Materials Science and Engineering
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Lecture – 35
Fatigue

Hello friends. Now we will see another very important the way the material fails and that is called Fatigue, through fatigue. And you must have tried this and you use this particular idea to break, let us say if you have a aluminum, wire and you want to break it; how you break it you? Keep on doing something like this ok and then it breaks. So, basically what you are doing is you are doing a fatigue test and, because my stress amplitude is very high it fractures in no time.

But, in actual practice of engineering application the lots of materials are subjected to this kind of loading ok. For example, if you have a shaft. So, continuously it is experiencing compressive and tensile stresses. So, when this is the shaft at the top it will be it is like sagging like this, because under it is own weight you will have compressive stresses here and tensile here and when it rotates ok. Now this is tensile and this is compressive.

So, it is continuously seeing this cyclic loading of tensile and compressive and sometime and for example, in automobile any material used in automobile application, they will always see this kind of fatigue loading, because you are continuously moving on a road you are going to see bumps and all that and these are going to introduce a fatigue kind of loading on the material ok.

So, this is a some very popular pictures you will see for problem with the fatigue as you can see this is the actually a aeroplane and the upper portion of.

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That is already blown away ok, and the problem when it was investigated it was trace back to the fatigue loading of the structure and because of that it failed and if you do any fatigue testing these are the typical features you will see ok. So, somewhere here the, you had the origin and then you see this kind of markings here. And then you will have a final failure zone. So, this is the sudden problem with fatigue.

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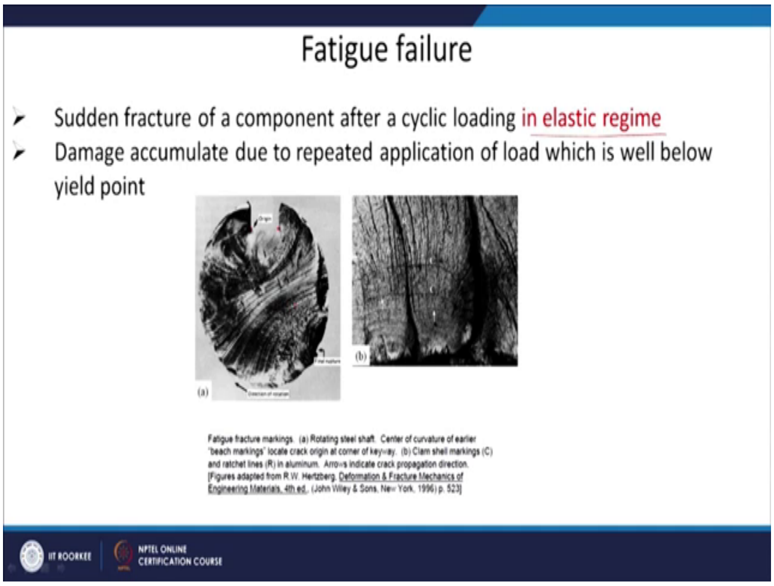

Failure also is that it is sudden fracture after a certain cyclic loading of the material and the cyclic loading can be in elastic regime only ok. So, during the design you have taken care that the stress is on any structural component is not going to go beyond the elastic limit. In fact, you have taken some factor of 50 also ok. So, your loads are much lower than the yield stress of the material, but of it is the material is loaded under the fatigue loading ok, it may fail under that kind of service loads also ok.

So that is the problem and if you have you are not able to detect, what will happen? Initially it is a slow process and then you have sudden fracture catastrophic fracture and that is the problem with the fatigue failure.

So, damage accumulates due to repeated application of load which is well below the yield point ok. So, load can be well bellowed the yield point and it is still the material will fracture ok. And as I told you again these are the typical markings. So, here actually it is a shaft and you can see there is a key hole here and, because of the key hole you have some sharp corners at these two locations and that will initiate the crack ok. So, there the crack has initiated you can see the origin is marked there. So, the crack will initiate here and slowly it will move and finally, you will have fracture in the final portion.

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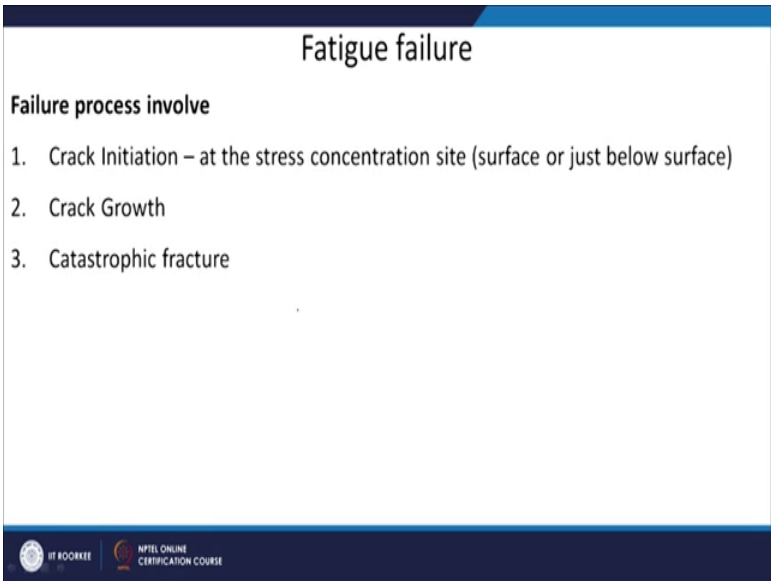

So, fatigue failure if I want to divide I can divide it into three zone, ok. So, it can be first is crack initiation, then you will have crack growth and then it is a catastrophic fracture final fracture. So, I can divide the; failure into these three categories ok. And as I told you I have shown you couple of micrographs where people I have shown very nicely in that there are different features present on the fracture surface.

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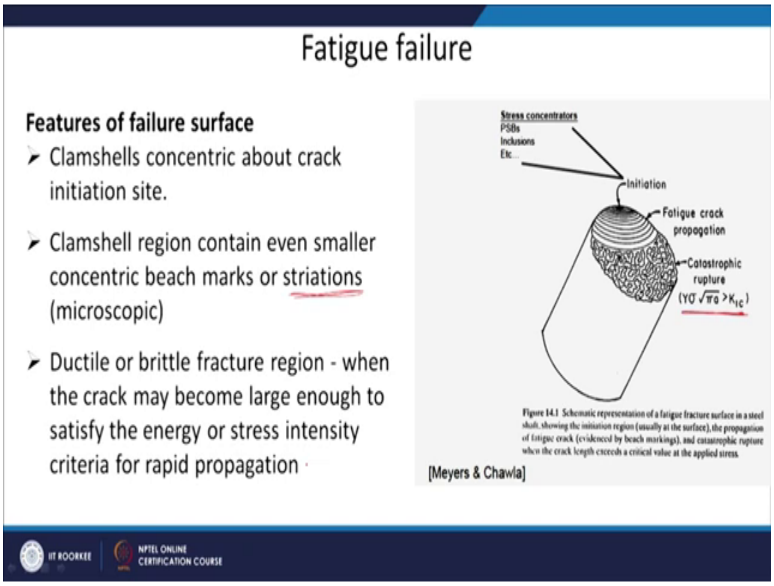

So, features you will see the features will be this concentric, what we call as clamshells ok? It looks like the shell surface of the shell you see there are markings like this. So, there is a crack initiation site somewhere where ever the flaw is there; wherever there is a stress concentration is there from there the crack will slowly propagate ok.

And you will get this kind of clamshells concentric circles basically in this clamshells region also, there is there are some concentric beach marks or striations these are microscopy. So, clamshells are microscopic you can see that I can I could easily see in a in a simple photograph these kind of markings, but if I go in the using some microscope within this clamshells also you have another feature which is called striations then you have this final fracture.

So, when of course, as we have already discussed that, when my stress intensity factor goes beyond critical intensity stress intensity factor then there be fracture. So, this is this is a crack which is initiated and propagate up to this point. So, for this given crack length if my stress intensity factor is more than the critical stress intensity factor of the material then the fracture will takes place.

So, it can be a ductile it can be brittle depending upon; what is the stress state of stress or what is the condition of the material? So, when the crack may become large enough to satisfy the energy or stress intensity criteria for rapid product propagation it will fail under ductile or brittle fracture mode.

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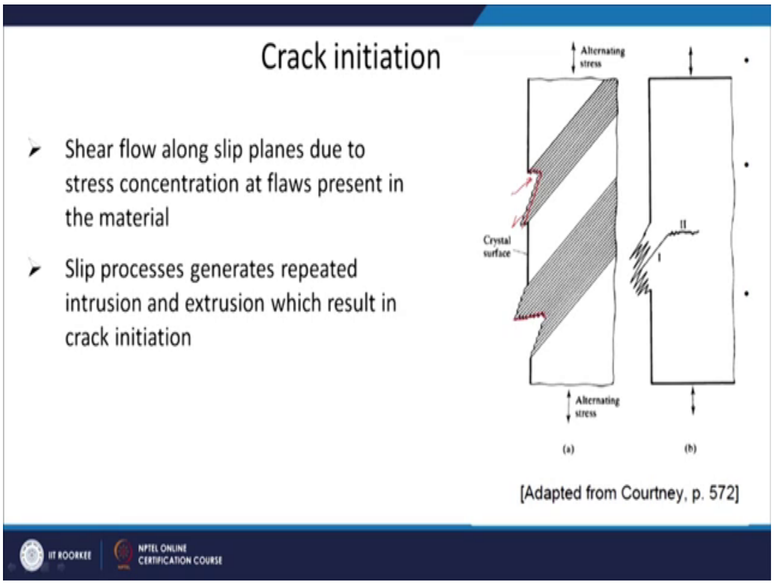

Now, how the crack initiates ok. So, when this cyclic loading is going on what will happen wherever there are some flaws ok, there will be some plastic deformation local plastic deformation, because of the some stress concentration. So, there can be flaws or there can be flaws in the design itself ok. So, what will happen locally the stress will be high enough to initiate the deformation. So, because of this cyclic loading the deformation will kind of go in and go out ok

So, there will be this inclusion and exclusion of the crystal plane. So, wherever the; maximum shear is there shear stress is acting. So, you will have slip process ok. So, slip process will be like this, because of the cyclic loading. In some cases it will go slip will go in and some cases this because of the slip the material will come out ok.

So, that is, what is shown here and this is going in this is coming out and because of this going in and coming out you can see that if I want to show it as like a crack it will show a crack like this ok. So, you have a crack with this radius of curvature like this and, because this is at atomic scale almost the crack will be quite sharp here. Similarly, if I want to show it as a crack I can show it like this ok. So now, you have initiated a crack in the material by this repeated loading.

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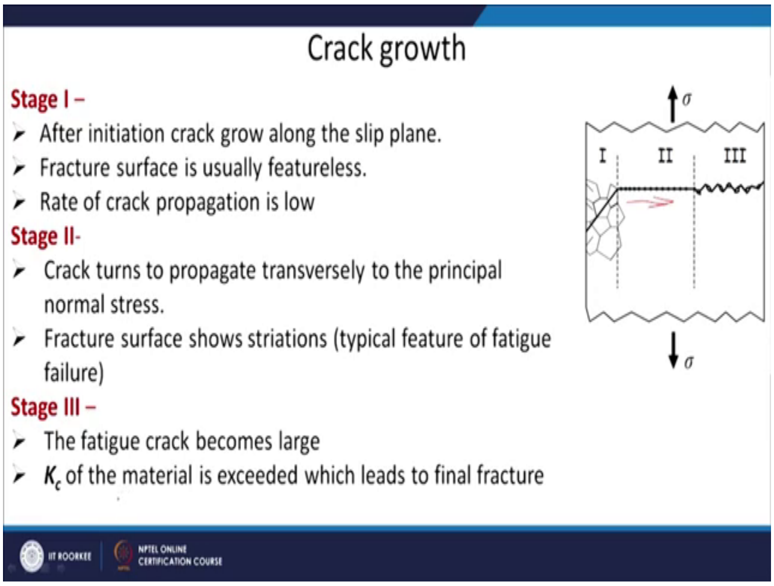

So, crack initiates like this, then once it initiates it is it has to grow ok. So, after initiation it will grow and this growth can be divided into three stages: the stage one, stage two, stage three which is also shown schematically here. So, in a stage one after initiation of crack grow, it grows along the slip plane.

So, the crack will grow along the slip planes ok. So, it is similar to what you will see in a trans granular brittle fracture where the crack is going through the grain along the slip planes fracture surfaces. Usually, feature less this will have a cleavage kind of fracture. So, and usually it is feature less you wont see very nice features here and rate of propagation is slow.

So, in this early part it is the crack going to grow very at a very slow phase ok. Stage second is crack turn to propagate transversely to the principal normal stress. So, suppose you are applying a stress like this. So, whichever is the maximum principle stress ok? So, crack will grow transverse to that. So, if stress is applied in this direction my growth is going to be at ninety degree to that ok.

So, it propagates transverlies transversely to the principal normal stress and fracture surface shows a striations typical features of fatigue failure. So, here you see the clamshells and the striations. So, microscopically you will see the clamshells microscopically you will see the striations, then the stage third one will come the fatigue crack become and if it crosses the critical stress intensity factor of the material it will have the very catastrophic fracture in the last stage.

Now, how the striations will look like. So, clamshells we have already seen and microscopically, we said that it will be striations and this; striations are also kind of a very nice morphology is there and these are also called beach marks. So, on the beach you will see the sand is arranged in this fashion ok, because of each wave is coming like that ok. So, these are called beach marks also.

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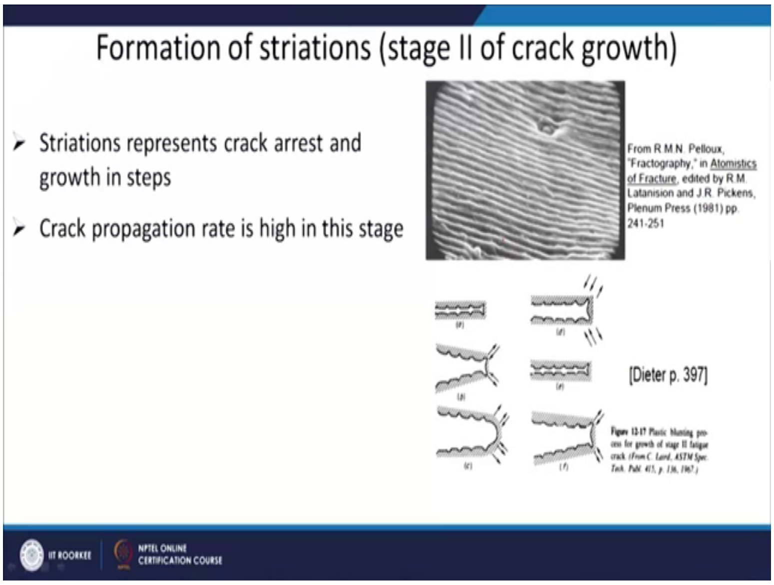

And what it represents is it represents the crack arrest and growth in steps ok. So, crack propagation rate is high in this stage; so how it forms.

So, as I told you that the crack propagates only under tensile mode ok. So, suppose the cycle is such that that it is going into tensile mode, then it is going into compressive mode and so, on. For example, taking the example of a shaft so, when the shaft is like this you have compressive here tensile here. Suppose it is sagging in it is own weight, and if I rotate it by one eighty degree the tensile will become compressive and compressive will become tensile. So, my material is continuously going in this cycle.

Now, what will happen, as I told you that in tensile mode the crack will open up in the compressive mode actually crack will close down? So, the crack will propagate only in the tensile mode and, then it will close down then again it will go again it will close down ok. So, that is why you see the striation, because of the crack propagating in each cycle and schematically it is shown here that; how it will grow in each cycle ok. So, when we are going into tensile mode it will go forward in the compressive mode it will be closed again in tensile mode it will go forward and so, on.

So, you can almost see that if you can measure; the distance between the two striations that, how much crack has propagated in one cycle ok. Then that you can easily find out from a micrographs like this.

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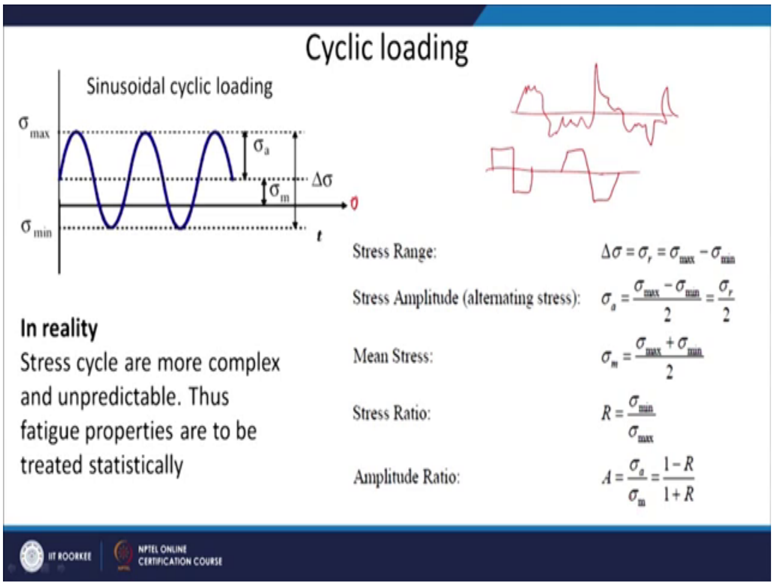

Now, coming to the stress cycle which you are going to impose just want to understand that, what do we means by this cyclic loading ok. So, of course, this is a very theoretical kind of cyclic loading sinusoidal cycle cyclic loading in practice it will be very random cycle. So, you can have some kind of a loading like this may be with lot of suddenly some spike or something like this it can be a very random cycle we cannot impose that in our machines ok. So, what we usually choose is sinusoidal cycle or may be a some simple cycles like a square wave like this or may be a trapezoid kind of cycle like this and so on ok. Suppose we have a sinusoidal cycle ok. So, it is going like this.

So, you have now there are different terms defined here and those are expressed here with relationships. So, as I told you in reality stress cycles are more complex and unpredictable, thus fatigue properties are to be treated statistically. So, you have to do lot of fatigue test to actually find out what should be the fatigue properties of a given material and you have to treat the whole analysis statistically ok.

So, let us see what we have in this sinusoidal cyclic loading. You have maximum stress; this is the minimum stress ok. Now depending upon how you are imposing it can both can be in tensile or maximum this sigma max can be tensile this sigma minimum can be compressive ok. So, there can be different modes in which you can impose the; the cycle as I told you compressive mode the crack does not propagate.

So, usually to accelerate the testing usually both the sigma max and sigma minimum are choose in tensile mode so that the crack will propagate quickly ok. So, this is maximum and minimum then you have what we call as stress amplitude ok. So, basically wherever is your mean value ok, above that you have half a sigma max another half as a sigma minimum.

So, stress range will be basically sigma max minus sigma minimum, that is given as sigma r or delta sigma stress amplitude is subtract sigma max minus sigma minimum and divide it by 2 to get this average. So, it will sigma max minus sigma minimum upon 2 or sigma r by 2 sigma mean is basically maximum and minimum and divided by 2. So, this is your sigma mean above this; my I think the 0.

So, it will be compressive here and tensile there then you have stress ratio which is minimum sigma minimum on sigma maximum and amplitude ratio is sigma amplitude divided by sigma mean. So, the all this parameters have affect the fatigue life or fatigue properties. So, of course, we are not going into detail of all affect of all this parameters on the fatigue life of the material or fatigue properties of the material, but this is what you have to choose when you are doing any fatigue testing. So, basically when you do fatigue testing what you get is.

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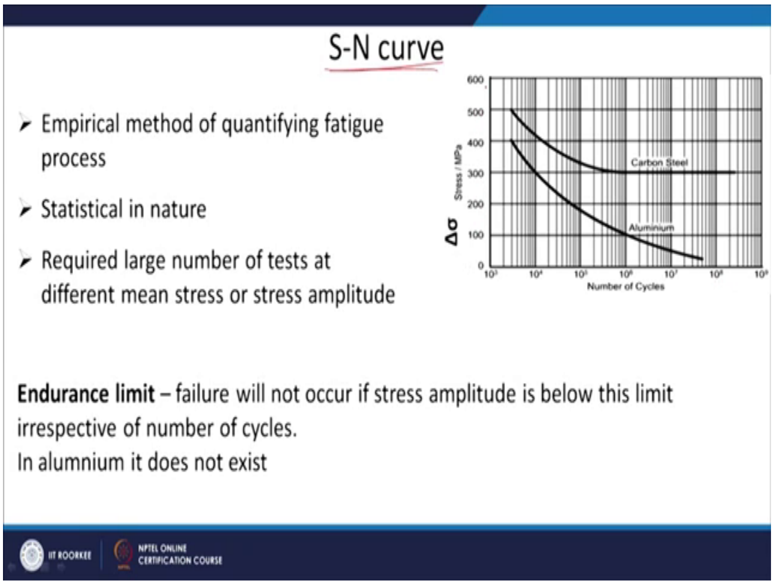

We call we call it as S-N curve. So, s is basically stress and N is number of cycles.

So, you take the delta sigma that is the stress range ok, as we have just shown here delta sigma is equal to stress range on the y axis and there you have a number of cycles. So, for different stress range they are trying to find out that, how many numbers of cycles the material is going to survive or sample is going to survive?.

So, you can that for higher stress range where sigma max and sigma minimum gap is more. So, you are applying higher stress range here you can see that my material is surviving lower number of cycles if I reduce the stress range sigma max is reduce sigma minimum and sigma max the difference is reduced delta sigma is reduced then you can say that my material is going to survive more number of cycles.

So, this is the empirical method of quantifying fatigue process or fatigue properties statistical in nature on. So, you have to do lot of test to get this kind of curve require large number of test at different mean stress or stress amplitude. So, you have to keep changing all those parameters, which we discussed in the previous slide ok. To get this kind of curves for some material that is also a proper fatigue called endurance limit and it says failure will not occur if stress amplitude is below this limit irrespective of number of cycles in aluminum it does not exist.

So, you see that we have done one fatigue curve for carbon steel another for aluminum. So, in carbon steel if you see if I keep on in reducing the stress amplitude my material is able to survive for more number of cycles and after a certain stress amplitude it is it has become independent of stress amplitude. So, now, my material can survive for any number of cycles if the stress amplitude is below this value. So, it is a very thing for a designer that if he can maintain the stress amplitude below this endurance limit he is not worried about the fatigue life of the component in aluminum; however, you see that it does not behave like this it is continuously decreasing as a function of stress amplitude.

So, it is always going to fell at some point at some number of cycles that can very high 10 to the power 7 is a very high cycle or 10 to the power 8 and so, on ok. So, this is a very good property for steels that they have endurance limit. So, your stress amplitude if it is below this stress ratio is below stress range is below this then, you will not have any fracture for any number of cycles ok. Now crack growth rate is kind of characterized by paris law and what it says is it is important to know that how the crack is going to at what rate the crack growth will take place.

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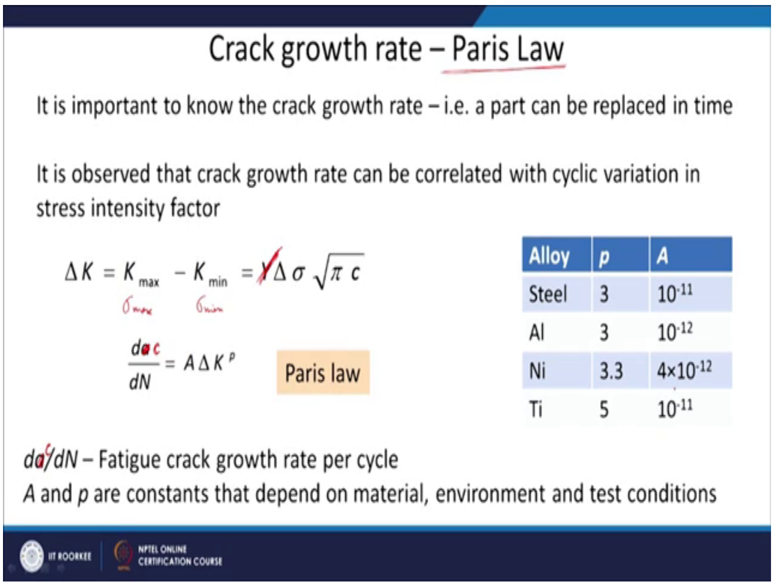

So, that know that when I can replace a part ok.

So, it is observed that crack growth rate can be curve correlated with cyclic variation in the stress intensity factor. So, what we have done is we have again brought the stress intensity factor here. So, delta sigma is expressed as delta K now. So, K max is for sigma max. Using sigma max K minimum is used by putting sigma minimum in the equation ok. So, I can say that it is delta sigma basically Y is again your value on which you are this thing will depend ok. So, may be if I put under root pi here already I do not have to put y here ok, because I have already taken care of that.

So, the delta K gives me K max K minimum. So, K max correspond to sigma max in your stress cycle and K minimum correspond to sigma minimum and this Paris law suggest that; this is related to your crack growth rate let me put instead of a let me put it as c sorry ok, because this is the crack growth rate growth rate as a function of number of cycles. So, because c we are using as length I am going to use c here. So, it is d c by d N extension in crack for a given number of cycle ok so d c by d N. So, crack growth rate per cycle. So, again here also I am going to put as c.

So, that is related to this stress intensity factor delta K and to the power some p and A is your some constant A and p are constant that depend on material environment and test condition. So, for some material the P and A are given here. So, for steel P is 3 for aluminum also it is 3 nickel it is 3.3 for titanium it is 5; and these are the value for different these materials ok. So, by knowing that I can find out that what will be the crack growth rate as a function of number of cycles and this is how the crack growth rate growth rate will behave.

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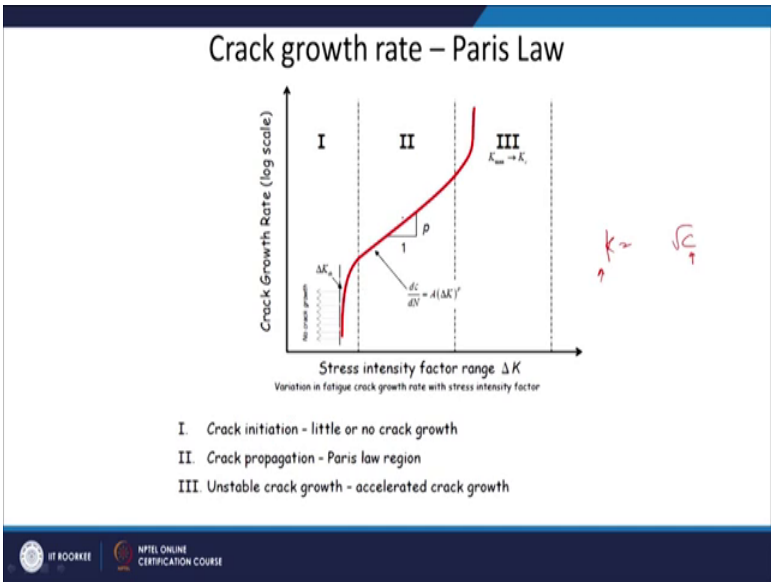

So, again you can have see that there are three zones here ok.

So, I can divide it into three zones. So, as function of stress intensity factor delta K the crack growth rate is plotted here. So, if stress intensity factor is lower in the initial part the crack growth rate will be very high as you increase the delta K, then in some in one zone it becomes the delta K and d a by d N they almost start following a linear relationship. So, P is here one here for example and.

Then you have the final catastrophic failure. So, in the same test actually delta K will keep on changing ok, why? Because my crack is growing, so as you can see that for in K you get some under root of C the remaining things I am not writing here ok. So, my this crack is growing continuously. So, my K is also going to be increasing as a function of number crack growth rate or crack growth. So, this is for a one single test that initially; you will have this crack growth rate, then it will become where it is start following the Paris law and then you will have the unstable crack growth rate where it is going to fail catastrophically.

So, this is your crack initiation part ok. And then you have crack propagation, where Paris law is followed and then you have accelerated crack grown growth rate ok.

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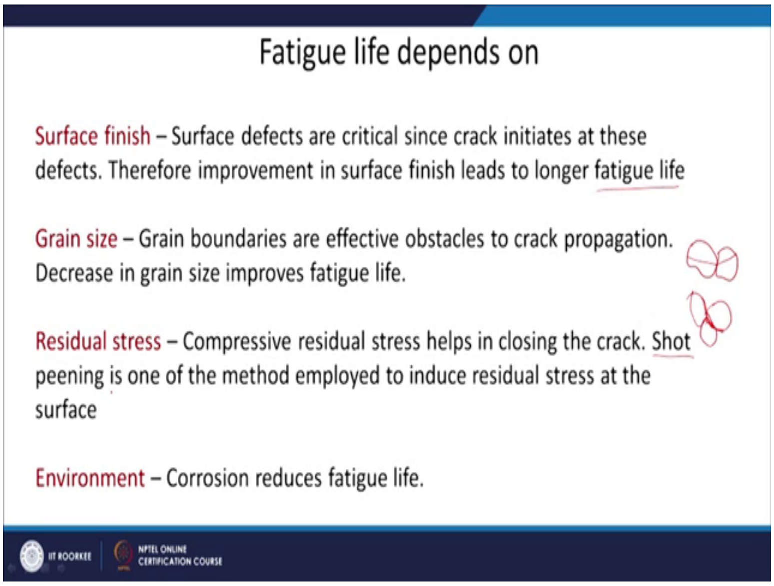

Now, fatigue life depends on these parameters ok. So, surface finish as you can see that when we said that the initiation of crack takes place, because locally; if there is any going to be any defect the material will start the locally the stress will be high. So, it will it will have some plastic deformation locally and because of this inclusion exclusion you will initiate a crack there.

So, I can improve the; fatigue life of a material if I do a very good surface finish good nice surface finish with using buffing and. So, on grinding buffing and so, on so, if I improve the surface finish kind of remove all the small defects on the surface I will be able to improve the fatigue life ok. So, so, surface finish is very important ok

You have to have very good nice surface finish of your material whatever application you are using in then grain size. So, grain boundaries are effective obstacle to crack propagation ok. So, decrease in grain size improves the fatigue life. So, suppose as I we showed you that these are the two grains. Suppose if it is a trans granular fracture also the crack propagate in this direction on a certain crystallographic plane. In the next grain this crystallographic plane may be in some other orientation. So, now, crack has to deviate from this location to this direction to some other direction ok.

So, this kind of provide an obstacle to that, suppose the crack is going through the grain boundary ok, then what will happen that it is growing through the grain boundary then the grain boundary orientation has change. So, it has to move in a different grain boundary now.

So, grain boundaries provide very good obstacle to crack propagation. So, if I decrease the grain size, I will increase the grain boundary area ok. So, I am able to provide more obstacles to crack propagation, then the residual stress as I told you compressive stresses are good because they close the cracks ok. So, if I induce compressive stresses in the material on the surface ok, what will happen is that when I am applying a tensile stress some tensile stress will go in cancelling out the compressive stress and my material will experience only some part of that tensile applied tensile stress.

So, inducing any compressive stresses on the surfaces is very good for residual stress for a improvement in fatigue life ok. So, compressive residual stress helps in closing the crack one of the method to introduce this compressive stresses on in on the surface of the material is called shot peening ok. Shot peening means we take small steel balls and we strike the surface at very high velocity these steel balls go and hit the surface of the material ok.

So, what it does when it hits it induce compressive stresses in the material ok, and when you have this kind of compressive stresses, then it will be good for your fatigue life environment if your material is corroding this corrosion itself will act like a flaw will initiate cracks. So, we should not have any corroding environment around a component where which is going to experience the fatigue cycle ok. So, these things we have to keep in mind when we are using any material under fatigue application ok.

So, with that I thank you this is one of the very important topic and I hope that you have understood the topic and you will appreciate it.

Thank you.