Fracture, Fatigue, and Failure of Materials
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Lecture 49
Failure of Materials (Contd.)

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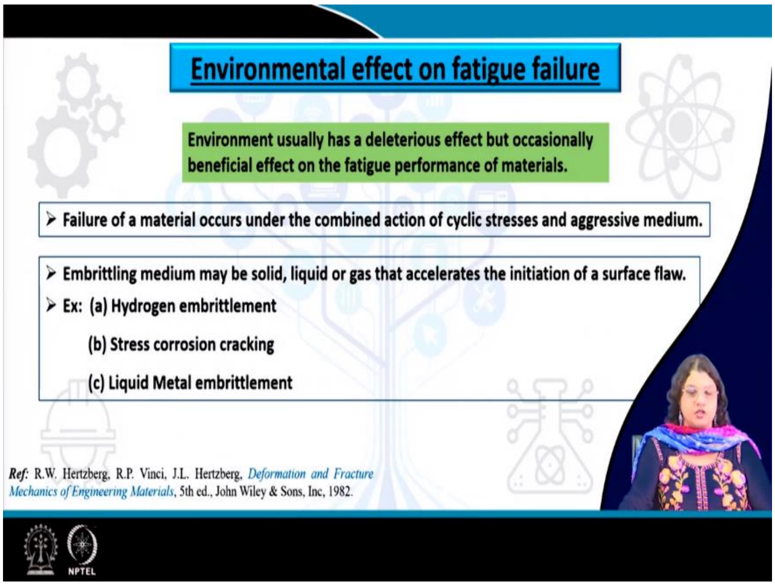

Hello everyone, and welcome back to the 49th lecture of this course, Fracture, Fatigue, and Failure of Materials. And in this lecture, we are also going to talk some more about fatigue, but particularly we will be talking about the effect of environment on the fatigue behaviour of materials.

And when we say that, the first thing that comes to our mind is the effect of corrosion or the presence of aggressive environment, how does that influence the properties or the mechanical behaviour or the failure tendency of materials, and for that it is very interesting to note that environment, most of the cases it has a deleterious effect.

And when we are talking about the environment, we are mostly concerning about the corrosive or aggressive environment. But in some cases, like in occasionally there are some beneficial effects are also seen for the case of the presence of environment on the failure behaviour of materials. So, in this lecture we will be digging into deeper end of that, and it is to be noted that a failure of material occurs under the combined action of cyclic stresses as well as aggressive medium, particularly when we are talking about the influence of environment or the corrosion fatigue kind of behaviour.

And there are different mechanisms through which corrosion can actually affect the mechanical properties of materials, and these are the following as the hydrogen embrittlement, stress corrosion cracking, liquid metal embrittlement, etcetera. And we have talked in details about each of these mechanisms in the environment assisted cracking lecture. So, in this lecture we will see that how the presence of such environment along with the cyclic loading can lead to a change in the overall properties or the fracture or the fatigue behaviour of materials or components in general.

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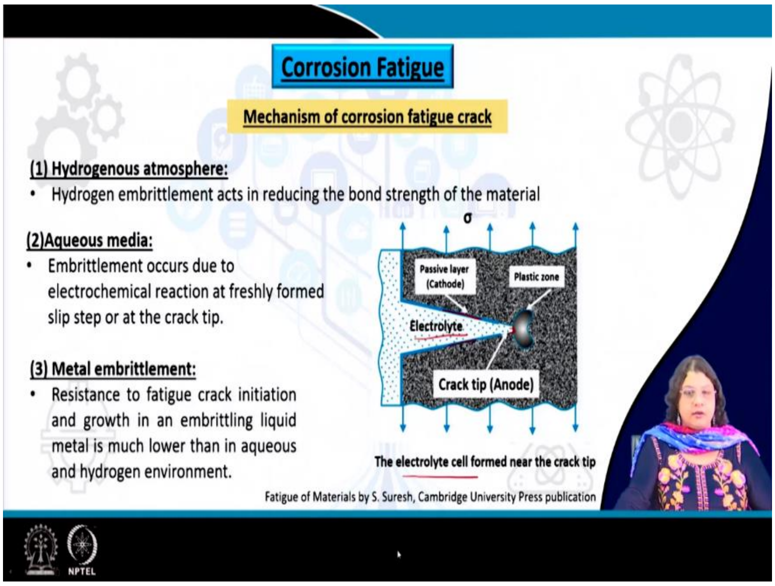

So, the mechanisms of corrosion fatigue are still relying on this kind of environment assisted cracking such as the hydrogen atmosphere, if it is present then that leads to an embrittlement based on the fact that it reduces the bond strength of the material. In case there is an aqueous media, like this could be moisture or any other presence of some liquid that also may lead to an embattlement due to the electrochemical reaction at the freshly formed slip step or at the cracked tip. Now, crack once again is a surface which is a free surface and freshly formed surface is very much prone to undergo any kind of chemical reaction.

So, basically the entire system acts like an electrolytic cell, in which if there is a crack tip here that acts as the anode, the liquid media or whatever aggressive environment is there that acts as the electrolyte, whereas the layers the corrosion product layer that is forming on the wake of the crack that acts as the cathode. And overall this entire system acts like an electrolyte cell and that reads, leads to the chemical reaction to of occur and as a result the crack progresses and new fresh surfaces are being formed.

There are often liquid metal embrittlement also, and this is although less aggressive and or the resistance to fatigue crack initiation, and growth is a much lower in case of the liquid metal embrittlement in comparison to that for the aqueous and hydrogen environment. And this is particularly occurring for some particular combination, or specific combination of materials, so this is not valid for all the any two particular metals which are coming in contact but rather if a combination of metals is in contact that may lead to the metal embrittlement. And we need to understand or we need to know this combination beforehand again in the previous lecture on environment assisted cracking.

We have also seen that what kind of materials are reactive to each other, for example, the gallium and the aluminium, they react a lot and that may lead to early onset of fracture or brittle fracture, okay.

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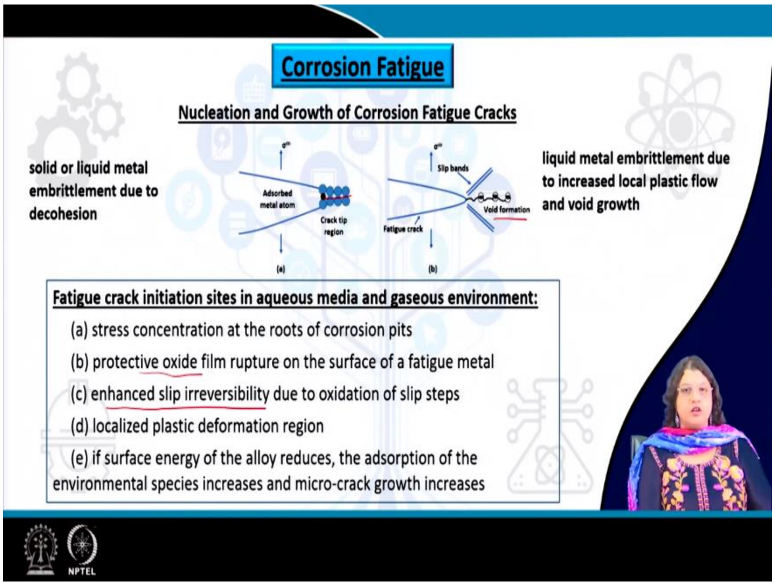

Now, in any case, if there are the solid or the liquid metal embrittlement that is happening that basically leads to decohesion of the bonds. And accordingly, the fatigue crack based on the cyclic loading that is available, that can move on through the voids that are being formed, and that can lead to the overall enhancement in the crack growth. If we simply try to understand the mechanisms for the fatigue crack propagation or initiation in the first place, in presence of some environment these are the following steps for that.

A stress concentration at the roots of the crack tip is associated with some corrosion pits, So based on the chemical reaction during the corrosion, there could be some pit formation and that may act as the location for the crack initiation. Particularly, when we are talking about the presence of cyclic loading, this kind of pits can actually lead to a strain imbalance with respect to the surroundings. And as a result, because of the strain imbalance that can lead to formation or initiation of the crack at the very first place, okay.

And now, the protective oxide, typically that forms as a result of the corrosion chemical reaction that in most of the cases are beneficial in the sense that it forms a passive layer, so it protects the inner material to come in contact with the corrosive environment and restricts the chemical reaction to occur.

But again, this may be fine during the monotonic loading condition, but when we are talking about the cyclic loading in reverse direction or loading and unloading or repeated loading even in the tensile direction, what happens is that, this protective oxide film ruptures, and wherever this film ruptures, there is the free nascent surface which comes in direct contact with the environment, the aggressive environment. And certainly, that is very much reactive to such chemical condition and that leads to further corrosion reaction to occur and with more corrosion reaction that may lead to the propagation of the crack, growth of the crack or formation of new fridge surfaces.

Now, enhanced slip irreversibility is another way which occurs particularly due to oxidation of the slip steps which are forming on each of the cycles of fatigue and that may lead to the further growth of the crack. Localized plastic deformation may also happen once again due to the presence of crack or notch or any other stress concentration sites that may lead to formation of the localized plastic deformation.

And plastic deformation is associated with permanent volume change, and whenever that happens that may also lead to some rupture of the protective oxide layer, if it is present or even if it is not, then simply such kind of volume change can lead to early onset of the crack initiation.

If surface energy of the alloy reduces, the absorption of the environmental species increases, and that may lead to formation of micro cracks, and then the micro cracks can coalesce and that lead to further growth of the crack in a finite way. So, these are some kind of ways by which the fatigue occurs under corrosive atmosphere and which can lead to the overall failure of the component.

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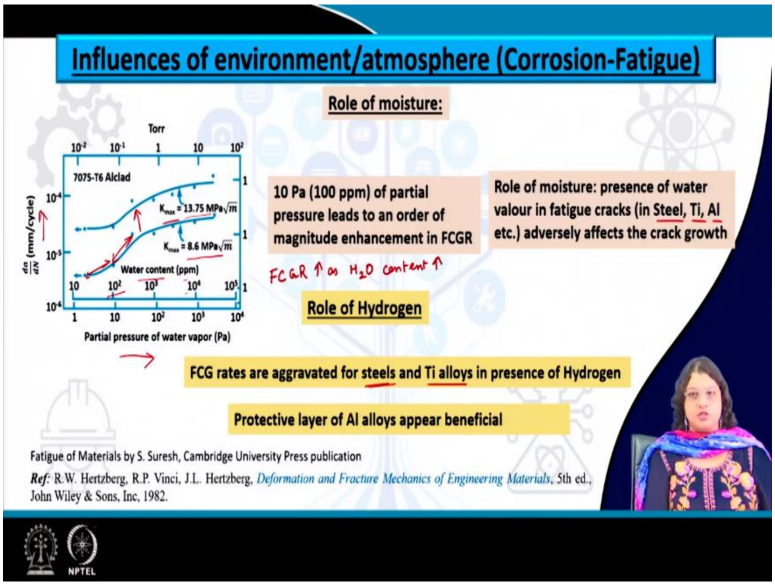

Now, let us see how the different kind of atmosphere are actually affecting the corrosion fatigue behaviour. When we are talking about the role of moisture, as we know the humid environment is often not favourable and that may lead to the corrosion reaction to occur. And this can be very commonly seen as rust in case of the iron-based products, you can see for your daily usage materials that if the iron is coming in contact with the moisture that may lead to the formation of the rust and rust is nothing but the corrosion product.

So, here is the example of an alloy for the da/dN on the y-axis which means the crack growth rate as well as the x-axis shows the partial pressure of water vapor, okay, so there is some moisture content already there. And how with the change in the moisture content, we can see that there is a change in the crack growth rate. So, there are actually two axis provided in the x-axis, one is the vapor pressure which is in Pascal, and then the water content or the moisture content is also shown in the ppm, Parts Per Million.

And we can see that for every enhancement in this partial pressure by 10 Pa or for that matter, the ppm level is being increased by an order of magnitude, so just from 10 to 100, or 100 to 1000, we can see that there is a significant change in the da/dN. So, that means that the crack growth rate is increasing, as the vapor pressure is increasing or the moisture content is increasing. So, we can very well say that fatigue crack growth rate increases as the moisture content increases, and that is quite significantly.

Not only that, we can also see the influence of K here, so if we are applying higher value of the stress intensity factor, particularly for the maximum one we are talking about, and you can see that for 8.6 $MPa\sqrt{m}$ to 13.75, so almost like 1.5 times enhancement in the maximum stress intensity factor level, and you can see that there is a significant jump in the crack growth rate.

So, for particular amount of moisture content of let us say 100 ppm, we can see that the da/dN increases from around 10^{-5} to 10^{-4} or something like that, so almost like one order of magnitude jump in there. And that is more or less following for all the different moisture content that has been shown here. So, we have to be careful of using any particular metal or material for that matter or alloy for any environment which we know is used in presence of moisture.

Now, this is particularly applicable for the case of steel or titanium, aluminium, etcetera, and we have to be using this kind of material and with concern when we are knowing that the application of the service requirement involves presence of moisture in it. Now, hydrogen is another such element which leads to embrittlement, we have already seen that how the presence of hydrogen can reduce the bond strength and overall makes the material behave or fail in a brittle fashion.

And this is once again for a specific metal system, hydrogen acts very much detrimentally and we have to be careful for using that. Now, for the particularly for the case of Steels and titanium Alloys any presence of hydrogen, particularly for high strain steel any presence of hydrogen is a bad news and that can lead to significant enhancement in the fatigue crack growth rate. So, once again we have to be careful in not using such material in presence of hydrogen.

Aluminium on the other hand is not that much affected by hydrogen particularly because of the protective oxide coating that it forms which appears beneficial and prevents the material to come in direct contact with hydrogen or react with hydrogen. So, we can use mostly aluminium but not high strength steel in certain applications, if we know that those are prone to be used in presence of hydrogen.

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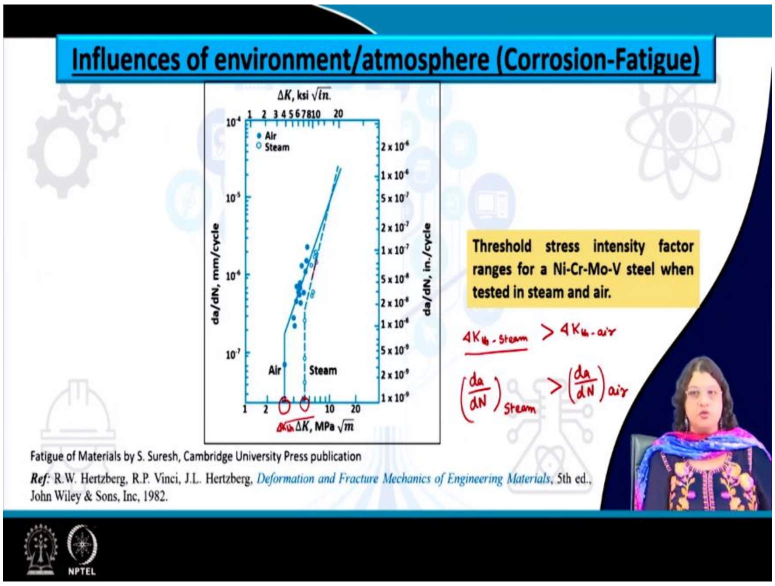

Now, this example has already been shown earlier which shows that how the ΔK_{th} value typically, the threshold stress intensity factor level for air and steam are different. And we have seen that the ΔK_{th} for steam is actually greater than ΔK_{th} air. So, at the very first slide in this lecture we mentioned that it is not always detrimental, corrosion does have some beneficial effect occasionally.

And this is one such occasion where you can see that the presence of steam so steam means basically moisture as well as high temperature, and that leads to very much pronounced corrosion reaction to occur and that leads to formation of the corrosion products on the crack way, and that leads to closing of the crack.

And as a result, crack or notch whatever is there an existing and as a result the growth of the crack, at the beginning of the growth of the crack is being retarded and we leads to have higher value of ΔK_{th} in presence of steam than that in presence of air. But at the same time if we are looking for the cracked propagation path, particularly for region 2, we can see that for the case of steam the da/dN for steam is actually higher than the crack growth rate under air. So, that is another point for concern which says that the crack grows at a faster rate in presence of steam.

Once again, the high temperature as well as the moisture makes it easier for the crack to grow. So, although the onset of the growth of the crack is being delayed or hindered by the presence of this corrosion product, but once it is already advancing, at that point since we are talking about repeated cyclic loading and with the repetition of the loading whatever protective barriers it forms gets ruptured on every cycle and which means that the nascent surface can leads to further corrosion and further growth of the crack.

So, in that sense da/dN or the crack growth rate increases in presence of steam, so we have to be careful depending on what kind of ΔK_{th} or the stress intensity factor level that we are going to use the component in service, we have to choose what kind of material will be more suitable.

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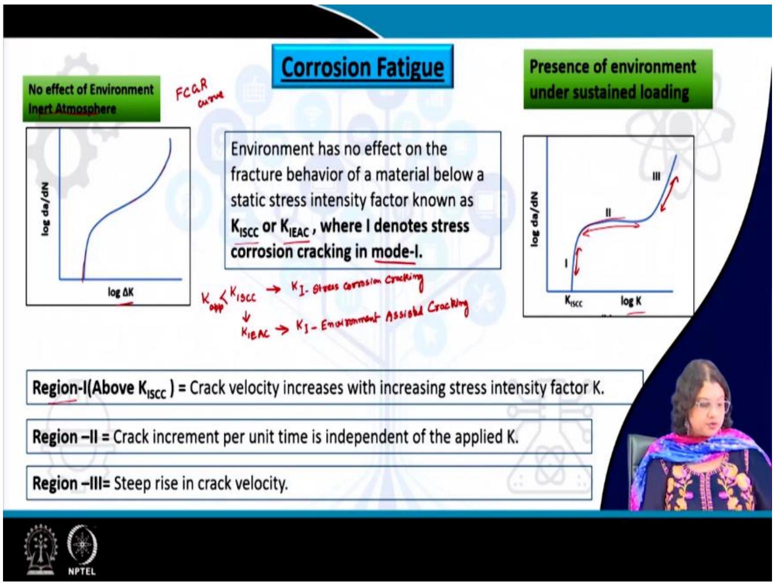

Now, if we are talking about the fatigue crack growth, so there are different ways to understand the individual effect of cyclic loading as well as the presence of any kind of aggressive environment, how does that influence the fatigue crack growth behaviour, and from there we can figure out that with the simultaneous presence of aggressive environment as well as cyclic loading, how the performance of the material is being changed.

So, this is the typical da/dN versus ΔK_{th} curve, as we have seen for the fatigue crack growth rate curve. And this can be seen when the effective environment or any such aggressive corrosive reaction is not so much prominent or this can be also seen in presence of inert atmosphere, so whenever there is no chemical reaction to occur. And for such cases, environment has no effect on the fracture behaviour, until it reaches the value of K_{ISCC}, so or K_{IEAC}. So, K_{ISCC} stands for K_I, so I as it says is for mode 1 and SCC stands for stress corrosion cracking, okay.

So, there is a limiting value of K_I for the stress corrosion cracking to be activated. And if we are applying the ΔK value less than that, then there will be no damage associated with the corrosion, there will be damage related to the cyclic loading obviously as per this kind of curve, but if we are applying the K value, applied K is less than K_{ISCC}, then there will be no influence of environment, so far. And this is also not only SCC, but K_{IEAC}.

Now, EAC here stands for environment assisted cracking, we have already seen that, okay. How the presence of environment can reduce the applicable value of K_I, that can lead to fracture. So, often this K_{IEAC} value is significantly lesser than the K_{IC} value, so which means the fracture toughness value. So, although it is not supposed to fracture for the applied ΔK value less than the fracture toughness, but still fracture can occur because of the presence of this corrosive or aggressive environment leading to the environment assisted cracking.

Now, with the presence of environment and under sustained loading condition, this is the kind of da/dN versus ΔK curve that we are going to see. It has a very prominent three regions that you can see, and first of all this region I is when the crack velocity increases with increasing stress intensity factor, so we can see a very steep slope. And particularly, this is all related to the growth of the crack, just the beginning of the growth of whatever notch or crack which is already existing.

Region II, on the other hand is associated with crack increment per unit time and that is independent of the applied K and you can see that there is more or less the da/dN is achieving almost a constant value for certain range of ΔK for this particular case in presence of the environment. And region III once again shows a steep rise in the crack growth rate or the crack velocity along with the ΔK enhancement, okay. So, these three regions are very very distinct in presence of the environment.

Now, in actual practice we cannot simply differentiate between the behaviour at inert atmosphere or in presence of atmosphere. So, it is not possible in most of the cases we see a combined effect unless we do the experiment in inert atmosphere obviously for that particular specimen. If we are doing the test in just an inert atmosphere, we are going to see a curve like this, and then from the actual environment we can figure out that how much is the effect of environment as such.

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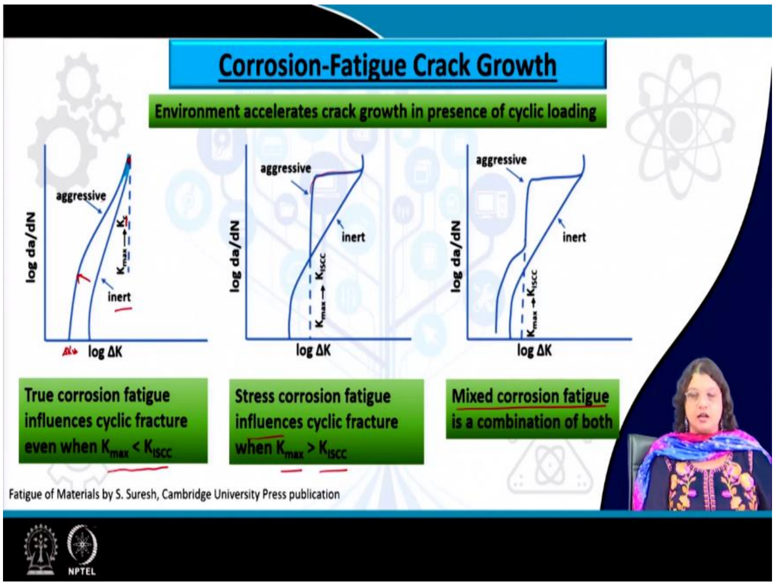

But what we can actually see is based on the da/dN versus ΔK_{th} curve which considers the presence of both, cyclic loading as well as environment. Now, we know that environment accelerates the crack growth, environment sometimes may act as beneficial in hindering the onset of the growth of the crack as we have seen that ΔK_{th} value may increase, but in most cases the crack growth rate is typically increasing as the with the presence of the environment.

Now, there are three ways by which this can be appreciated. The first one shows the true corrosion fatigue behaviour, and which influences the cyclic fracture when $K_{max} < K_{ISCC}$. So, in this case for the true corrosion fatigue to occur that can happen even when $K_{max} < K_{ISCC}$. Please note that I am not talking about K_{IC} here, K_{ISCC} which means the stress corrosion cracking, whatever is the limiting value even fracture or fatigue can propagate, crack can propagate for a value of K max, even less than K_{ISCC}, now this is for the true fatigue condition.

You can see that how the presence of the aggressive environment has shifted the curve to the left, which means that the onset of the growth of the crack also is getting lower as well as the crack growth rate also is being affected by the presence of the aggressive environment in comparison to the inert atmosphere. So, in presence of the inert atmosphere at the point of K_{max} when it is equivalent to K_C, then only fracture will occur, but this may not be the case in presence of the aggressive environment.

Now, in case of the stress corrosion fatigue, actually that is being influenced by cyclic fracture when K_{max} is greater than K_{ISCC}. So, that means the applied K condition is exceeding the K_I or the limiting value for the stress corrosion cracking to occur. And for such case, we can see how the influence of the aggressive environment is again different from that of the inert. So, inert 1 shows a typical three step region that we are used to seeing for the case of fatigue crack growth rate curve, but for the aggressive environment we can see that there is a very steep slope when we are applying K_{max} more than the K_{ISCC}.

And typically, we have to combine both of this to get the mixed corrosion fatigue behaviour, so that we can get the real situation, and we can understand that how the crack growth rate changes in presence of the corrosive atmosphere as well as the cyclic loading.

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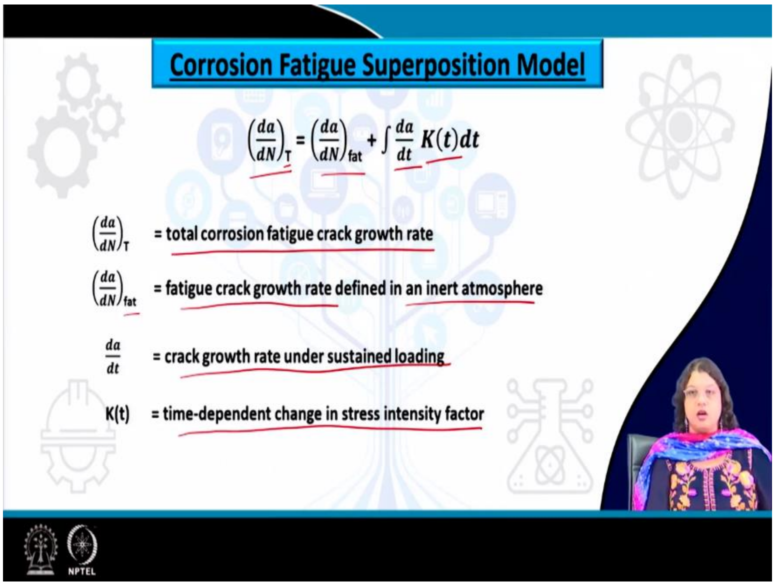

So, there is a corrosion fatigue superposition model which actually super imposes both of these factors. So, it says that the $(da/dN)_T$, so T stands for the total, the total corrosion fatigue crack growth rate is actually equivalent to the summation of $(da/dN)_{fat}$. So, this means a fatigue crack growth rate in an inert atmosphere, so when there is no influence of atmosphere at all plus the crack growth rate under sustained loading in presence of the atmosphere, so that is represented by da/dt, so instead of N, we are considering here dt which means the time, and then we are also multiplying it and integrating for the entire time period with the factor K(t) now. This K(t) is the time dependent change in the stress intensity factor.

So, it is not only about the stress level or the maximum and the minimum stress or the mean stress or R ratio that is of important. When we are talking about corrosion or presence of any kind of environment, for that matter we also need to consider the importance of time, because more the time is available more will be the corrosion reaction, and that may influence the fatigue crack growth behaviour completely differently in comparison to when there is not sufficient time for the corrosion reaction to materialize, okay. So, this is how the real-life corrosion fatigue situation is being determined.

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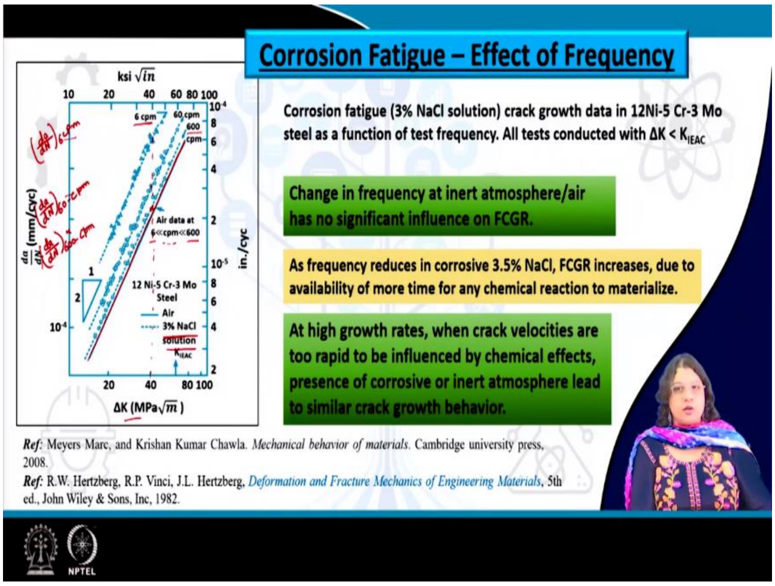

Now, the effect of frequency, frequency of the loading. As I have mentioned that time plays a very significant role in case of such kind of chemical reaction, so obviously frequency means how fast or how slow, the loading levels are being applied. This is an example for a particular steel which has been tested in presence of air as well as in 3 % NaCl solution, okay.

The solid curve here which I am now colouring it with red just to differentiate it from the rest of the curves, signifies the crack growth rate versus ΔK in presence of air that is an ambient condition. When the frequency of loading has been changed from 6 cpm to 600 cpm, so cpm here stands for cycles per minute, okay. And what we can see is that there is no variation in the da/dN versus ΔK behaviour, if we are varying the frequency over two orders of magnitude.

But this is not the case when we are talking about performing the fatigue test in presence of 3 % NaCl. 3 % NaCl aqua solution is typically used as a representative sea water kind of environment in laboratory scale. So, this is particularly suitable if we are talking about applying certain material for marine applications, we often need to pursue the test in presence of 3 % or 3.5 % in NaCl Aqua Solution.

So, here we can see that there are three different curves, particularly for region II in all the cases. And we can see that the one done with the lowest cycles per minute or lowest frequency of 6 cpm is at the left most end, and the one done at the highest cycles per minute is at the right most end, and actually very near to that for the air data, air or inert atmosphere here. So, the reason behind this variation in the da/dN versus ΔK behaviour in presence of different frequencies are the fact that different amount of time are now available for the chemical reaction to occur.

As I was discussing about the importance of time in case of the corrosion fatigue, this is particularly evident if we are talking about the frequency. So, when we are performing a test with 6 cpm there is enough time available for the reaction to occur and that may lead to the crack growth at a faster pace. So, for that we actually for any particular value of ΔK, let us consider the ΔK value as 40 $MPa\sqrt{m}$, and if we simply extrapolate this line we will see that for 6 cpm, this leads to a very high value.

So, this is for the da dn of 6 cpm, on the other hand for the same value of ΔK, if we are pursuing the test at 60 cpm, we can see that the crack growth rate has been decreased significantly. So, we can see that for 60 cpm the crack growth rate has come down, significantly and not only that if we are doing the test at 600 cpm, the crack growth rate actually decreases even further.

So, that means that if we are having the corrosive atmosphere, it is always preferable to have the loading at a very high frequency, why? because if we are pursuing the test or the environment condition is such that the cyclic loadings are being done very fast, so that means that not enough time is available for the corrosion reaction to occur and that may lead to a reduction in the crack growth rate or overall the fatigue life will be enhanced.

And this however is not an issue if we are talking about the fatigue test or the fatigue cycling in air or in inert atmosphere, particularly in inert atmosphere but in absence of moisture or temperature, even regular air or the ambient condition is also not that detrimental. So, that is what we need to keep in mind, that while the inert atmosphere or air has no significant influence on fatigue crack growth rate, frequency is playing a dominant role in case we are talking about the presence of aggressive environment there. And we have seen that as frequency reduces in presence of the corrosive saline atmosphere of 3.5 % NaCl, then the fatigue growth rate increases to a certain extent.

However, at the high growth rate when crack velocities are too rapid to be influenced by any other chemical effects, so at high growth rate it is more or less like an unstable growth. So, presence of corrosive or inert atmosphere again lead to a similar crack growth behaviour, so even it does not matter whether we are doing the test or whether the service condition includes a corrosive or inert atmosphere, a high growth rate is not that influenced by the presence of the corrosive atmosphere.

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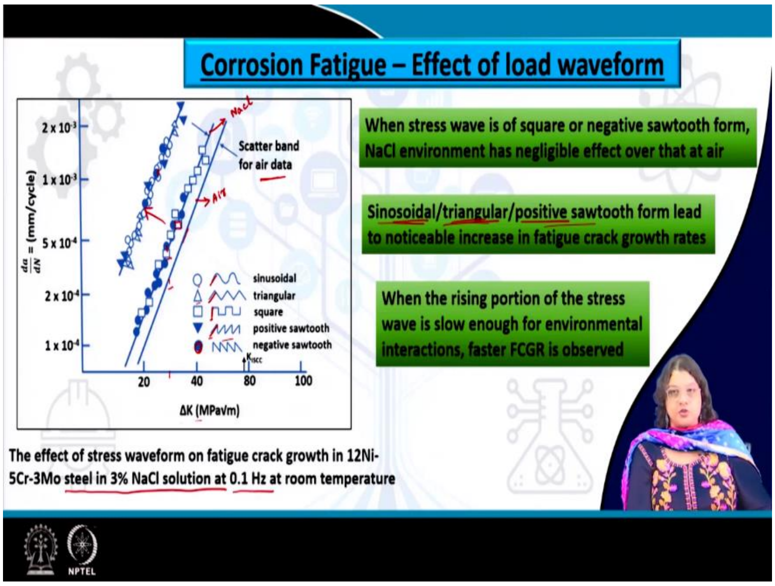

Now, not only frequency but the load waveform also has a very significant effect in case of corrosion fatigue. So, you can see here once again the experimental results, which shows the da/dN versus ΔK curve for different waveform. So, this is once again for steel in presence of 3 % NaCl solution. In this case the frequency has been maintained constant to 0.1 Hertz that means 0.1/sec, okay. And what we can see here is that for the case of air, we can see that different waveform which are represented by the different symbols are giving us the different da/dN versus ΔK curve.

Now, this is particularly for the case of air, however if we are having the square or negative Sawtooth form, then the NaCl environment is actually having negligible effect over that of air. So, this is the square, this symbol here as well as the negative Sawtooth which is the solid circles here, and you can see that these values are quite similar to that for the air, so this one is done in NaCl solution.

But, if we are talking about the sinusoidal or triangular or positive Sawtooth kind of behaviour, then the load form if it is in such shapes, then we can see that there is an enhancement in the da/dN versus ΔK curve. Actually, the crack growth rate increases significantly for any particular ΔK value.

Again, we can do the similar kind of exercise, we can take a particular value of ΔK of 30 $MPa\sqrt{m}$, and you can figure out that first of all air and NaCl will have some differences in the value for a particular ΔK, we can see that the crack growth rate is more for the case of NaCl in comparison to that for air.

But even for the same environment, same material, same specimen dimension as well as same loading condition, if even if we keep all these parameters same just by changing the loading form or the waveform instead of using a negative Sawtooth if you are using a positive Sawtooth kind of behaviour then we can see that there is a significant change in the da/dN value for the same ΔK value of 30 $MPa\sqrt{m}$.

And this is particularly related to the fact that the rising portion of the stress wave, load wave or stress wave, so rising portion means for the case of positive sawtooth, this is the one which is happening over a certain slope, instead of the square one which is like a drastic one, a triangular or a sinusoidal or even a positive Sawtooth one has a particular slope over which the stress is being increased. So, that means this is already in an corrosive atmosphere, so if we are applying certain slope for the stress to increase from 0 to the maximum value, that means it is getting some time for the reactions to occur.

In comparison, if we are talking about a square one, there is no time involved here, so we are having 0 load or whatever K minimum to the maximum value of K in no time, so there is no chance for the reaction to occur. And that is the reason that why such kind of waveform are actually most detrimental. Often when we perform the test in the laboratory condition, we choose a triangular or a sinusoidal waveform, just to make sure that we are estimating the properties in the worst possible scenario.

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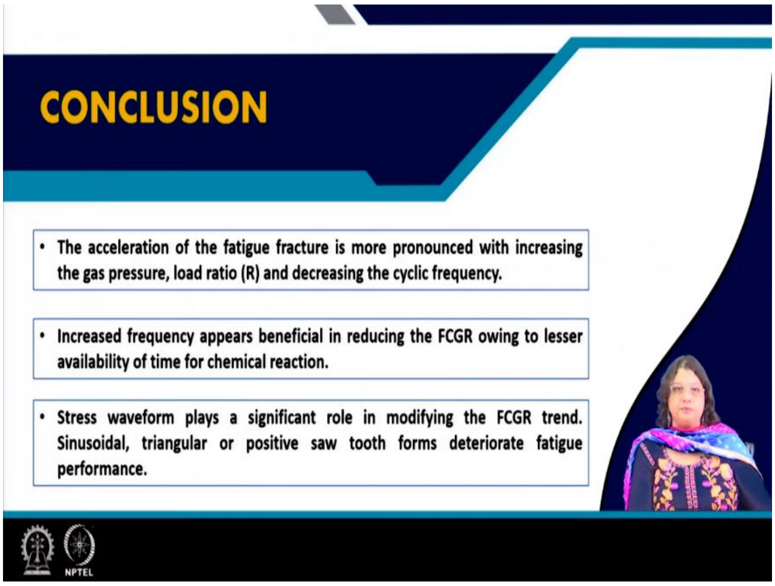

So, based on this, let us conclude this lecture as the deterioration of fatigue properties in engineering materials can be caused by an external corrosive medium, which could be hydrogen embrittlement or stress corrosion cracking or liquid metal emblement. In whatever way this corrosive medium is present, as solid, liquid, or gas that can lead to a significant change in the fatigue crack initiation as well as the crack growth behaviour.

Stress corrosion fatigue occurs when the applied maximum value of stress intensity factor exceeds the limiting K_I for the stress corrosion cracking. And the combination of true corrosion fatigue and stress corrosion fatigue results to the mixed corrosion behaviour. In fact, corrosion fatigue superposition model takes into account both the true corrosion fatigue crack growth rate as well as the stress corrosion fatigue crack growth rate, and by that method it actually accounts for the total fatigue crack growth rate in presence of corrosive atmosphere as well as cyclic loading. Adsorption of the embrittling species at sleep step leads to formation of crack in the aggressive environment.

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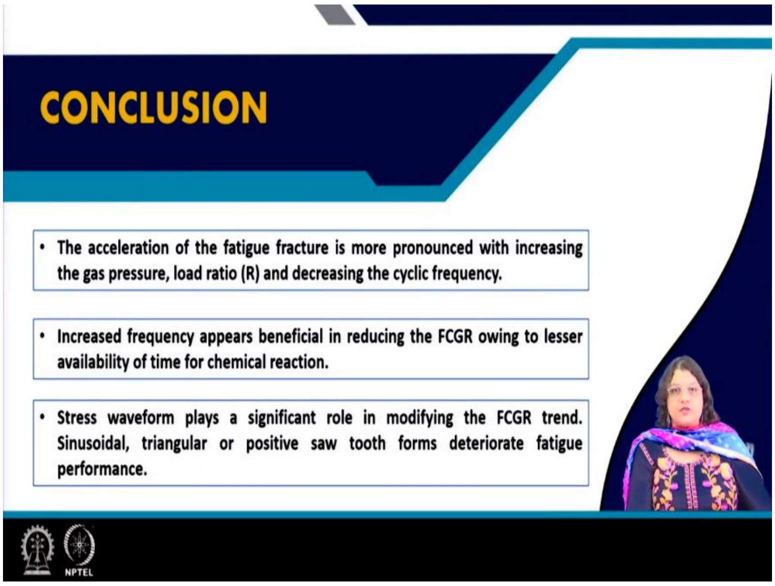

The acceleration of the fatigue fracture is more pronounced with increasing gas pressure, load ratio as well as the cyclic frequency, we have seen that how increased frequency is acting beneficial in reducing the fatigue crack growth rate in presence of a corrosive atmosphere. And this is particularly because of lesser availability of time for the corrosion reaction to occur.

Stress waveform also plays a dominant role in modifying the fatigue crack growth rate, and we have seen that sinusoidal or triangular or positive Sawtooth forms, which are having some slope over which the stress is being increased that involves more amount of time for the corrosion reaction to occur, and that leads to deterioration of the fatigue performance.

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So, following are the references which are used for this lecture. Thank you very much.