Fracture, Fatigue and Failure of Materials
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Lecture 45
Fatigue Crack Propagation (Contd.)

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Hello everyone, we are at the 45th lecture of this course Fracture, Fatigue and Failure of Materials and we have come towards the end of the second module that is on fatigue and in this lecture also we will be continuing on the fatigue crack propagation.

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But the particular topics that will be covered for this lecture are the following we will be talking about the fatigue crack propagation particularly in Regime 1 and there, we will also look into the influence of the different factors, different parameters such as the R-ratio or the mean value of the stress intensity factor range and so, on.

We will be also looking at the effect of crack closure and the influence of environment on the fatigue crack propagation behavior particularly in this regime and then we will be also discussing about the concept of internal crack.

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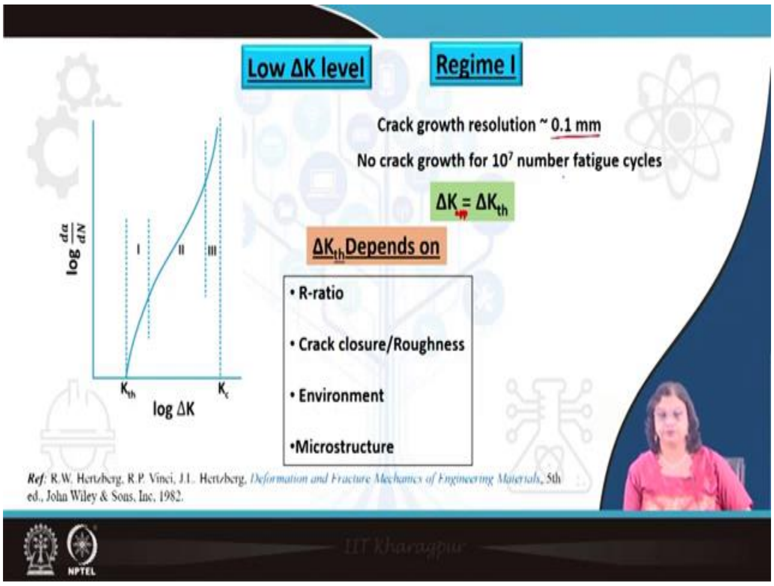

So, to begin with, we have already introduced the concept of ΔK_{th} or that is the threshold stress intensity factor range that is required for the onset of the growth of the crack. So, even if a crack is existing in a material, we need a certain value of ΔK to be applied such that the crack can start growing. So, let us say we use some instrument to resolve the crack and let us say the resolution of that instrument is 0.1 mm.

So, we can only figure out if the crack has attended a length of around 0.1 mm through this some kind of microscope or any other device for that matter. So, with such resolution, we can say that if there is no crack growth for 10^7 number of cycles, then we can consider that particular value as the one, at which no crack growth is occurring. So, that is the threshold value. So, the ΔK applied at such condition can be termed as ΔK_{th} or the threshold value of the stress intensity factor rate that is the beginning value.

Now, this ΔK_{th} of course, is not a constant value and we can change it with some circumstances and again, we are always finding the ways to control the different properties, so, that we can engineer the properties and we can achieve different kinds of performances based on the service requirement.

So, the same goes for ΔK_{th} also and this particular parameter actually depends on several factors such as the R-ratio or the ratio of the minimum stress intensity factor to the maximum stress intensity factor or for that matter the mean value, the average value of stress intensity factor is also very much important to control the value of ΔK_{th} we can either enhance or reduce the value of the threshold stress intensity factor range at which this onset of the crack growth can begin.

The second most important factor is the crack closure, if there is a crack or a notch or a defect, but there is some other activities, which is assisting in closing the crack, this could be like roughness induced closure as well, then that can act as a hindrance to the growth of the crack and that can delay the process of the crack growth and eventually, that can lead to an enhancement in the ΔK_{th} value.

Similarly, environment also plays a big role in influencing the ΔK_{th} value and particularly, there are certain environments which can delay the growth of the crack and which can enhance the value of the ΔK_{th}. So, if the value of ΔK_{th} increases that means, we need to apply more and more stress intensity factor range to start the growth of the crack. So, that could be favorable in some circumstances, when we know that enhancing ΔK_{th} can actually lead to enhancement in the overall life of the component that depends from situation to situation.

And of course, microstructure is the one which controls most of the mechanical properties and in this case also microstructure plays a lead role in controlling the threshold value of the ΔK. But we will see that how in this case the influence of microstructure is different from the regular strength in which the microstructure controls the other properties such as strength and ductility and toughness that we have seen so far.

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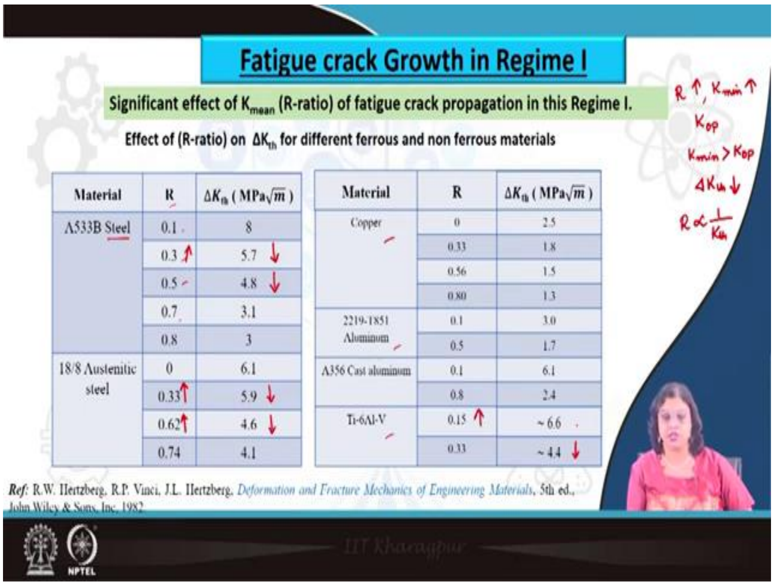

Now, let us see what do we mean by the effect of mean stress intensity factor on the fatigue crack propagation in Regime 1, actually what happens that in case this R-ratio increases, so, if the R value increases, that means, we actually have enhancement in the value of K minimum.

The minimum value of the stress intensity factor actually increases and in some cases in case there is a closure and there is some amount of stress intensity factor that is required for opening the crack for further growth, in such cases, if we are applying higher and higher minimum K value, such that this K_{min} exceed the $K_{opening}$ stress intensity factor, then in that case actually the effective stress will be also influenced and in that case the ΔK_{th} will reduce.

So, that means that if the minimum value of K is being increased such that it is exceeding the opening value of K in case of there is a crack closing activity is already there. So, in such case this will act as a beneficial move so, that the crack can grow at a much easier way, which means, of course, that we will need to supply or apply lower value of ΔK_{th} or eventually ΔK_{th} will reduce. So, overall we can see that R and ΔK_{th} are inversely related.

So, this is an empirical way of comparing R and ΔK_{th} and we can see such influence of R ratio on the ΔK_{th} for different ferrous and non ferrous materials such as here we can see for the case of this particular steel as we are increasing the R value from 0.1, 0.3, 0.5 and 0.7 you can see for every steps for every enhancement in the R value, there is a reduction in the ΔK_{th} from 8 to 5.7 in case we are increasing the R from 0.1 to 0.3.

Similarly, from 0.3 to 0.5 also there is a reduction in ΔK_{th} and so on and this is not only for this particular steel, but the regular 18/8 Austenitic steel also we can see that there is a reduction in the ΔK_{th} every time we are applying a higher value of R, or K_{min} / K_{max} and this is valid for even the non-ferrous alloy such as in copper, aluminium, titanium alloy every for all the cases we can see that enhancement in R leads to a reduction in ΔK_{th} value.

But this extent of reduction may vary from materials to materials and even for the same materials depending on the microstructure and other factors there can have some influence so, we still need to figure out the exact relation for any particular specific material if we are thinking of using that for some particular application, but overall we can so, far say that ΔK_{th} and R inversely related.

So, that we prefer to use lower value of R such that the ΔK_{th} is getting higher and higher value and which means that the onset of the crack growth will be delayed and that may lead to an overall enhancement in the fatigue life or fatigue performance of the material.

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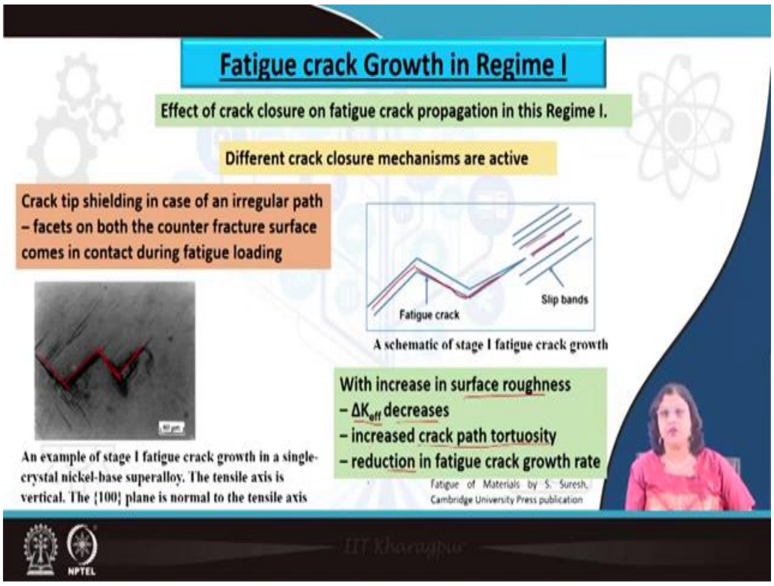

Now, let us see how the effect of crack closure is active for the case of Regime 1, actually what happens here is because of the torturous nature of the crack path, often we see that there is a crack branching or there is a deviation in the crack growth direction and that is one of the way by which the crack closing activity is valid for this Regime 1, there are other different crack closure mechanisms are active and particularly we have the crack tip shielding effect.

So, in this case what happens is, as I mentioned that there could be an irregular path and that leads to that the facets the both the crack faces actually come in contact with each other during the fatigue loading, because we are continuously applying cyclic loading, so, higher tension and lower tension value of load and that may lead to the crack faces to come in contact and if they are coming in contact that actually acts in rubbing it off.

So, basically there is a frictional force also being applicable and overall that acts as a hindrance to the growth of the crack, certainly, this is not a crack opening mode that gets activated in such cases, and obviously, that leads to a reduction in the the process of the growth of the crack or the ΔK_{th} value may increase in such cases.

So, this is what you can see the crack path is quite irregular and that depends on the slip bands in whichever way these are available. This is an example shown here for a superalloy, where you can see that how the crack path is very, very torturous, and they have a zigzag kind of motion and obviously, that means that more and more energy will be required for the crack to overcome the barrier and to move to a completely different direction at every step, and certainly, that will require for higher and higher energy and energy in this case is reflected as the ΔK value.

So, with increasing the surface roughness, what we can see is that the ΔK effective decreases and that leads to an enhancement in the crack path tortuosity and reduction in the fatigue crack growth rate.

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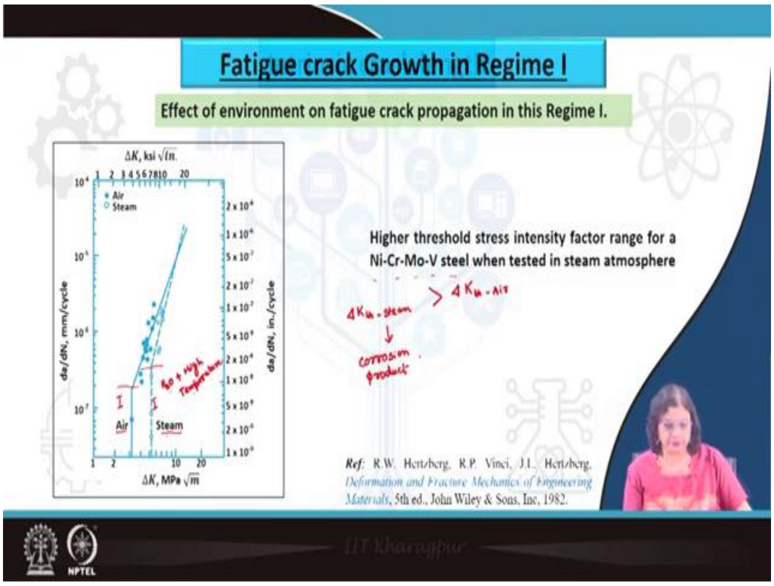

So, that was one of the factors, the other thing that is of interest here is the effect of environment. Now, environment we have seen earlier also that how fatigue could be influenced by the different environment or different atmosphere for that matter. So, here for example, we will show one experimental results for the failure of steel in different environment, one is in air and the other is in steam.

So, when we are talking about steam, it suddenly means that it has moisture in it and it has higher temperature also. So, both the things are acting simultaneously, we have the H_2O plus high temperature and we have seen such kind of cases for the environment assisted cracking that how higher temperature or the presence of moisture can influence the growth of the crack or for that matter the fracture behavior.

So, in this case, since, we along with that along with the moisture and the high temperature, we are also applying cyclic loading. So, that is bound to influence the crack growth mechanism for sure. So, let us see how it does in this da / dN versus ΔK curve, if we are focusing only on Regime 1 itself.

So, Regime 1 starts from the base up to this part here. And comparing these two, we can actually say, that the ΔK_{th} for steam is actually higher or greater value than ΔK_{th} for air and this is what is seen here. So, this is a nickel chromium moly vanadium steel and it has a higher threshold stress intensity factor range when it is tested in the steam atmosphere.

Now, it is very interesting to note here that the presence of both this moisture and the temperature are the one which actually controls the behavior in this case. So, what happens is that, in case of the presence of steam, this moisture and temperature helps in corroding the surface.

So, the temperature is nothing but a source of energy that influences the corrosion behavior or the chemical reaction that is happening is getting aggravated by the temperature moisture also acts in corroding the surface for the steel and as a result of this corrosion, this corrosion products that are forming that is acting as a barrier to the growth of the crack this corrosion products are forming at this wake of the crack front.

So, this again leads to the shielding process. So, this also comes in contact with the crack faces and that acts as a method of closing the crack and that leads to an enhancement in the ΔK_{th} requirement. So, that means that higher and higher values of ΔK needs to be provided to overcome this hindrance that are coming from the corrosive atmosphere or from the corrosion product.

So, particularly the corrosion products that are forming in presence of steam and that are falling of the crack is leading to the delay in the onset of the crack growth and that can further lead to an enhancement in the requirement for ΔK_{th}.

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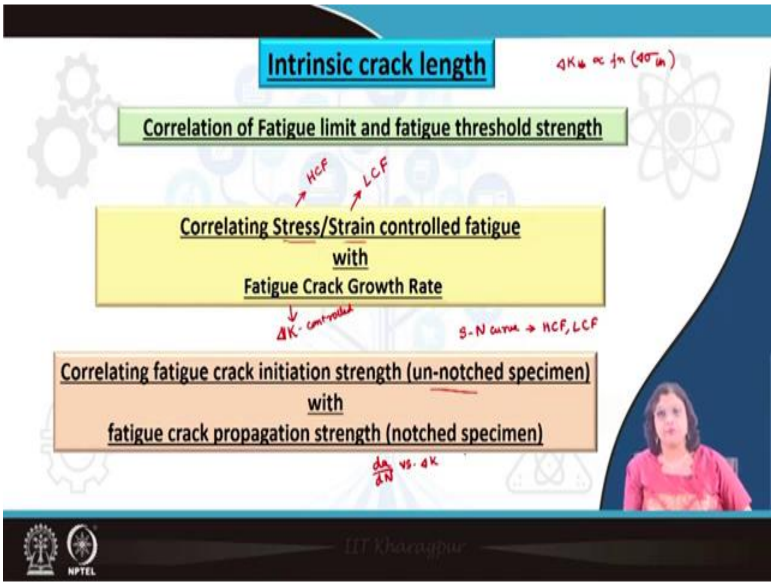

So, far we have seen how the external parameters can be controlled to get the value of the ΔK_{th} or the threshold value for the onset of the crack growth and let us see how physically this can be related to the other kind of fatigue that we have talked so far.

So, basically what we are talking about is correlating the fatigue limit with the fatigue threshold strength. So, when we are talking about ΔK_{th}, we know that this ΔK_{th} is related to the $\Delta\sigma_{th}$ or the threshold stress range. And we have so, far also seen the importance of fatigue strength or the fatigue limit or the endurance limit from the high cycle and the low cycle fatigue that we have discussed so far.

So, there should be a relation between this fatigue strength as well as the fatigue threshold stress range. So, now is our target to somehow correlate these 2 different kinds of fatigue behavior. So, basically what we want to figure out is the relation between the stress or the strain control fatigue that we are seeing in one case, we are getting the high cycle fatigue or the low cycle fatigue typically the stress or the strain control fatigue respectively and in the fatigue crack growth rate, we use the notch specimen in this case we use the ΔK controlled.

And so, we need to figure out that how the strength if you are talking about the fatigue strength that we are getting from the un-notched specimen based on the S-N curve or based on the HCF and LCF results versus the da / dN versus ΔK curve. So, how these 2 can be correlated.

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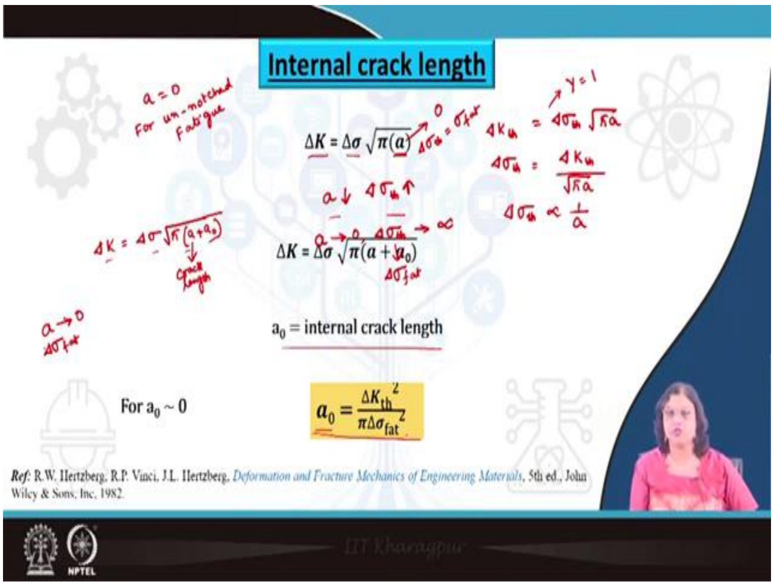

Now, so, far, we have seen that these are the external ways by which we can control the ΔK_{th} values. So, now, let us focus more on what actually is the physical significance of ΔK_{th} and how is that related to other kind of strength, other kinds of fatigue strength and to understand that, we need to look into it in more details in the sense that overall, we know that the stress intensity factor range is related to the stress range as well as the a value.

So, at the point of threshold, we can say that this ΔK_{th} is given by $\Delta\sigma_{th} \sqrt{\pi a}$ or in other words, we can say that this $\Delta\sigma_{th}$ is related to $\Delta K_{th} / \sqrt{\pi a}$, we have considered the value of Y here as 1, let us say this is an central crack that we are talking about, and this is what we are getting.

So, eventually what it means is that the $\Delta\sigma_{th}$ is inversely proportional to a. So, that means that as a is decreasing, we are expecting higher values of $\Delta\sigma_{th}$. Now, one thing to clarify here is that, when we are talking about $\Delta\sigma_{th}$ or ΔK_{th} we already assumed that there is a crack existing there, we are talking about the crack growth rate the threshold for the onset of the crack growth.

So, obviously, there is a crack and there is a finite value of a here. Now, if we want to correlate that with the un-notched fatigue data, for the HCF, LCF for the S-N curve, where we have considered that there is no dominant notch or crack present of course, there could be internal defect, but there is no dominant notch or crack of dimension a is present there.

So, that means that for the stress or strain control fatigue to be active for the un-notched specimen, we need to have a equals to 0, for un-notched fatigue. Now, this is a little bit alarming for us. So, that means when a equals to 0. So, when a is equivalent to 0, at that point $\Delta\sigma_{th}$ is nothing but $\Delta\sigma_{fat}$ or the fatigue limit or the endurance limit that we have talked so far that is valid for the condition when there is no crack.

Now, if such is the case as we can see here that a and $\Delta\sigma_{th}$ are inversely related so, that means that when a tends to 0, $\Delta\sigma_{th}$ actually tends to achieve an infinite value. Now, that does not make sense in the practical situation when we know that $\Delta\sigma_{th}$ cannot achieve such a high value and this essentially means that this is nothing but $\Delta\sigma_{fat}$ of course, this is not making any sense that means that we might have overlooked something when we are talking about a or the crack length.

So, for that part, the concept of intrinsic crack length has come into the picture and we have used a relation like this, where ΔK is $\Delta\sigma \sqrt{\pi(a + a_0)}$ I have rewritten the relation because this one is not visible here. So, this a_0 is actually the internal crack length here.

So, we consider that there is an already existing internal crack. So, when we are talking about the defect, internal defect, this is what we actually meant. So, let us consider this as a finite thing. And so, basically the K and σ are related by not only a but the summation of a which is the notch defect and this is the internal crack defect.

So, this is the crack length and a_0 is the internal crack length. So, if such is the case, then the point when a equals to 0 at that point, we know that when a tends to 0 then what we have is $\Delta\sigma_{fat}$ and if we do that, we will see that how a_0 is related to ΔK_{th} and $\Delta\sigma_{fat}$ So, you can simply put the value of a here as 0 and we can get a relation something like this, which signifies the importance of a_0 the internal crack and the actual value of this.

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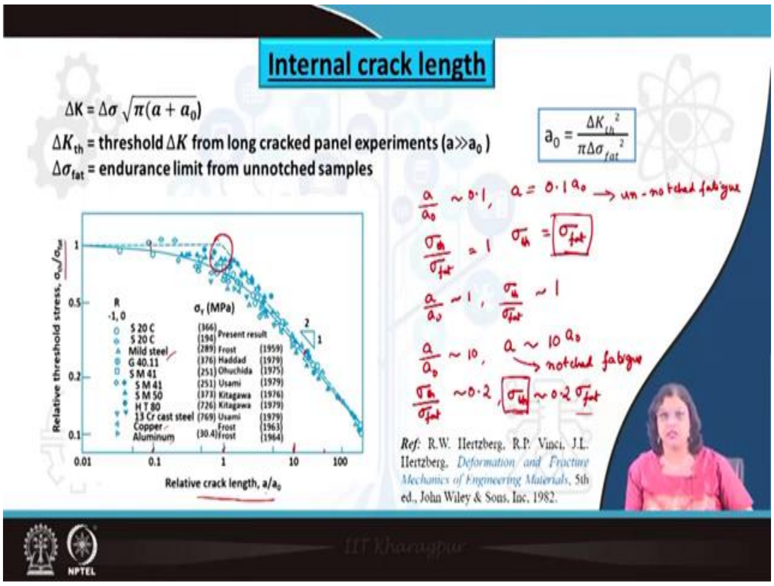

So, this intrinsic crack length has been defined so, far and now, we also needed to look into the practical significance of this and this can be only validated through some experimental results, which has been shown here for different kinds of materials such as different varieties of steel as well as non-ferrous materials such as copper and aluminium these are studied by different groups of scientists all across the world to get the different values.

So, what this graph shows here is very interestingly it shows along the x-axis is the relative crack length that is a / a_0 and on the y axis, we have this $\sigma_{th} / \sigma_{fat}$ or the the threshold strength versus the fatigue strength.

So, what we see is that at a very low value of this a / a_0. So, let us say when a / a_0 is 0.1. At that point, what we have the external crack that means, whatever we consider as crack or notch, that is equivalent to 0.1 a_0. So, that means that it is a very very small external crack that we are talking about of course, the internal crack anyway has a very small dimension and 0.1 times that is certainly the crack length, which is almost ignorable or negligible for that matter, what we are getting is the value of $\sigma_{th} / \sigma_{fat}$ equals to 1.

So, that means, basically for such a small crack, which is like a scratch marks or something like that, which is almost like negligible for that whatever fatigue strength that we are getting is actually σ_{fat} and if we want to figure out the threshold value actually this threshold value is nothing but the fatigue strength there because we are talking about the un-notched fatigue in this case, as if there is no notch at all because the a value is very very small and this continues up to we have the condition when a equals to a_0.

So, up to the condition of a / a_0 equivalent to 1 that means a equals to a_0 more or less this sigma by $\sigma_{th} / \sigma_{fat}$ is equivalent to 1 of course, there are some discrepancies in the numbers particularly from the experimental results, but more or less it reaches very close value to sigma threshold and sigma fatigue.

Now, when we are increasing the value of a, such that a / a_0 is let us say 10. So, that means a is equivalent to 10 times a_0, of course, a is not ignorable anymore. So, in that case, we are talking about the notched fatigue and in this case, we are getting the value of $\sigma_{th} / \sigma_{fat}$ that is equivalent to say here is equivalent to 0.2 or that means that σ_{th} is 0.2 times the σ_{fat} of course, the threshold value of stress range that is required for the commencement of the crack growth is much much lesser than the fatigue strength for the un-notched fatigue.

So, for the notched fatigue part the σ_{th} is much less than the the fatigue strength and more is the value of a in comparison to the a_0, we can see that lesser and lesser is the value of σ_{th} so, the value of σ_{th} with respect to σ_{fat} keeps on decreasing, if we are having higher and higher crack length, obviously, physically this means that longer the crack lesser stress will be required for the onset of the growth of the crack.

So, let me also write it down here that when a by a_0 is very, very small. So, this represents more or less like a condition of un-notched fatigue and for that σ_{th} does not make any sense. So, basically what we are talking of in that case is σ_{fat} which is of interest and in case of notched 1, it is the σ_{th} that is of interest and that obviously is much lesser than the fatigue strength of the material.

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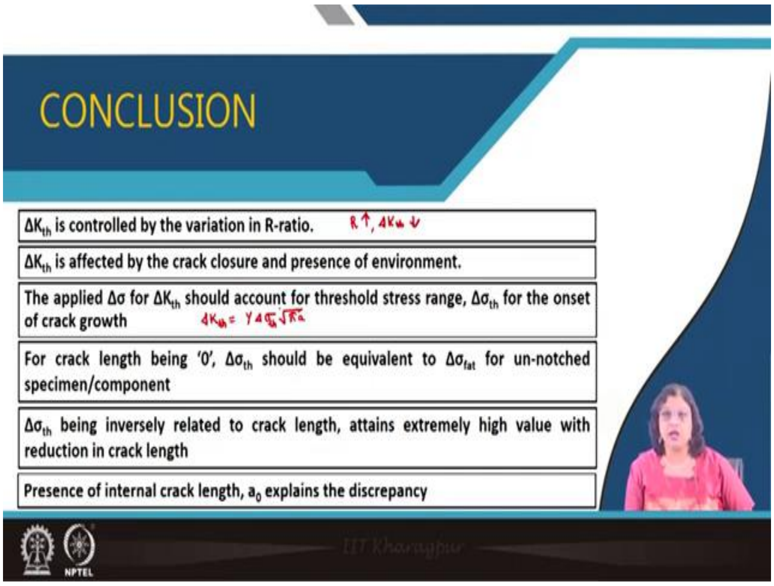

So, let us conclude this lecture with the following points that the ΔK_{th} or the threshold value of the stress intensity factor range is controlled by several factors the prime one being R-ratio or the ratio of the minimum value of K by the maximum value of K and we have seen that an inverse relation is being followed, which means that R increases and ΔK_{th} decreases.

So, we should be careful while employing this in the actual service condition that we need to maintain the lower and lower values of R such that the ΔK_{th} value can be enhanced. ΔK_{th} is affected by the crack closure as well and we have seen that how the the torturous path of the crack acts in closing or the crack tip shielding mechanism and that leads to higher and higher value of ΔK_{th} to be required for the growth of the crack.

And similarly, the influence of environment has also been seen particularly an example of air and steam has been shown, where we have seen that in case of the steam because of the presence of moisture and higher temperature, the corrosion product that are forming in the crack wake helps in closing the crack and that leads to delay in the onset of the growth of the crack.

The applied Δσ for ΔK_{th} actually should account for the threshold stress range for the onset of the crack and growth. So, we have seen that the typical relation between ΔK and Δσ which is given by Y Δσ √πa. So, in case of the threshold value of ΔK that should represent the threshold value of the sigma that is required for the commencement of the growth of the crack.

In case the crack length is 0, which is nothing but the un-notched fatigue condition. So, in that case, $\Delta\sigma_{th}$ is actually representing sigma fatigue or fatigue strength but at the same time, we have also seen the $\Delta\sigma_{th}$ being inversely related to a or the crack length, if the crack length reduces to 0, so, that is supposed to give extremely high value of $\Delta\sigma_{th}$, which is not practically feasible and for such case to avoid this discrepancy the concept of internal crack length a_0 is being used, so, that we can consider the presence of the internal defects that can take part in the fatigue failure of materials.

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Following are references that are used for this lecture. Thank you very much.