So, this is austempering let me call it interrupted quench and this gives you bainite.

Then if you cool it extremely fast, this process is called quenching. Let me call it 5 to match with the sequence which I gave of the hardness in the previous, I am calling it 5, this is quenching, this is very fast cooling, very fast cooling let us say by putting it in water, this gives the microstructure martensite. For many applications this martensite is extremely hard and brittle, for many applications this is not suitable, and you may like to then change the hardness of this martensite by a further treatment and that is what leads to tempering.

So, you will heat the quenched steel to a higher temperature and then cool. This is 4, this tempering, this is heating, after quench, and this gives you tempered martensite. Now if you look at the phase diagram we do not we cannot explain all these microstructures from the phase diagram alone, because phase diagram only gives us alpha plus Fe 3 C, and we have seen that on slow cooling this alpha plus Fe 3 C is in the form of pearlite.

So, may be coarse pearlite and fine pearlite we can probably relate it to the phase diagram, but then bainite tempered martensite and martensite are not even present anywhere in the phase diagram. So, to understand them, we have to use a different tool, and that tool we have already developed in connection with the liquid to solid transformation in freezing and that is the TTT diagram. So, the time temperature transformation diagram can come as a rest as help or an aid to us in understanding how these different treatments give us these different micro structures.