Fracture, Fatigue and Failure of Materials
Professor Indrani Sen
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Kharagpur
Lecture 44
Fatigue Crack Propagation (Contd.)

Hello everyone. So, we are at the 44th lecture of this course Fracture Fatigue and Failure of Materials. And in this lecture also we will be talking some more about the Fatigue Crack Propagation, particularly, we will continue from where we left.

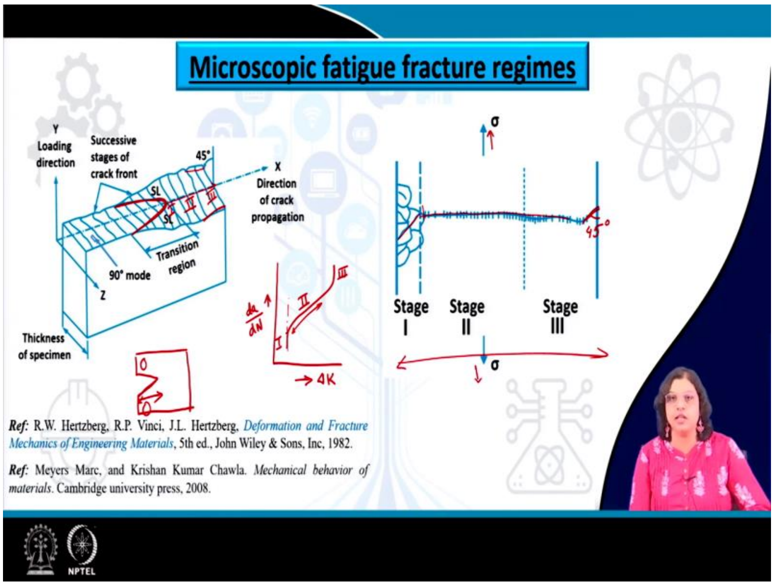
(Refer Slide Time: 00:43)

Concepts Covered

- Fatigue Crack Propagation in Regime II - Fatigue Striations
- Fatigue Crack Propagation in Regime I
- Fatigue Threshold Stress Intensity Factor Range

So, basically, we will be talking more about the Fatigue Crack Propagation in regime II, and we will be talking about the fractographic behaviour or particular features that are seen for the case of regime II crack growth. On the other hand, the importance of Fatigue Crack growth for regime I will also be discussed in this lecture. And particularly the Threshold Stress Intensity Factor Range for the onset of the growth of the fatigue crack will be elaborated.

(Refer Slide Time: 01:14)



Microscopic fatigue fracture regimes

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

Ref: Meyers Marc, and Krishan Kumar Chawla. *Mechanical behavior of materials*. Cambridge university press, 2008.

So, let us see what are the different regimes that we have already seen in the da/dN versus ΔK curve, which looks something like this, we have the crack growth rate on the y-axis and we have ΔK on the x-axis both this y and x-axis are in the logarithmic scale and we can see that this curve can be divided into 3 regimes.

The first one signifies the onset for the growth of the crack the second one signifies the steady state growth where we have seen that how the Paris law is being used to describe the growth rate here and then we have the regime III for the unstable fracture materializes. Now, if we look into the fracture surface, we can also distinguish between these 3 regimes which will have some different features.

For example, we can see that at the at the very first stage like this is the initial machine notch that is present in a CT specimen, if you remember the CT specimen that we typically use for doing the fracture toughness test or the Fatigue Crack Growth test, it looks something like this and we have the machine notch here and this exactly is this machine notch part.

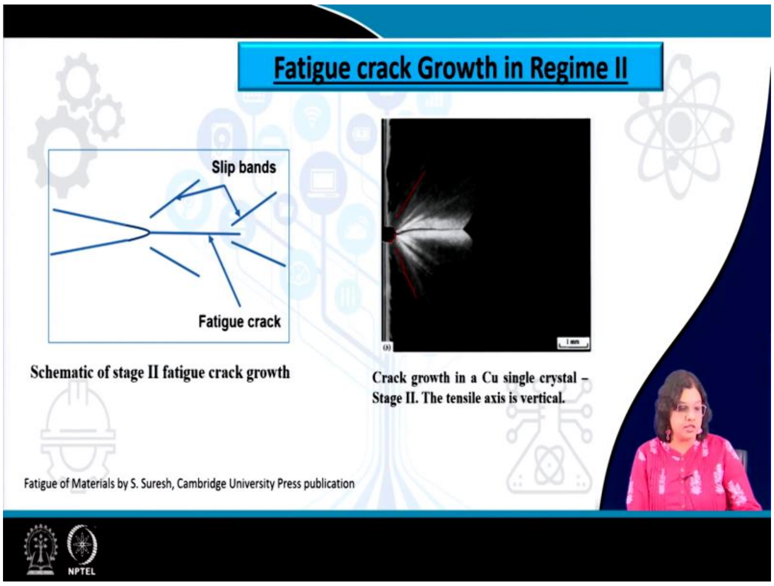
So, that means that all the crack growth things happen at this portion here, and initially we have regime I followed by regime II which covers the most of the span and then we have regime III at the end where actually the plane stress condition will be followed and that leads to deviation to 45° leading to the formation of Shear lip at the end depending on the material depending on the thickness and the other parameters we can control or engineer this regime III or the Shear lip formation fine.

Now, if we look into the microstructural features are how it looks like you can see that the initial growth of the crack is a very small section of the entire regime. So, the overall stages and then after that quite some part is being maintained under typically under plane strain condition where we see that the crack growth is actually 90° to the loading direction the loading direction is in this case where we are applying Tensile loading.

And we can see that the crack more or less goes in a steady state fashion in a straight manner with respect to the loading direction, and near to the end at the stage III we have this 45° deviation as I explained forming the Shear lip. Now, if we look into this mid-section here that is stage II under the microscope.

We will also be able to identify some typical features which signify that the component has undergone fatigue loading or repeated loading or cyclic loading. So, these are the beach marks or the clamshells markings or the ratchets that we have discussed in the very first initial lectures about the different kinds of fracture surface that we can see.

(Refer Slide Time: 04:35)



Fatigue crack Growth in Regime II

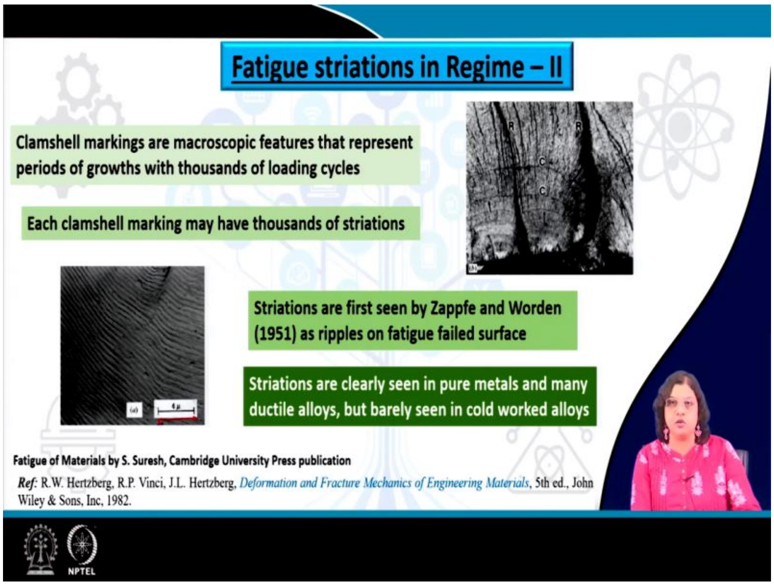
Schematic of stage II fatigue crack growth

Crack growth in a Cu single crystal – Stage II. The tensile axis is vertical.

Fatigue of Materials by S. Suresh, Cambridge University Press publication

And that is particularly related to the growth of the crack in this regime which is affected by the slip bands present in the particularly in the ductile kind of material. So, you can see here, the left one is a schematic one and the right one is the actual image where you can see that this is the machined notch part here and how the crack is growing. And then there are the sleep bands and there are two opposite directions very well distinctly visible here.

(Refer Slide Time: 05:07)



Fatigue striations in Regime – II

Clamshell markings are macroscopic features that represent periods of growths with thousands of loading cycles

Each clamshell marking may have thousands of striations

Striations are first seen by Zappfe and Worden (1951) as ripples on fatigue failed surface

Striations are clearly seen in pure metals and many ductile alloys, but barely seen in cold worked alloys

Fatigue of Materials by S. Suresh, Cambridge University Press publication

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

Now, further if we are looking just the fracture surface with the very low magnification microscope 1, then we can see the clamshell markings. So, these are the macroscopic features and just by looking on those kinds of features like clamshell markings or beach marks, or ratchets, which looks like steps, we can figure out that the component has undergone repeated loading, and actually, if we are considering even at a higher depth of focus.

So, that means, that if we are looking at a higher magnification, we should be able to understand that each of these clamshell markings consist of actually 1000s and 10s of 1000s of striations shell marking, and striations were first observed by Zappfe and Worden in 1951, so, more than 50 years back and these are actually seen as ripples on the fatigue filled surface. So, by ripples, I actually meant this.

So, this is how the striations look like and you can see that the micron marker here of this length is 4 micrometres. So, that means that the striations mostly are in this hub microscopic level or of the order of around of a couple of micrometres at the most. And most of the cases of course, the sizes can vary, but this is how it looks like on the other hand the clamshells markings or the beach marks they are the macroscopic features, which we can see at very low magnification or sometimes even with our eyes itself.

Now, these striations are actually very distinctly seen in case of pure metals and some ductile allies, but not always be if the alloy has been cold work then the striations are not that much visible. So, not all the materials will show this kind of features distinctly, but striation is certainly a very important feature to identify whether the component has undergone any repeated loading or not.

(Refer Slide Time: 07:16)

Fatigue striations in Regime – II

Striations are more clearly observed on flat surfaces with plane strain condition

Each striation represents an increment; advancement of crack front per loading cycle

The extent of advancement varies with the loading range

Fatigue striations are evidence that fatigue damages are accumulated over each cycle

The striation features get damaged with time owing to oxidation

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

So, striations are particularly observed in case there is a flat surface and when the plane strain condition has been applied, as I mentioned, like regime II is the one where the crack growth is following 90° to the loading condition which is nothing but a plane strain condition being followed in such case only striations will be visible.

So, that is why it is particularly seen for the regime II, an each striation, in fact signifies an increment or advancement of crack front per loading cycle. So, that is the reason the striations are so, thinner in dimension, because it signifies the growth of the crack as if the crack is growing in steps. So, each of this striation actually signifies the crack growth per loading cycle.

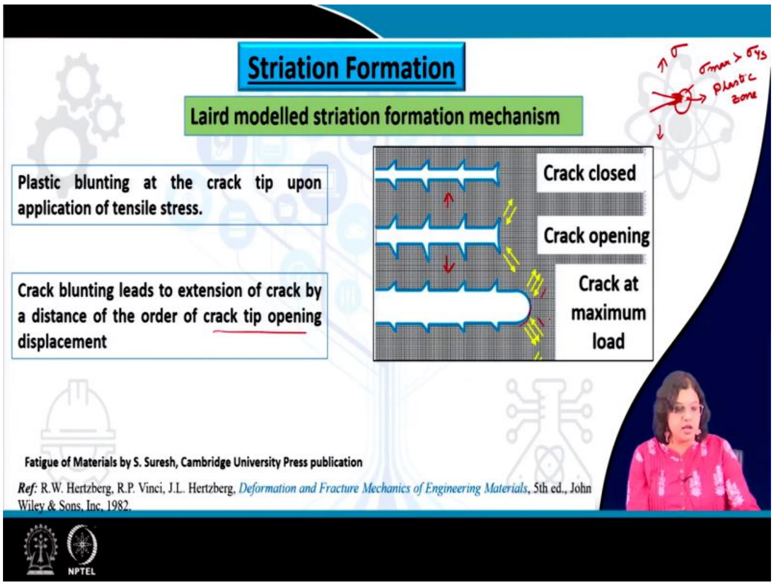
The extent of advancement however, varies with the loading range also from material to material. So, what should be the striation width that depends on several other factors. Fatigue extractions are evidence that fatigue damages are accumulated over each cycle. So, for every of the cycle these striations are forming and as we are progressing, the number of striations are also increasing.

So, number of striations the width of the striations, the position of striations all these are signature features which help us to analyse the fatigue deformation behaviour in a more elaborate way. So, striation features however gets damaged with time due to the Oxidation. So, striations are actually formed because of the extension of the crack.

So, extension of the crack is nothing but formation of a free surface and free surface we know are very much high in energy levels. So, they are very much prone to get oxidized. So, that said it is very, very important for the fatigue failed samples to be preserved very carefully in vacuum so, that it is not supposed to get oxidized because once it does or once we touch the fracture surface, then all the features can get lost, and we cannot understand.

So, that is another very important point that we should consider particularly because the focus of this course is to also implement the understanding about fracture and fatigue to failure analysis. So, if we want to do failure analysis properly, then we need to have a preserved fractured surface or fatigued surface so, that we can understand all those features distinctly and we can do the perform the analysis in a greater details.

(Refer Slide Time: 09:58)



Striation Formation

Laird modelled striation formation mechanism

Plastic blunting at the crack tip upon application of tensile stress.

Crack blunting leads to extension of crack by a distance of the order of crack tip opening displacement

Fatigue of Materials by S. Suresh, Cambridge University Press publication

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc. 1982.

So, how these striations are formed? This is the next question that needs to be answered. And for that there are several models actually but the one which is most frequently being considered or referred is the one described by Laird. So, it this kind of this module is particularly related to the crack tip blunting and then closing and reopening and some sort of things like that. So, let us see how this actually happens.

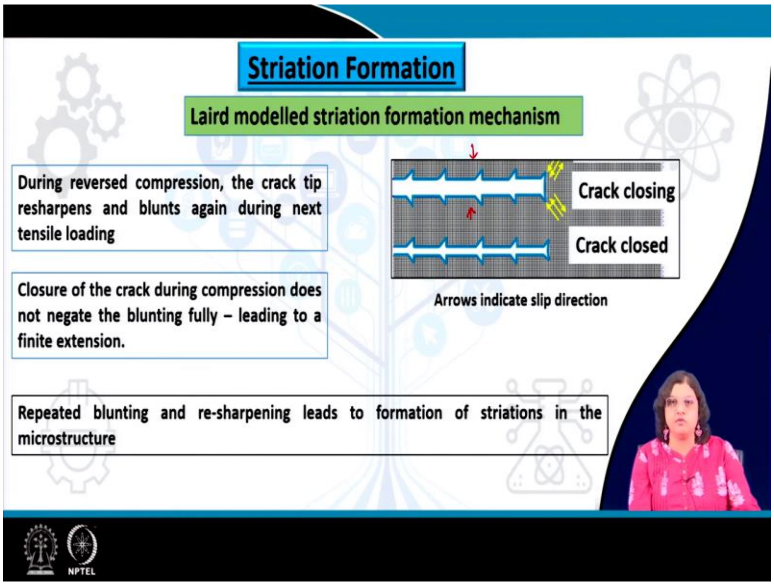
So, initially when we are applying tensile stress to a notched component, there is a stress concentration at the tip of the crack we know about this fact already that when we have a notch or a crack and we are applying tensile stress to it at the tip of the notch definitely there is the higher stress values there.

So, stress maximization happens based on the stress concentration factor and once the σ_{max} exceeds the yield strength of the material particularly for ductile material, then there will be plastic deformation or permanent deformation, and this will lead us to a plastic zone and not only that, this will lead us to a blunting of the crack.

So, that means that the crack tip is not sharp anymore, but this blunt crack tip actually signifies the growth of the crack as well because if we are can extrapolate this blunt tip, we will see that this will meet at the centre of this plastic zone site, so that leads to an extension of the crack. So, this crack blunting certainly leads to the extension of the crack as discussed, but, we can also determine this crack tip opening displacement from there.

So, this is how initially the crack was closed and then as we are applying the tensile loading to it, then the crack starts opening and then it is getting this kind of bland tips there. The arrows here signifies the slip lines.

(Refer Slide Time: 12:16)



Striation Formation

Laird modelled striation formation mechanism

During reversed compression, the crack tip resharpens and blunts again during next tensile loading

Closure of the crack during compression does not negate the blunting fully – leading to a finite extension.

Arrows indicate slip direction

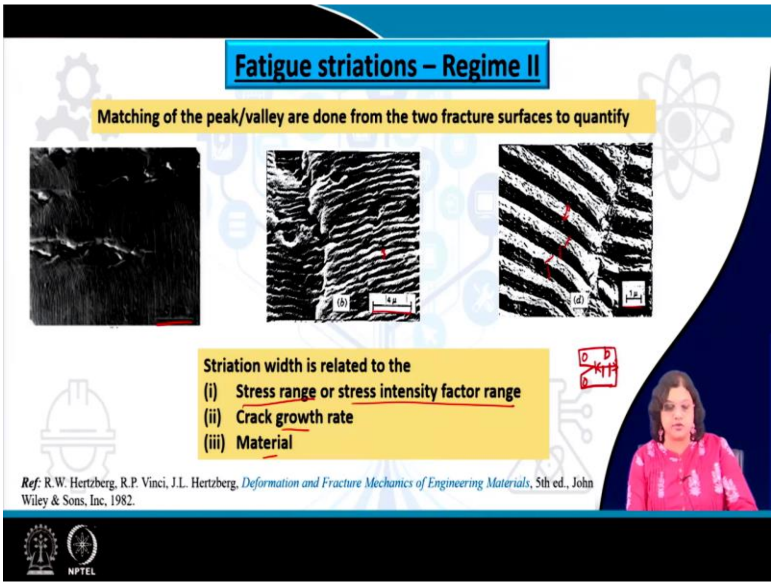
Repeated blunting and re-sharpening leads to formation of striations in the microstructure

Now, this is one side like when we are applying the tensile stresses and furthermore, when we are applying the compression, the reverse compression stages, then the crack tip resharpens and then again it gets bland during the following tensile loading mode. So, this keeps on happening on every cycle. So, once it gets bland and then it gets a closed and then it gets resharpen again and again and for each of the steps actually each striations are forming.

And that leads to finally a finite extension at every step, this closure of the crack during compression and as well as the crack blunting and the extension because these are not of the equal magnitude. So, whatever closure is happening because of the compressive loading is not fully cancelling the extension that has happened during the tensile loading and finally, we are getting a finite growth of the crack however, smaller that may be.

But for each cycle, we are getting some expansion in the crack length or extension in the crack length and that is reflected by forming the striations because striations are this free surfaces which for me and that is seen as a different kind of features like we can understand that how this is happening in steps. So, this repeated blunting and resharpening are actually the reasons for the formation of striations and these are reflected as this stepwise growth.

(Refer Slide Time: 13:51)



Fatigue striations – Regime II

Matching of the peak/valley are done from the two fracture surfaces to quantify

Striation width is related to the
(i) Stress range or stress intensity factor range
(ii) Crack growth rate
(iii) Material

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

So, this fatigue striations now, if we look into this, you will see the first one image here shows that there is a micron marker of 5 micrometres this red colour here is 5 micrometres, and you can understand that this striation with are very, very small. In comparison, we have another one here, where same almost same kind of micro marker level is there, which is 4 micrometres.

And now, we see the striations with are much bigger compared to the previous image. And then there is another picture here, which shows striation, which is actually even bigger, when the micro marker is not same here, but the point is that we can have different kinds of structures with in even in the same material, of course, for different materials for different loading conditions.

We may have different kinds of striations and different width of striations, but not only that, even for the same component if we are looking at different sections of regime II, we can see that there are different widths of the striations for me. So, that is what is apparent here and we actually try to match the peak and the valley for the striations.

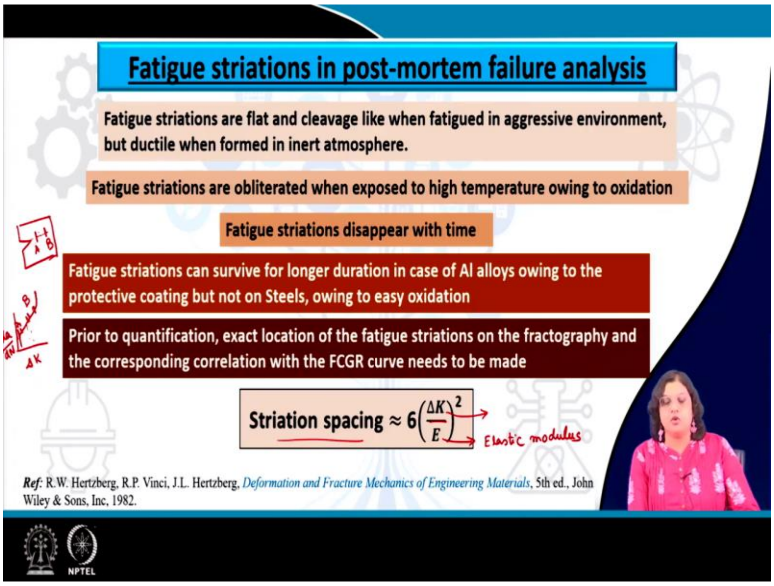
So, like this one here and that one there. So, we keep on matching this and measuring this from the counterpart of the fracture surface. So, the other fracture surface and we quantify this value. Now, this width of the striation is very, very important for our calculation and this video is related to several factors. The Prime important one is the stress range or the stress intensity factor range.

So, you know for an overall when we perform this test for a CT specimen. So, the total section to which the crack grows is this one this one here let us name this as small b, that was the ligament length that we have discussed earlier anyway. So, for this particular length, the value of the ΔK or Δσ in some cases also changes right as the crack length changes, then of course, Δσ value may change or if we are keeping the Δσ constant then ΔK may change and so on.

So, for each of these different values of Δσ or ΔK, the crack growth rate will also vary and as we have seen that striations are nothing but growth of the crack for each cycle. So, obviously, the width of the station will also change. So, that is how striations width is very much related to the stress range or the stress intensity factor range.

Now, if we are looking this under the microscope this section here versus that section may have different striations width, crack growth rate obviously, faster the crack growth rate different will be the striation width and material. Of course, different material will have different width of striation for any particular stress range if we are talking about.

(Refer Slide Time: 17:14)



Fatigue striations in post-mortem failure analysis

Fatigue striations are flat and cleavage like when fatigued in aggressive environment, but ductile when formed in inert atmosphere.

Fatigue striations are obliterated when exposed to high temperature owing to oxidation

Fatigue striations disappear with time

Fatigue striations can survive for longer duration in case of Al alloys owing to the protective coating but not on Steels, owing to easy oxidation

Prior to quantification, exact location of the fatigue striations on the fractography and the corresponding correlation with the FCGR curve needs to be made

Striation spacing $\approx 6\left(\frac{\Delta K}{E}\right)^2$ Elastic modulus

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

And particularly striation width is very, very important and not only the width, but other features of striations are very, very important for the Post-mortem failure analysis. So, let us see how it can be useful. Basically fatigue striations are the shape of this striations are very important to understand in case it is a flat one like a cleavage one, that actually signifies that fatigue has happened in presence of aggressive environment.

So, that could be because of the corrosion fatigue that may lead to such kind of flat features. But in case if it is done the fatigue testing has been done in inert atmosphere that may have some ductile features and so, by looking at the striations features itself, we can understand whether the component that has failed through fatigue loading.

Whether it has undergone the cyclic loading under an aggressive environment or maybe not so aggressive or an inert atmosphere. Now, this is also related to variation in the temperature. In fact, in presence of higher temperature because of the increased chances for oxidation, the fatigue situations are kind of getting erased or wiped off. So, it is not very well distinctly seen in case fatigue loading has happened in high temperature.

So, often particularly for example, in case we are doing the Post-mortem analysis of an air crashed component which has caught a fire that may be sufficient to remove this core striation features completely and then we would not be able to understand that whether the width of striation are distinct or not.

With time fatigue striation disappear and again this is particularly related to oxidation and as I mentioned, it is very very important to preserve the specimen in vacuum. So, that this kind of wiping off of the striations features should not happen. Fatigue striations can survive for longer duration in certain materials such as aluminium alloy, why?

Because it can lead to the formation of a protective coating that does not allow the oxidation or corrosion of the surface to happen. So, that acts as a protection for preserving the striation features. However, in case of steels because such kind of protective layer is not pretty and that may lead to easy oxidation and striation features can be wiped off quite easily. So, that means that quite a smaller duration of time.

So, that means that if we are using this concept for failure analysis, we can find out that whether the incident has happened much earlier or it has happened very recently based on the presence of striation as well. So, you can see that how just one small features can lead us to many important facts. Prior to quantification, we also need to know the exact location of the fatigue striations on the fracto graphs as well as on the FCGR curves.

So, that means, that da/dN curve as well as the specimen on the component as I explained that in case of the da/dN versus ΔK carve striations are seen for this regime II , but here also where exactly we are talking about that may lead to different values of ΔK. If it is at a position a. So, somewhere here versus position B that may have different values of ΔK and we actually need to correlate that.

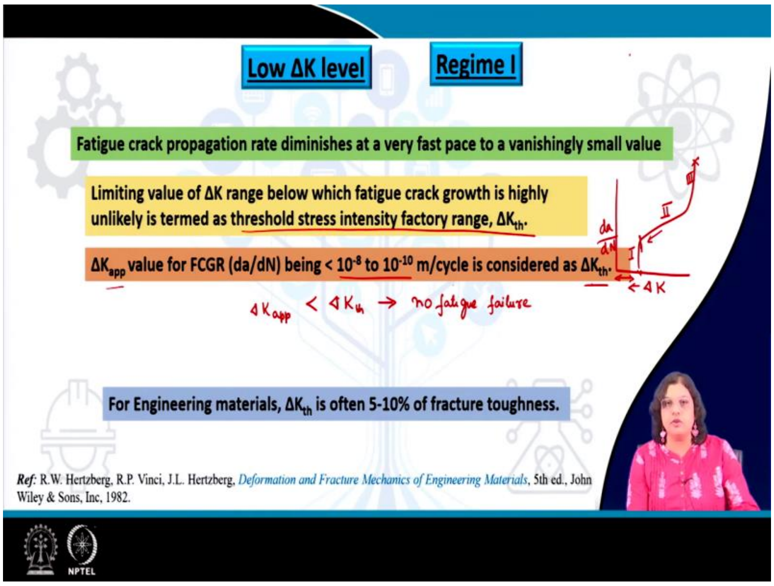
On the other hand, if we are talking about the component or the specimen there also we need to know that where exactly we are looking at the striations whether this is at position A or whether this is at position B again, we can correlate that with the exact value of the ΔK or more or less similar value of ΔK and we can correlate that with the striations width also.

So, let us see how we do that, actually the structural spacings now, this is an empirical formula, but very routinely used in failure analysis particularly to figure out what is the actual value of ΔK. Now, based on these striations spacing, we can see that that is equivalent to 6 times ΔK/E where E is the elastic modulus square.

So, based on this the post mortem analysis we can find out the ΔK at this point. And we can also see that how with the variation of ΔK at different locations such as A and B here or from the curve of the dN versus ΔK we can see how ΔK is very and how that is influencing this question with as well.

So, now that we have understood how regime II will be useful not only for estimating the life as per the Paris relation, but also from the fractography how we can determine the value of ΔK or what kind of environment the specimen has been fatigued what was the temperature etcectra. We also have seen that how the other part of this da/dN versus ΔK curve or the FCGR curve could be helpful in understanding the fatigue characteristics of the material.

(Refer Slide Time: 23:14)



Low ΔK level **Regime I**

Fatigue crack propagation rate diminishes at a very fast pace to a vanishingly small value

Limiting value of ΔK range below which fatigue crack growth is highly unlikely is termed as threshold stress intensity factory range, ΔK_{th}.

ΔK_{app} value for FCGR (da/dN) being < 10^{-8} to 10^{-10} m/cycle is considered as ΔK_{th}.

$\Delta K_{app} < \Delta K_{th} \rightarrow$ no fatigue failure

For Engineering materials, ΔK_{th} is often 5-10% of fracture toughness.

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

So, let us move on to the very first regime, which is the regime I, also known as the low ΔK level, because this is the starting point for the FCGR curve, but we are coming here later, because the we were initially talking about the part which was the most significant in fatigue crack growth behaviour.

Now, for the case of regime I, actually, what we are interested here is the fact that the fatigue crack propagation rate diminishes at a very fast pace to vanishingly small value and this is particularly when we are talking about going in the backward direction we have explained regime II first and then we are moving on to regime I.

So, let us see if the da/dN versus ΔK curve is like this, then we have talked about regime II first and then we are talking about regime I the reason behind it, this is the fact that when we do the experiment in the lab scale, we do not start it from regime I itself, rather we started from regime II so, that it attains attained a state growth and then we gradually keep on decreasing the value of ΔK until we reach the regime I.

The reason for that kind of testing mode is the fact that regime I is important to understand that what is the minimum value of ΔK that can lead to onset of the growth of the crack. So, if we are moving in the backward direction, we keep on controlling the ΔK and we keep on reducing the value of ΔK we will see that the fatigue crack propagation rate diminishes at a very fast pace to almost negligibly small value. And this limiting value of ΔK below which.

So, this range over which the fatigue crack growth is highly unlikely. So, that means that there will be no fatigue crack growth at all at this range here, this limiting value of ΔK is termed as the Threshold Stress Intensity Factor range or ΔK_{th}. Now, the ΔK applied whatever applied Stress Intensity Factor range that we are using for the case of fatigue crack growth rate if this value leads to crack growth rate of 10^{-8} to 10^{-10} meter per cycle that value of ΔK applied is considered as ΔK_{th}.

So, that means that for a particular value of the applied stress intensity factor range at which the growth of the crack for each loading cycle is around 10^{-8} meter or 10^{-10} meter that can be considered as almost stoppage of the growth of the crack. So, that is a very, very small number of course, we have seen in the striation and spacings and striation spacings is of the order of let us say 1 micrometre in the stage II.

So, that means, that a crack grows up to 10^{-6} meter per cycle for the case of regime II where the striations are formed. And now, we are talking about even far lesser than that, 4 orders of magnitude lesser than that of crack growth rate for the case of regime I, so, we can safely consider that almost the crack is not growing at all.

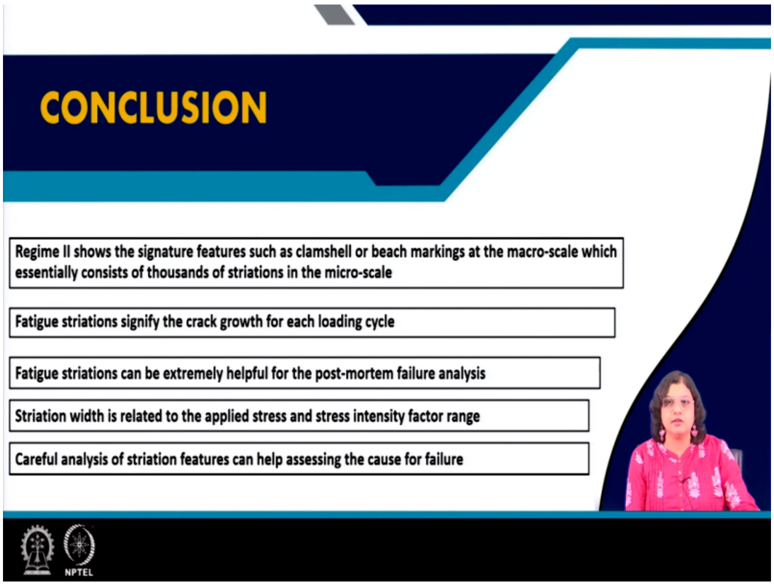
If we reach this targeted crack growth rate value of 10^{-8} to 10^{-10} and the corresponding ΔK applied is termed as ΔK_{th} or the threshold value or Stress Intensity Factor. So, that means, if the ΔK that we are applying is less than ΔK_{th} there will be no fatigue failure at all.

So, you might be very happy thinking that, why not using the value of ΔK applied less than the Threshold Stress Intensity Factor in so, that we can get rid of fatigue at all even if, there are cracks present they will not grow. So, they will be acting as a dormant crack right they will not be growing. But this may not be always feasible because of the fact that this ΔK_{th} has a very very low value.

And if you are even considering the maximum value that turns to around 5% to 10% of the fracture toughness value, remember fracture toughness signifies the value of K_{max} at which fracture occurs. So, this is actually in regime III at the highest point and ΔK_{th} is only around 5% to 10% of fracture toughness.

So, most of the engineering component that we are interested on will not work if we are applying such a low value of ΔK. So, that is one of the reason that although fatigue failure may not occur, but we may not be able to apply such a low value or Threshold Stress Intensity Factor range.

(Refer Slide Time: 28:42)



CONCLUSION

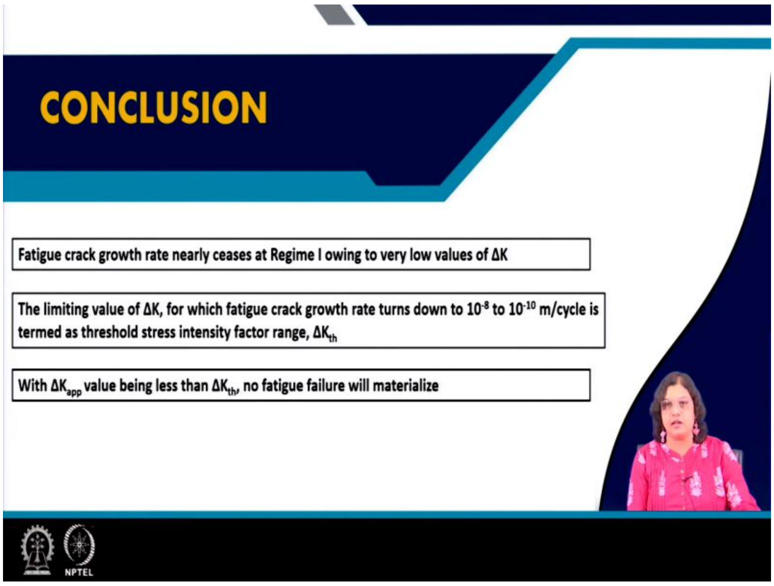
Regime II shows the signature features such as clamshell or beach markings at the macro-scale which essentially consists of thousands of striations in the micro-scale

Fatigue striations signify the crack growth for each loading cycle

Fatigue striations can be extremely helpful for the post-mortem failure analysis

Striation width is related to the applied stress and stress intensity factor range

Careful analysis of striation features can help assessing the cause for failure



CONCLUSION

Fatigue crack growth rate nearly ceases at Regime I owing to very low values of ΔK

The limiting value of ΔK, for which fatigue crack growth rate turns down to 10^{-8} to 10^{-10} m/cycle is termed as threshold stress intensity factor range, ΔK_{th}

With ΔK_{app} value being less than ΔK_{th}, no fatigue failure will materialize

So, let us conclude this lecture with the following point, that we have seen that regime II shows the most distinctive features of fatigue failure in the form of clamshells or beach markings particularly at the macro scale.

And when we are looking at the micro scale, each of these clamshells or beach markings actually consists of thousands of striations, and the striations are can be seen only at a very high magnification for the regime II only. This fatigue striation signify the growth of the crack for each loading cycle.

And this can be extremely helpful for the post mortem failure analysis we can understand what is the value of the ΔK, what kind of material it is whether it is able to form a protective oxide coating or not and whether the component has failed under repeated loading at a higher temperature or not, or in presence of aggressive environment or inert atmosphere and all those things can be understood.

If we carefully analyse the fatigue striation behaviour. Striation width is related to the applied stress and particularly stress intensity factor range as we have seen through an Empirical formula and careful analysis of distractions can lead us can help us assessing the actual reasons for the failure of an event.

For the case of regime I actually the crack growth rate nearly ceases almost, and we have seen that the particular value of the applied stress intensity factor range for which the drag growth rate reduces to almost 10^{-8} to 10^{-10} meter per cycle, we can consider that particular applied ΔK level as the Threshold Stress Intensity Factor range.

So, this signifies the minimum value of the stress intensity factor range that is required for the onset of the growth of the crack with ΔK applied value being less than this ΔK_{th} actually no fatigue failure will at all happened, but as we have seen that typically this ΔK_{th} value is very, very less compared to the fracture toughness of the material. So, it might not be always feasible to apply such a low value of Stress Intensity Factor range in the actual service.

(Refer Slide Time: 31:16)

REFERENCES

Hertzberg, Richard W., Richard P. Vinci, and Jason L. Hertzberg. *Deformation and fracture mechanics of engineering materials*. John Wiley & Sons, 2020.
Meyers, Marc André, and Krishan Kumar Chawla. *Mechanical behavior of materials*. Cambridge university press, 2008

Elements of Fracture Mechanics by Prashant Kumar, Tata McGraw Hill Publication

Fatigue of Materials by S. Suresh, Cambridge University Press publication

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