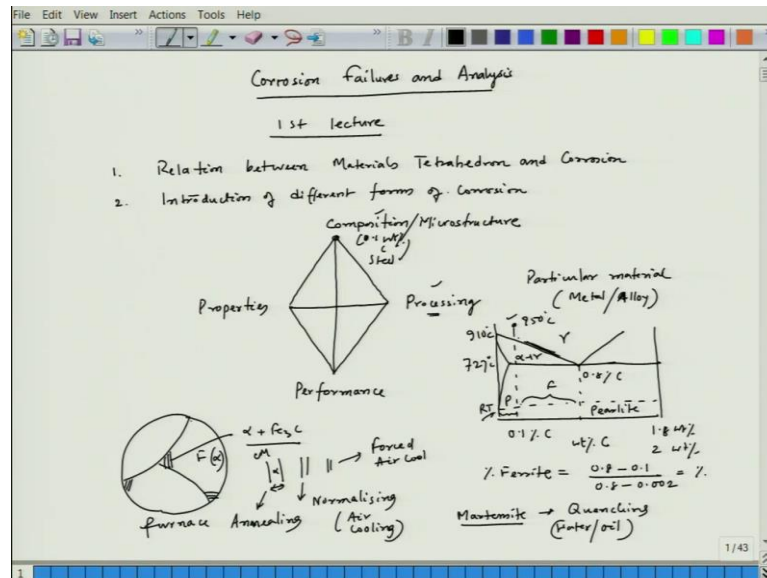


**Corrosion Failures and Analysis**  
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**Lecture - 01**  
**An introduction to corrosion failure and analysis**

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Hello everyone let us start the course on Corrosion Failures and Analysis. Now, in this particular course, as we have introduced that we will talk about different forms of corrosion and how those particular corrosion forms appear, what are the reasons behind that?

And we will also try to analyze the mechanisms and then we will look at some of the case studies, and try to also analyze or propose corrosion protection routes or methods. So that particular type of corrosion can be controlled to a great extent.

And the main intention is to improve the durability of the metallic or alloy components or engineering structures and just to make sure that the corrosion effect is minimally felt. Now, this is the 1st lecture and in this lecture, we will try to discuss few things. One is relation between materials tetrahedron and corrosion and the second part we will introduce different forms of corrosion. Rather we will just name those forms, different forms of corrosion.

Now, if we talk about the first point which is relation between materials tetrahedron and corrosion, let me first draw the materials tetrahedron. So, whoever tries to learn materials, that person needs to go through this tetrahedron, where the four segments which are basically nothing, but composition and microstructures. Then we have processing, then we have properties, and finally we have performance and this is specific to some particular material.

And since, we will be talking about corrosion failures and analysis of metals and alloys; so you can consider that this is either metal or alloy. In fact, we will also try to look at corrosion of ceramics also as well as sometimes we have to talk about corrosion of plastics; but mainly we will talk about metals and alloys.

Now, if you see this, for example, if we consider any metals let us say steel, particular composition of steel; you can that time you are fixing the composition, let us say 0.1 weight percent carbon steel. So, that time this apex part will be microstructure.

And as you know that this 0.1 weight percent carbon steel can be processed differently, if we quench it we will get martensite, if we slowly cool we will get pearlite and ferrite, pearlite would be less fraction; fraction of pearlite would be less, because this is far away from 0.8 percent carbon steel. So, if we consider the phase diagram under the steel part, so I am just drawing the steel part only.

So, this is 0.8 percent carbon steel and 0.1 is coming here carbon. So, this is 910 degree Celsius, this is 727 degree Celsius ok and this is weight percent carbon and this is you can some book you will find 1.8 weight percent or some book you will find 2 weight percent. Now, if you consider this particular steel and if you take a at a room temperature, this is room temperature; if you take this is the pearlite ok and that times if you do a tie line calculation, this much fraction would be ferrite and only this part would be pearlite.

So, this is pearlite, this is ferrite; how do we get it? So, in order to find out the percentage of ferrite, it will be equal to  $0.8 - 0.1$  divided by  $0.8 - 0.002$  you can say; the carbon content would be very small at this particular temperature, so you can even neglect that particular fraction.

$$\%Ferrite = \frac{0.8 - 0.1}{0.8 - 0.02}$$

So, this will be the percentage of ferrite; so that means the pearlite would be very minimal.

So, if we see the microstructure; so the microstructure would be the triple point some pearlite should be there, otherwise mostly ferrite. So, this is ferrite, we call it alpha iron and this is pearlite, pearlite is a basically mixture of alpha and Fe<sub>3</sub>C, which has a lamellar structure. So, this structure can form if it is slowly cooled from austenite temperature beyond this particular phase boundary between alpha and austenite. This is austenite, so this particular boundary, this particular boundary, ok.

So, beyond that you have to take the steel, hold it there for some time, so that the complete austenitization takes place and then you cool it slowly. The one way to do slow cooling is, you hold that particular steel sample in the furnace at that temperature. Let us say this temperature is around let us say 950 degree Celsius, you hold it there for half an hour and then leave it in the furnace, put with the door closed of that furnace and switch off the furnace. So, it will be called as furnace cooling.

Now, that time you can have some spacing between these two cementite lamellae. So, let us say this is cementite lamellae; this is cementite and this is ferrite. So, this distance can be controlled or can be changed. If we do the furnace cooling, which is which we call annealing, that time this distance would be the maximum distance and if you increase the cooling rate from that 950 degree Celsius, your spacing would decrease. So, this spacing would become this much and then again if you cool it faster, it will go become like this.

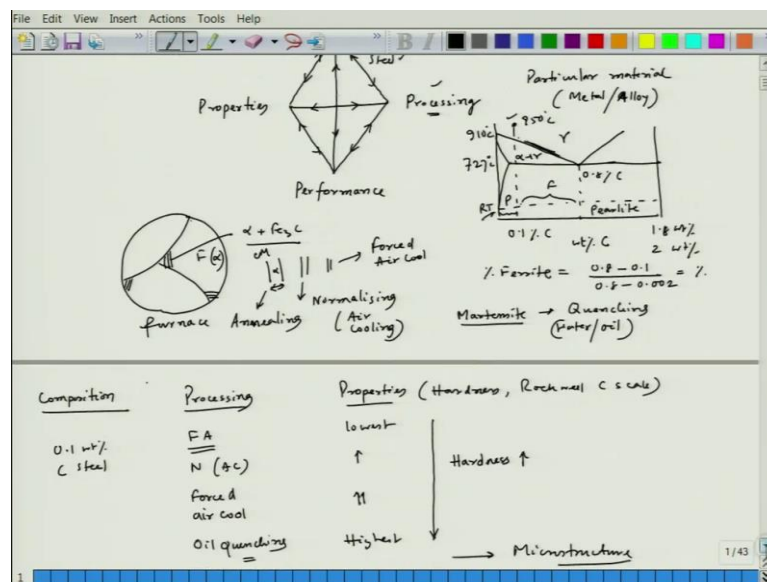
So, you can say that you take the sample after doing the austenitization, you take the sample out from the furnace and leave it in the air, it cools down. So, that we call it normalized. So, this is called annealing or we call it furnace annealing; this one we call it normalizing or air cooling. And if you decrease the spacing between two cementite lamellae that time it would be, we can do it by having a forced air cool, air cool.

How do you do that? You take the sample out after 9, austenitization at 950 degree Celsius and then take that sample in front of a fan ok, which actually forcefully takes the heat out and you have a higher cooling rate.

Now, if you take the sample from here and then quench it in oil or water, which is kept at a room temperature at room temperature, we would get martensite. So, we call it. So, when we get martensite, we call it, we have that particular heat treatment called quenching, ok. So, this is water or oil quenching, fine.

So, now, you could see that, if you fix the composition, the microstructure you can change by changing the processing. Because you see that you are doing furnace annealing, normalizing, force air cooling, quenching, you can change the microstructure and that is possible by doing processing. And when we do processing, so the each one would give you different properties.

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For example, if I consider only the hardness part, only the hardness part; so let us say processing, then properties and here I am composition, I have fixed it 0.1 weight percent carbon steel. Now, processing what I am doing? Furnace cooling, furnace annealing, normalizing or air cooling and forced air cooling, ok. And the third one, fourth one we are doing oil quenching let us say, fine.

So, now if I see the property and let us say hardness let us say this is Rockwell C scale, where we will use 150 kg load. Now you will see that hardness would be the lowest and here it will be the highest and in between it will increase, it will increase further. So, now, you see the hardness as you go down, hardness increases.

So, if we can also check the hardness, if we have a hardness tester; but that the value is not the important, the logic here is as we, the main aspect here is as we change the processing condition, the properties property is also changing, same would be true for tensile property. For example, in this case if I see the tensile property, in this case the tensile strength would be lowest; but the elongation would be highest.

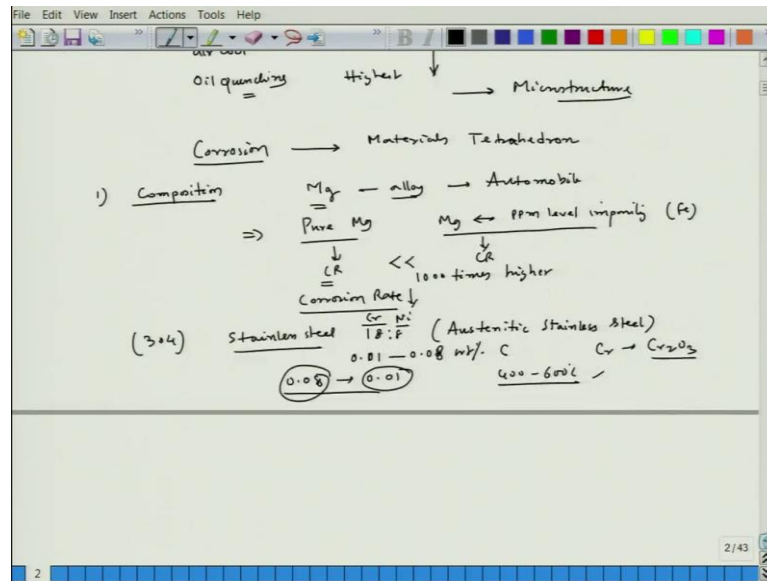
And in this case, tensile strength would be the highest, but elongation would be lowest. So, like that way the property would change as we change the processing, if we fix the composition and that is possible only by changing microstructure. And interestingly each one would have a specific purpose to give, ok.

For example, if it is a furnace annealing structure as well as if it is a force air cooled structure, same cannot be used for a specific purpose, we have to choose accordingly. For example, if we consider this rebar or reinforced bar, they are mostly air cooled, ok. So, there we need a kind of optimization of properties and air cooling is easily possible industrially ok big and also it takes; you know furnace cooling would take long time, but air cooling would take less time ok compared to furnace cooling.

So, that way we can also meet a specific performance, which is to be obtained from that particular structure, ok. So, now, you can see that, you could see that this particular materials tetrahedron. So, this is nothing, but the materials tetrahedron and we can see that everything is correlated, everything is correlated, all those sections are correlated. How come? Composition fixed, microstructure changes, processing I can change to get the different properties.

So, properties is in dependent on microstructure, processing changes the microstructure and entire thing properties, processing and composition as well as microstructure would finally, give you a specific performance, ok. So, that means the all those arms are related, intricately related. Now, coming to our purpose, our purpose is we have to see the corrosion part.

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Now, does it have any effect or any relation with the materials tetrahedron, materials tetrahedron? Now, let us see that ok, with our experience what it talks about. Now, coming to materials let us say composition, first let us talk about composition and let us take a magnesium, fine.

We know that magnesium is a very active metal; but in spite of that, magnesium is promising in the sense that it has a extremely low weight or density is less, that is what it can be used in some applications like automobile, where we need less weight in order to have higher fuel efficiency.

And if we see that it meets the strength requirement, I think we are fine with that. Magnesium alloys have those specific use; because they have high strength to weight ratio, because it has a very low density. But at the same time magnesium has a very high activity; means in terms of corrosion tendency, because it can corrode heavily and that is what you must have heard about magnesium anodes.

So, magnesium alloy can be used in automobiles, because they have a very low density; so that means the strength to weight ratio can be very exciting in order to reduce the total weight of the car body and that would definitely increase the fuel efficiency. But now in the magnesium, let us say I take a pure magnesium and let us say and magnesium with ppm level impurity, which is nothing but iron, fine.

Now, if we try to compare the corrosion rate, this is almost about close to around 1000 times higher. So, now, ppm level addition of presence of iron can increase the corrosion rate of magnesium to a great extent. Now, you could sense that the composition has a huge implication on the corrosion behavior.

Similarly in magnesium alloys, we will talk about that magnesium alloys in details later, that addition of a specific elements can improve the corrosion resistance; not only that we have to also talk about the microstructure development, so that we get a quite a good corrosion resistance, so that it can be used in that automobile applications.

But if we take this example, pure magnesium has a fairly good corrosion resistance; but if we consider CR means corrosion rate and please remember that if I use CR, do not take it as a corrosion resistance, it should be taken as a corrosion rate. And if it is a corrosion resistance, then I will definitely write full sentence, full words corrosion resistance. Now, if I talk about pure magnesium, its corrosion rate is low compared to magnesium with ppm level of impurity, which is iron.

So, now you could sense that, just by changing the composition a little bit, we get huge change in the corrosion properties. Now, if we talk about let us say an example let us say stainless steel let us say 18/8 and this is very popular and this is nothing, but austenitic stainless steel, austenitic stainless steel and here the carbon we have 0.01 to 0.08 weight percent carbon can be present.

Now, in the commercial grade austenitic stainless steel, which is also called 304 stainless steel; so there the carbon content is around of the level of 0.06 to 0.08 weight percent. And there if we change the carbon content from 0.08 to 0.01, there will be huge implication on the corrosion rate. If it is 0.08 weight percent, by chance during operation the temperature goes between the range between 400 to 600 degree Celsius. What happens, that stainless steel loses the property of stainlessness.

It is going to be extremely bad stainless steel, because there will be huge amount of intra granular corrosion; that means the corrosion happens along the grain boundaries, we will understand why. But even the processing is little bad, I would say the let us say, there is a; there is a chance that point between 400 to 600 degree Celsius, the steel sample is held for certain time.

And even if the carbon content is less, still the stainless steel, that austenitic stainless steel will not lose its stainless property; because there is an inherent nature or inherent tendency of that carbon present in that particular steel to form chromium carbide along the grain boundary. And why chromium carbide, because 18 percent is basically chromium and 8 percent is nickel; nickel helps to achieve austenite structure and chromium gives you the corrosion resistance property.

And the chromium how come it gives you corrosion resistance? Because chromium forms chromium oxide passive layer, so that passive layer would give you corrosion protection. But there is a problem if you have that particular steel between 400 to 600 degree Celsius that is called sensitization temperature range, where the stainless steel gets to a sensitized state and at that point, the chromium carbide forms along the grain boundary.

Now, if the carbon content is 0.08 percent, there is a lot of carbon in the steel, in the solid solution and there is a greater chance of formation of chromium carbide along the grain boundary. But if the carbon content is less 0.01 percent, since even if the steel is by chance taken to this particular temperature range; since the carbon content is less, chromium does not have a sufficient carbon atmosphere to form chromium carbide.

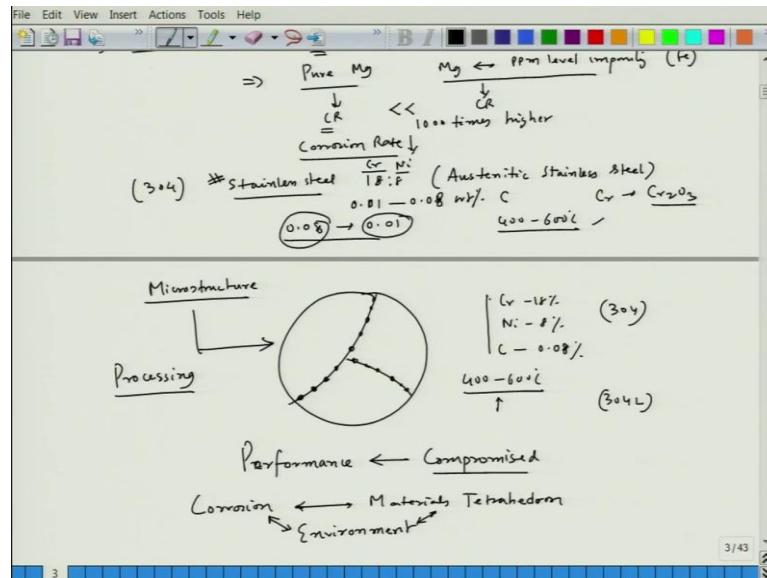
So, chromium carbide does not form along the grain boundary, sensitization tendency would be less, would be less; but there still will be chance, because if you hold it for a longer period, finally it will form.

But at least the chance of formation of chromium carbide along the grain boundary will be less if the carbon content is less. So, now, again you are coming to that fact that, if you change the composition of a particular material, you can get a huge implication on the corrosion properties.

Now, on this aspect, we will talk about processing part; but at least you could sense that in that material tetrahedron, we have an apex which is composition that has an effect on that.



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Now, coming to the microstructure. Now, we can take this example, we can take this example. Stainless steel if we see the microstructure, this microstructure is like this, if it is all solution condition; that means chromium 18 percent, nickel 8 percent, carbon 0.08 percent, ok.

So, and this is called 304 stainless steel and another part is, if we consider this low carbon 0.01 percent, that time we write this one as 0.304 L, ok. So, this is the only difference in the nomenclature, this L indicates. If you find in any stainless steel grade that L word is mentioned, so that is nothing, but low carbon, ok. So, in that case, for example, if we take the same composition; if we hold it at a particular temperature let us say 400 to 600 degree Celsius.

Let us say you have heated it to a certain temperature and then while cooling; if the cooling rate is slow, then the time of retention between these temperature range will be much higher. So, that time the chromium carbide precipitated would form along the grain boundaries, along the grain boundaries; rather it forms on the, sorry let me draw it again, actually it forms along the grain boundary, it can form on the grain boundary itself.

So, these are the chromium carbide. If you cool it slowly between and that time the time of retention between 400 to 600 degree Celsius is bit higher. But if you cool its rapidly, so that the time of retention of that particular steel component between this temperature is less; the formation of chromium carbide would be less on the grain boundary. And this

chromium carbide formation along the grain boundary is the sole culprit to give you a very high intra granular corrosion tendency of that stainless steel.

So, that means you fix the composition, you are changing the processing, you are getting different properties. And that where that effect is coming, because your microstructure is changing, your microstructure is changing; ofcourse this microstructure change is possible because of processing, fine. Even if you change the composition, if you fix the processing, still the microstructure can change; but here I am saying that composition is fixed, the microstructure can only be possible, change can be possible if we change the processing.

Here the processing; what is the processing change? We are cooling slowly; you are cooling rapidly, so that is the change. So, now, here also you are seeing that the processing has an effect on the corrosion tendency, which is manifested in the form of microstructure.

And now coming to the performance part as we have mentioned that, if you change composition, if you change microstructure, there will be change in processing; but now because of that there is a corrosion effect, definitely the performance is also going to be suffered, is not it.

So, that means you are also seeing the performance is a compromised; if in case of stainless steel at least, we could see the performance is compromised. So, that means it is very clear that, the corrosion and materials tetrahedron they are hugely related. So, while we talk about corrosion, we have to also bring in all those factors microstructure, composition, processing those factors.

But it is not only that, when we talk about corrosion; we have to also bringing another factor, which is environment, ok. So, that environment will also combine between these corrosion as well as materials tetrahedron; so that means we will talk about corrosion, materials tetrahedron as well as environment. There are other issues also, so we will talk about that part in our next lecture. So, for the time being, let us stop here; we will continue in our subsequent lecture.

Thank you.