Fracture, Fatigue and Failure of Materials
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Lecture 47
Fatigue Crack Propogation (Continued)

Hello everyone, we are at the 47^{th} lecture of this course. Fracture, Fatigue and Failure of Materials, and in this lecture, we will be talking some more about the fatigue crack propagation.

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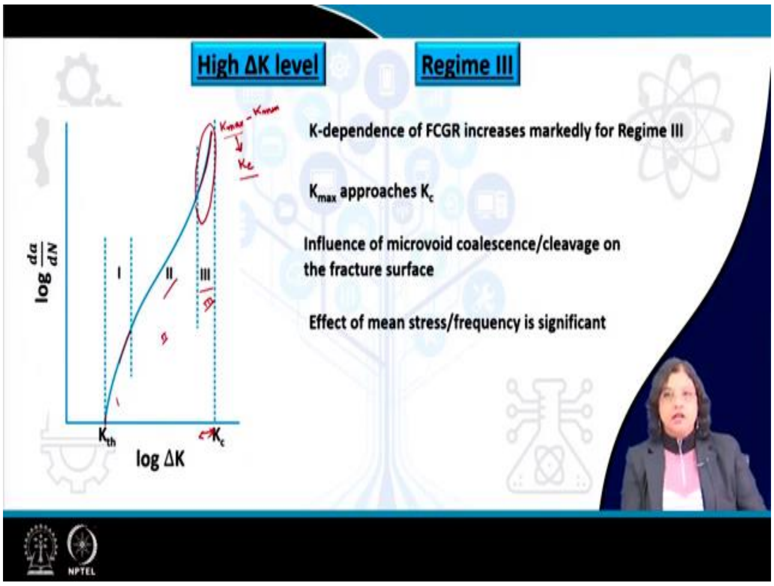

Particularly we will cover the topic on the fatigue crack propagation in regime III that means the high ΔK regime and then we will be also talking a bit on the influence of the parameters in regime II which essentially controls the main fatigue crack growth rate part, and subsequently we will have a comparison of all the three regimes of fatigue crack propagation and how are they different from each other.

So when we are talking about the high ΔK regime, we are mostly concentrating on this part of the da/dN versus ΔK curve and as you can see here the slope of the curve da/dN versus ΔK is very steep in this one which signifies that the crack growth rate is very high. Now crack growth rate was also looking like similar for the case of regime I, but in this case what happens is even if there is a notch or a crack that may not lead to the growth and that depends on the value of the ΔK_{th} which represents the initiation of the fatigue crack growth rate.

So the crack growth rate is very slow, but when it comes to the regime III, we are already at the very high ΔK regime, which means that the crack growth rate will be very high, of course the length of the crack has also been increased quite a bit for this regime and we have seen earlier that how crack length and the crack growth rate are directly related.

So more is the length of the crack certainly, the crack growth rate will be also higher and higher which is what is reflected in regime III. So the K dependence of the fatigue crack growth rate is very much significant for this case for regime III. And the most important part is that in this case the maximum of the K, so we are talking about the ΔK, we apply here $K_{maximum}$ - $K_{minimum}$ at every point.

Now at this point in this regime this K_{max} reaches to K_c which is the critical value of K for the fracture to happen and that means that whenever this maximum value of the stress intensity factor reaches this critical value of stress intensity factor required for fracture, it fractures finally.

So after all the growth rate of the crack for regime I, and II, and III finally whenever it reaches this critical value then only the fracture will materialize. So that is very much significant for this particular regime, and most importantly in this case also for regime III also we see the influence of microvoid coalescence or cleavage depending on the kind of material that we are talking about and the fracture mode, we can see different kind of signature features in the fracture surface itself.

So, if we are studying the fractography we should be able to understand that what are the typical mechanisms of fracture that was valid or that was active in this regime whether it has undergone microvoid coalescence or through cleavage kind of fracture.

Once again like we have seen for the regime I, in regime III also the effect of mean stress so that means not only the average value of the stress intensity factor but also the minimum value of stress intensity factor is taking a lead role in controlling the behavior or controlling the crack growth rate for regime III, also the influence of frequencies very much significant for the regime III.

So unlike that for regime II which is mostly devoid of any such influence of the different parameters regime III is the one in which we see significant influence of mean stress and frequencies and we can see different fracture features and most importantly the maximum value of K has to reach K_c then only fracture will occur and that is the terminal point for the fatigue crack growth propagation curve.

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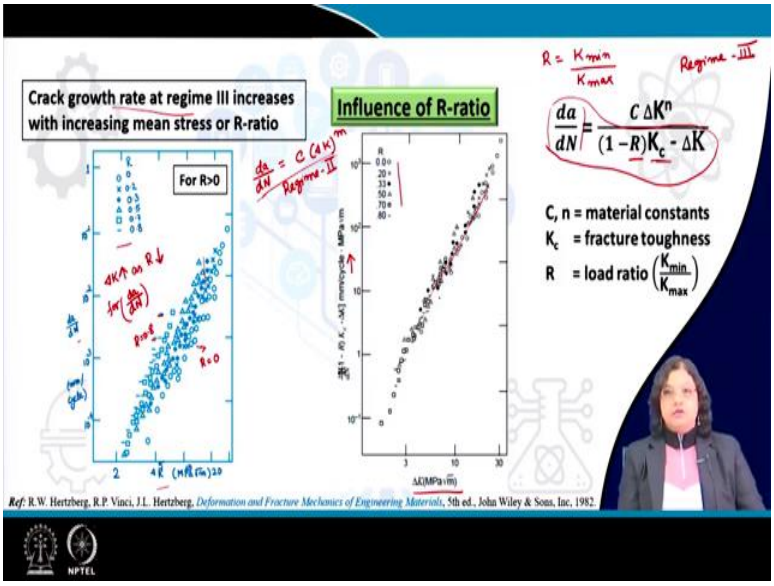

So let us see what do we mean by the influence of R-ratio. R-ratio is nothing but we have seen this earlier also that R in this case is given by $K_{minimum}$ / $K_{maximum}$. So if we are increasing the R-ratio means essentially we may increase the $K_{minimum}$, and what we see is that the crack growth rate at this regime III increases with increasing mean stress or R-ratios that means that as R-ratio increases or even $K_{minimum}$ increases that leads to an enhancement in the crack growth rate, crack growth rates is very very faster in such cases.

So let s see what do we actually mean by that, so these are some experimental data which shows the different values of R and the corresponding da/dN versus ΔK curve for each of this. The circular points here reprsessents R equals to zero, so that means that no minimum load as such or $K_{minimum}$ is equivalent to zero and the highest point here is when R equals to 0.8, this dashed point here signifies that and for that we see, for any particular da/dN value actually we can see that the ΔK increases as the R value decreases for a particular da/dN or vice versa. We can also say that the crack growth rate at this regime increases with increasing the mean stress or the R-ratio.

So, this is very much significant which means that we have some control on the experimental parameters based on which we can change the crack growth rate or we can delay or extend the remaining life of the component which may already having a crack. So that essentially gives us the power to control the fatigue life or the fatigue performance of a component and we should carefully utilize this based on the service requirement.

Now as we can essentially see here that of course there is a relation between ΔK and da/dN in this regime, particularly in regime III, but most importantly the typical relation that we have seen for the case of Paris equation which says that da/dN equals to $C(\Delta K)^m$ which is valid particularly for regime II.

Now this one might not be valid anymore for regime III because, the crack growth rate here is very fast and the dependency on ΔK is also quite high which makes it quite steeper, the slope of the curve and that means that we need to have some modification, we need to incorporate the parameters such as R to in this kind of relation so that we can have one which is valid for the case of regime III and this can be obtained by considering the R factor in the denominator and a relation something like this will be considered for regime III.

So, essentially it includes the factor R as well as $K_{C.}$ Both of these are very significant and has very important role to play on the crack growth rate in regime III. So if we are plotting this part here, so da/dN and multiplied by this denominator on the y-axis instead of simply da/dN this is what we are going to get so you see that da/dN multiplied by this factor $(1 – R) K_c - \Delta K$. This entire thing is plotted in the y-axis in the logarithmic scale and then the x-axis signifies as the same as the ΔK.

And in such case however we do not see the influence of R anymore the same values of R are also provided here in fact the same results are actually replotted in this way so that we see that now all the data points are merging with each other and we see a particular trend. So no significant role of R can be seen we if we are modifying the Paris relation something like this.

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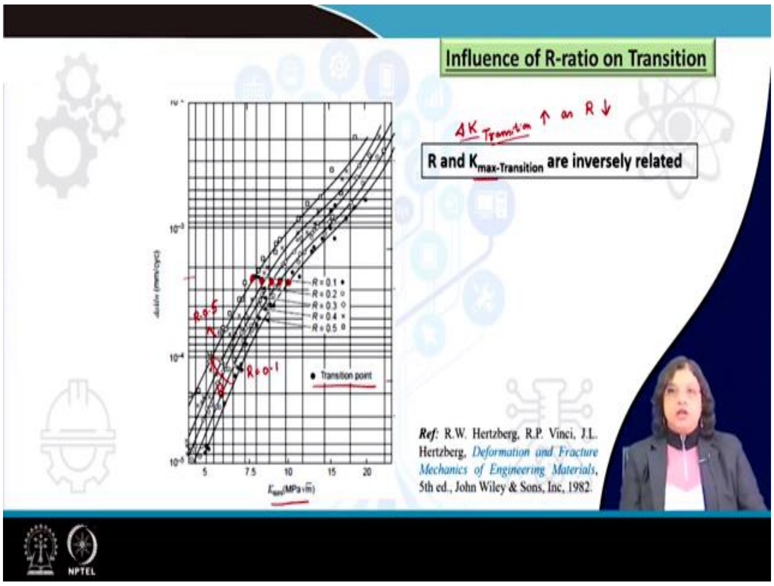

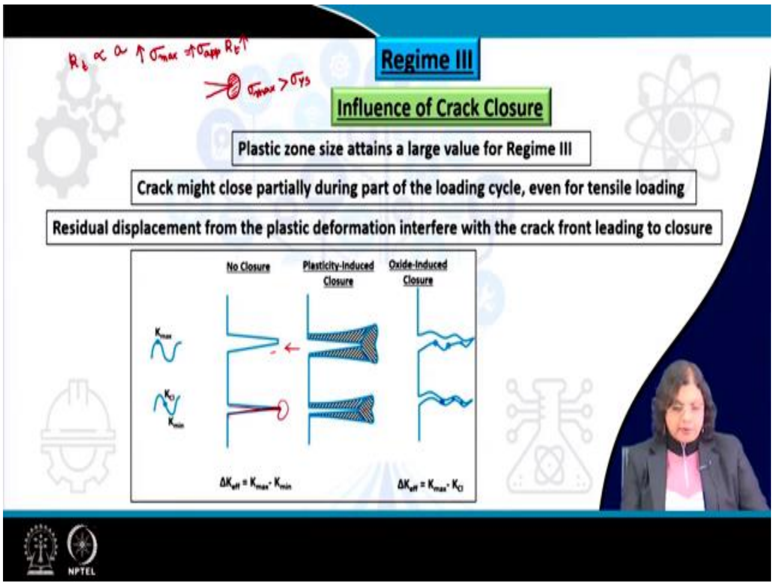

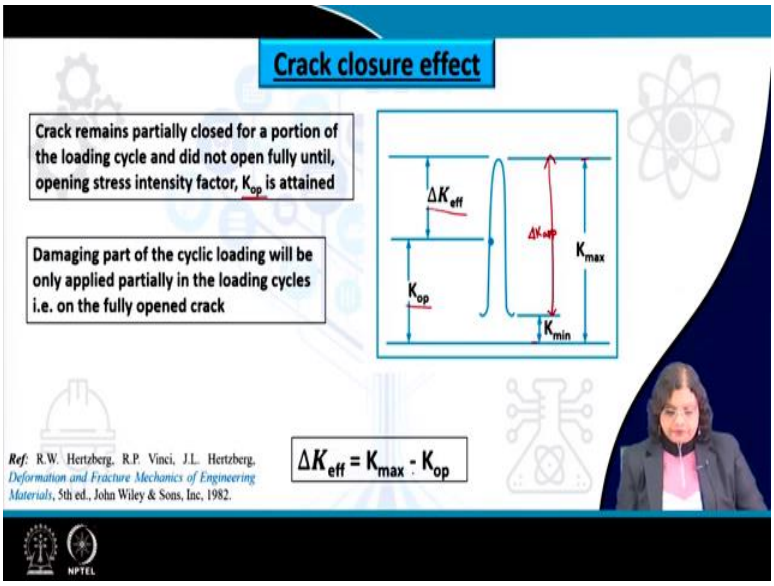

Now the other thing that we can also see for the influence of R-ratio is that if we are changing the R-ratio such that this one the black points here signifies R equals to 0.1 and the hollow square ones signifies R equals to 0.5, so that means that R is increasing in this direction. On the other hand whatever is considered here or determined here are the transition points and this black dots here let me color this with red this signifies the transition point.

So we can see that if we are considering this transition point based on a particular crack growth rate, particular da/dN value then we can see that this transition point actually the ΔK value for this transition point let me write it here so ΔK for the transition actually increases as we see that R decreases. So here also we see an inverse relation that R and $\Delta K_{maximum}$ transition are inversely related.

Now we can either consider this as the ΔK transition or we can simply consider the maximum value because that is what is significant here, so in this case instead of ΔK, $K_{maximum}$ is plotted and we can see that this K_{max} for the transition to happen that and as well as R are inversely related. So once again not only in regime III, but we can also control the other regimes if we are in influencing or if we are altering the R value or the $K_{minimum}$ or in that sense K_{mean} value also.

Now, the other important topic that needs to be discussed for the case of regime III is the influence of crack closure. Whenever we are talking about regime III as I mentioned that we are talking about a longer cracked length, because the crack has already extended through regime I and regime II which means that it has attained sufficient crack length and not only crack length we are also talking about the high ΔK value.

So if we are applying such a high ΔK value at a longer crack certainly the stress concentration will increase to a large extent, stress concentration factor just to brush up we know is related to a, so as we are increasing the a value then obviously the stress concentration factor will increase and not only that the σ_{max} that is related to the stress concentration factor is again directly proportional to the applied stress.

So this means that as the crack is getting longer and as we are applying higher and higher values of sigma applied, the value of σ_{max} at the tip of the graph will keep on increasing and that as we know is supposed to generate the plastic zone ahead of the crack tip in case there is a possibility of plastic deformation or there are dislocation movement which are possible particularly for ductile materials.

So that means that this plastic zone will develop in case sigma maximum exceeds the yield strength of the material. And not only that this plastic zone will certainly act to blunt the tip of the crack, we have already seen the influence of plastic zone on the crack tip sharpness or the value of row and we have seen that plasticity actually acts as a way to close the crack or make the crack tip blunt, which means that it becomes more and more difficult for the crack to progress forward if the plastic zone size is bigger and bigger.

And that may lead to partial closing of the crack even during the part of the tensile loading. So even if we are loading under tension they are also part of the stress or the available stress intensity factor will be used up just for making the crack resharpen again and then to move forward. So this kind of effect will be very much pronouns for regime III considering that the plastic zone size will also be very significant in this regime.

This residual displacement from the plastic deformation interfere with the crack front and that is one of the other reason to close the crack, so these are some of the things that are shown here as the mechanisms for the cracked closing and you can see that if such is the crack before any kind of plastic deformation and if there is a plastic zone formation that may lead to the blunting of the crack tip you can see that how the plasticity induced closer is valid in this case, a small plastic zone versus a large plastic zone leading to a blunt crack tip.

There could be also oxide induced closing which may also happen in any case for any of the regimes this is particularly significant also for regime I as we have seen, and what we basically see here for this regime is that the crack remains partially closed for a portion of the loading cycle. Even if it is a tensile one then also part of the stress intensity factor will be used up for opening the crack and that is known as the $K_{opening}$. That part of the stress intensity factor is termed as $K_{opening}$, and hence the damaging part of the cyclic loading will only be applied partially.

What do I mean by partially is the fact that let us say if this is the K-curve and we can see that we are applying $K_{maximum}$ and $K_{minimum}$, so essentially this is the value of ΔK that we are applying, but because of this crack closing mechanism there is some amount of $K_{opening}$ that needs to be provided or that needs to be used up out of this entire ΔK applied some part will be used up just for opening up the crack, resharpening the crack and the rest of the ΔK that is available for the further growth of the crack that is termed as the $\Delta K_{effective}$.

So that means that part of the ΔK applied will be used up in some other mechanism and obviously that means that less amount of ΔK will be available for the growth of the crack which will act as a beneficial mode in the sense that that may delay the growth the fatigue crack and that finally may lead to an enhancement in the life in whatever way. So essentially this is what is significant here for this particular regime that the $\Delta K_{effective}$ which leads to the crack growth.

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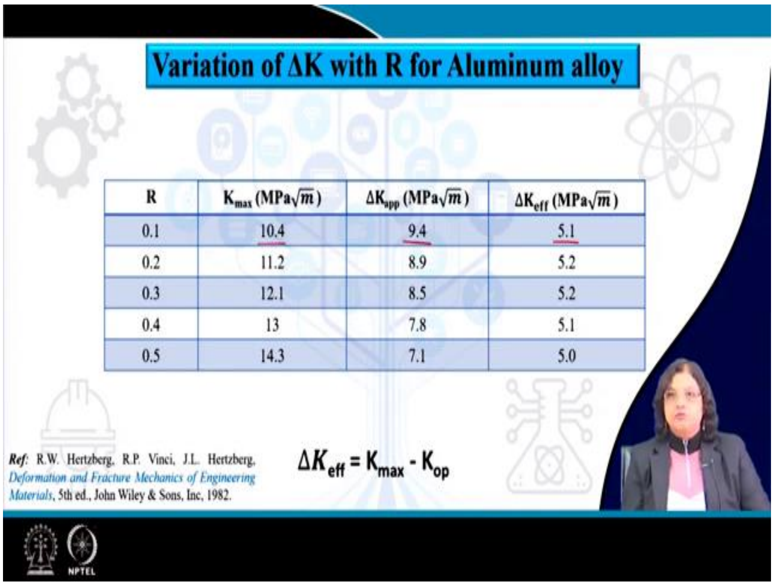
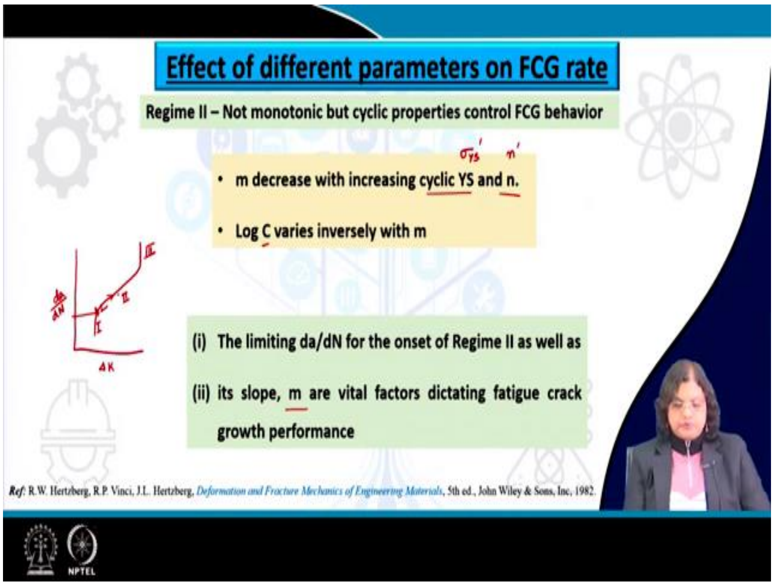
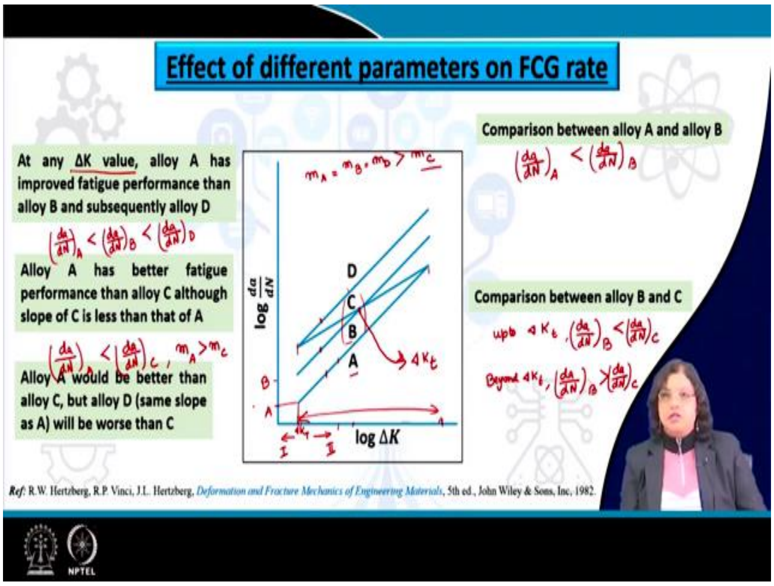


R	K_{max} (MPa$\sqrt{m}$)	ΔK_{app} (MPa$\sqrt{m}$)	ΔK_{eff} (MPa$\sqrt{m}$)
0.1	10.4	9.4	5.1
0.2	11.2	8.9	5.2
0.3	12.1	8.5	5.2
0.4	13	7.8	5.1
0.5	14.3	7.1	5.0





This is some values from the experimental results of aluminum alloy. And you can see that if the $\Delta K_{applied}$ value is quite high whereas the K_{max} value is even higher because that is the maximum value of the K that we are applying as well as the effective value of ΔK that is available for the crack to grow forward is significantly less and this also along with the variation in the R, we can see that how both of this can act simultaneously for the crack closure mechanism to be active and that may lead to a variation in the crack growth rate for regime III.

So once again we need to discuss some other parts which control the fatigue crack growth rate particularly for regime II, and the transition of regime I to regime II as well. Before we look into the overall picture let us dig into it in more details to understand that in case of regime II, not the monotonic properties like the yield strength or the other factor but rather the cyclic behavior or the fatigue properties are important here.

What do I mean by the fatigue properties is that when we are talking about the way fatigue crack growth rate is being controlled that can be dictated by the cyclic yield strength as well as the cyclic n. So this are determined or these are represented by the symbol like σ_{YS}' and n' that we have seen earlier in case of cyclic softening and hardening part and these are the parameters which control the fatigue crack growth rate rather than the yield strength of the material.

Monotonic behavior and cyclic behavior could be completely different in fact we have seen that the one which is hard under monotonic loading is supposed to get cyclically softened and vice versa. So that means that after cyclic loading actually even the hard or the soft one under monotonic loading more or less attains a stabilized condition which is supposed to be equivalent for both the cases.

The C value for the Paris relation that is seen to be inversely related with m. Now this is very much significant if we are talking about the transition point between regime I and regime II. The limiting da/dN for the onset of regime II as well as the slope are actually the vital factors that dictate the fatigue crack propagation performance. What I mean by this is if we are having the da/dN versus ΔK curve and if this is what we are getting as regime I, II and III then this part here so what is exactly the onset like in terms of the da/dN value?

Now as I mentioned that this da/dN value could be different, it could be 10^{-8} to 10^{-10} or even 10^{-11} meter per cycle. So if we are talking about a material which undergoes this transition at 10^{-8} versus the one which undergoes this transition at 10^{-10} meter per cycle there can be some differences and obviously the slope of this curve here is significant in controlling the fatigue behavior.

So, let us look into this in more details in the sense that there are examples of four different alloys A, B, C and D for which the da/dN versus ΔK curve is shown. Particularly at this transition regime, so below this lies regime I and above this lies regime II and this is the transition point here.

So what we can see here if we are let us say comparing between the different alloys first of all what we see is the m value for A is same as the m value for B is same as the m value for D, and all of this are actually greater than m value of C. C is the only one which is having lesser slope, all A, B and D are having the same slope but yet there are some differences. For example, if we are talking about comparing the alloy A and alloy B for any particular design, for any particular application then which one to consider?

If we are in that dilemma we should understand that we need to consider the alloy A for this particular application since it is having lower da/dN versus ΔK value. So for that particular ΔK at which the transition is occurring, this value of da/dN for A is lesser than for the case of B. Obviously we will go for lower values of the da/dN for any particular application such that the crack growth can be minimized or it can be delayed up to a certain extent.

Now if we are talking about all the alloys in general then at any ΔK value at any particular ΔK value even in regime II, we can see that alloy A has improved property compared to alloy B and alloy D or overall we can write here that da/dN for the case of A is less than da/dN for the case of B and that is also less than da/dN for the case of D, for any particular ΔK value. If we need to compare between A and C obviously as you can see that the m value for C is less than that of the m value of A.

So again we are tempted to use C in such condition because we know that lower is the slope lower will be the crack growth rate that is definitely fine, but if we are talking about the certain ΔK range we have to also go through this data to understand that for any particular ΔK value up to this range from here to here for which the data has been provided we can see that for any particular ΔK value the da/dN of A is lesser than that of da/dN for C.

So da/dN for A is lesser than da/dN for C although m of A is higher than m of C, still up to this range at least we can see that the crack growth rate is lower for the case of A. Now if we are comparing between A, C and D we can see that alloy A would be better than alloy C. At any point as we have seen that alloy A is always better than that of C but, if we are talking about alloy D in such case we can see that although A and B are having the same slope that means the same value of m but still C will be having lower values of da/dN and at any point between this ΔK range such that C will perform better or have lower crack growth rate under fatigue condition in comparison to that for D.

So we have to choose carefully which of the alloy will be suitable for any particular design provided that we know that the ΔK range that it will be applied for. Now one more comparison if we want to do between B and C where we see that there is a cross over at a particular ΔK value then we should also consider that which delta K range we are talking about.

If let us name this as, so that is ΔK_t and what we can see here is that up to this level so up to ΔK_t we can see that da/dN for B is less than the crack growth rate for the case of alloy C. On the other hand beyond ΔK_t however, we can see that the da/dN for B is greater than the crack growth rate for the case of C. So obviously if we are talking about the stress intensity factor range below the transition or below this crossover point we should use alloy B. On the other hand if we are using for higher ΔK values then we should use the other alloy which is the alloy C.

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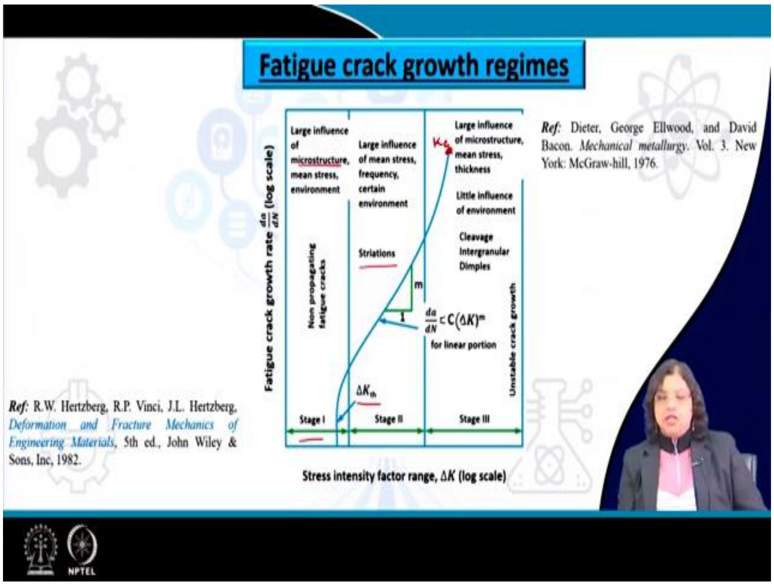

So now we have seen the details of all the three regimes, let us just now have a comparison of all the three regimes and what we can see here is that the stage one which is particularly important for understanding the minimum value of ΔK that is required for the onset of the growth of the crack which is termed as delta K_{th} or the threshold value of the stress intensity factor, we see that up to this limit there is no crack propagation basically. And a significance influence of microstructure has been seen here.

We have seen that coarser is the grain size more difficult it is to initiate the crack or the crack path torturecity actually makes it difficult even for the growth of the crack. So we prefer for coarser grained materials if we want to erase the crack growth condition, also the effect of mean stress and environment has been significantly found for this stage I or the regime I.

On the other hand, this kind of influences are not typically seen, particularly the influence of microstructure is not at all valid or negligible for the case of regime II, and there are some influence of mean stress and frequency as well as certain environment that are seen and the signature feature of fatigue which can be observed from the fractograph such as the presence of striations, this can be seen for regime II.

So, striations is a very important feature which signifies that fatigue loading has been provided to the component and not only that we have also seen that how striation weed can be of very important factor to determine the ΔK value at the point of fracture or at any point of loading as well as even the environment condition, the temperature condition can also be understood based on the detailed analysis of the striations.

Regime III on the other hand once again and the influence of microstructure is seen here and not only that thickness plays a very important role, once again the factors such as the plane strain or the plane stress conditions becomes very much viable to control the fatigue crack growth rate behavior as well as the final fracture regime, and most importantly we have seen that how K_{max} reaches the point of K_C at this terminal point when the fracture occurs.

So whatever is the situation, whatever is the size of the crack or the mode of loading at the poin of fracture it has to attain the value of Kc or the critical value of stress intensity factor then only fracture will occur and this is met in this regime III, and we should also see the presence of cleavage or intergranular fracture or dimples in this regime.

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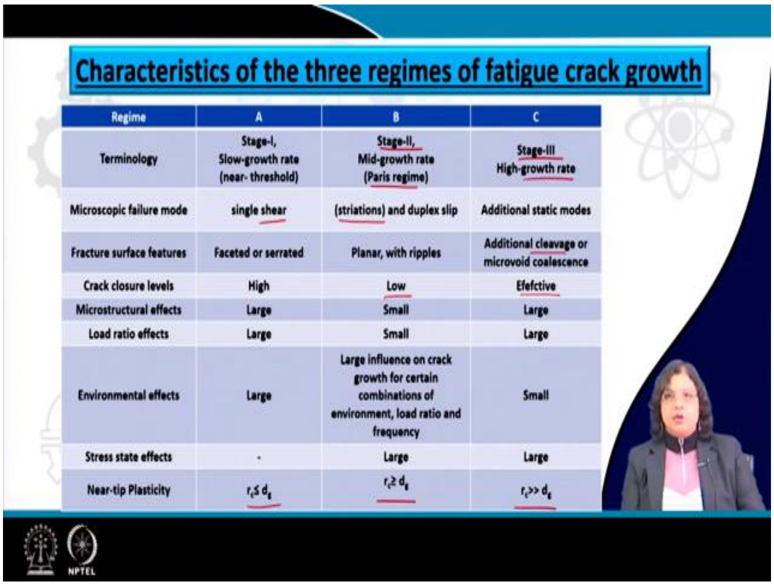

Regime	A	B	C
Terminology	Stage-I, Slow-growth rate (near- threshold)	Stage-II, Mid-growth rate (Paris regime)	Stage-III High-growth rate
Microscopic failure mode	single shear	(striations) and duplex slip	Additional static modes
Fracture surface features	Faceted or serrated	Planar, with ripples	Additional cleavage or microvoid coalescence
Crack closure levels	High	Low	Efefctive
Microstructural effects	Large	Small	Large
Load ratio effects	Large	Small	Large
Environmental effects	Large	Large influence on crack growth for certain combinations of environment, load ratio and frequency	Small
Stress state effects	-	Large	Large
Near-tip Plasticity	$r_c \leq d_g$	$r_c \geq d_g$	$r_c >> d_g$

So regime I is particularly the one which shows slow growth rate, very slow actually this is also known as the near threshold regime considering the onset of the crack growth starts from this regime itself and it shows a sheer kind of behavior and we have seen that how faceted surface is seen, branch crack is seen for the regime I.

Crack closure level is significantly high here particularly also related to this faceted fracture surface as well as the crack branching and microstructural effect is significant we have seen how grain size or the microstructural size, large size, colony size, etc. can be increased to increase the crack path torturecity or in turn reduce the crack growth rate.

Load ratio effect or influence of R-ratio is significant for this regime and environmental effect is also quite large and we have already seen that how the presence of steam can actually aggravate the situation in one sense, but on the other hand it also restricts the onset of the growth of the crack or ΔK_{th} may increase because of the presence of high temperature and moisture leading to higher corrosion products.

Near tip plasticity in the sense a plastic zone size that is forming that is significantly less than the microstructural size and at the point of transition from regime I to regime II actually we have seen that how the influence of this microstructural size can take over. In case of regime II which is also known as the Paris regime because in this case the da/dN versus delta ΔK follows a particular relation and this covers the major span of the crack growth and that is why we can determine the remaining life of a component based on this Paris regime here.

Particularly it shows the presence of striations and duplex sleep in this case and crack closure level is significantly low, in fact the crack grows in a very steady state and no activities of crack closure is typically found for regime II. Microstructural effect is also nominal in fact no microstructural effect is found for the case of regime II and as I mentioned that the crack growth is very much stable, not influenced by the factors, same goes for the the load ratio effect also.

Environmental effect however is seen here large influence on crack growth for certain combination of environment load ratio and frequency are typically seen here and the stress state effect is also quite significant. More or less the plastic zone size exceeds the grain size or microstructural size in this case whereas for the case of regime III, which is the high growth rate regime and the crack grows very fast here and we have seen that how the ΔK dependence is also very much significant and the fracture surface in this case shows the presence of cleavage or microvoid coalescence features like that depending on the material that we are talking about.

Crack closure level is also active one of the prime reason is that the plastic zone size in this case is very large typically it exceeds the microstructural size and as a result the crack closure mechanism based on the high plastic zone is quite effective for this case. Microstructural effects are also high and we have also seen in this lecture that how R-ratio influences the behavior for regime III.

Environmental effects however are not so significant in this case and we have also seen the importance of the stress state effect, also the thickness of the component leading to the plane stress, plane strain conditions will also influence the crack growth behavior at this regime.

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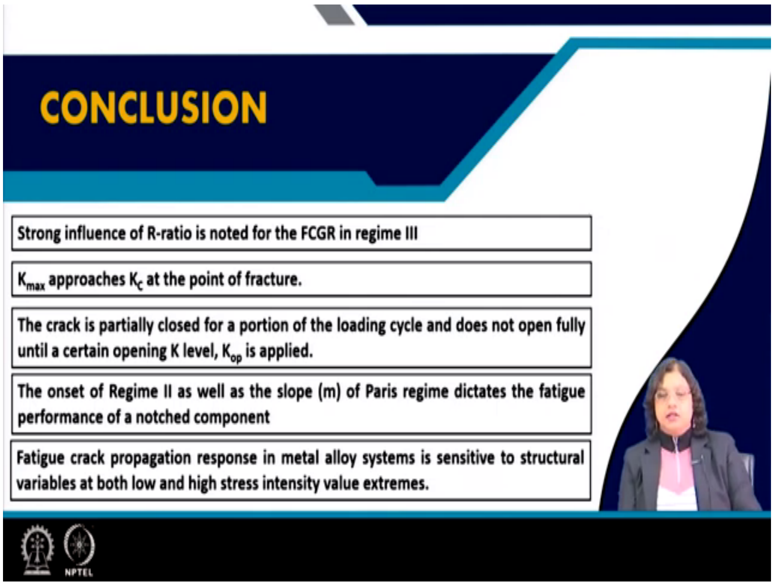

So with this let us conclude this lecture with the following points that strong influence of R-ratio is noted for the fatigue crack growth rate curve, particularly in regime III and K_{max} approaches the critical value of K at the point of fracture and that is the terminal point of the da/dN versus ΔK curve.

However, the crack is partially closed for certain section of the loading cycle and does not open fully until a certain opening K level which is termed as K_{op} is applied and this is related to the plasticity or the plastic zone that is forming ahead of the crack tip. The onset of regime II, the exact value of the da/dn as well as the slope of the m are the ones that control the crack growth rate behavior and based on this we need to decide that what kind of alloy depending on their particular values can be used for a certain applications.

A fatigue crack propagation response in metal alloy system is sensitive to structural variables at both low and the high stress intensity values, and we have seen this for regime I and regime III, but however regime II is most of the cases regime II is devoid of any such influences particularly the influence of microstructure is very much nominal for the case of regime II.

So, following are the references that have been used for this lecture. Thank you very much.