**Surface Engineering for Corrosion and Wear Resistance Application**
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**Lecture - 08**
**Fatigue**

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## Fatigue – Surface Dependent Property

What is Fatigue, its Characteristics

Fatigue Parameters

How to evaluate fatigue property

Hello, in this talk I am going to discuss another important mechanical properties of the matter it is Fatigue. So, in this lecture with a brief introduction to fatigue I will discuss about its characteristics, then the parameters which influence the fatigue as well as the way it is represented and how to evaluate the fatigue properties and finally, the techniques by which we can into the fatigue properties of the material.

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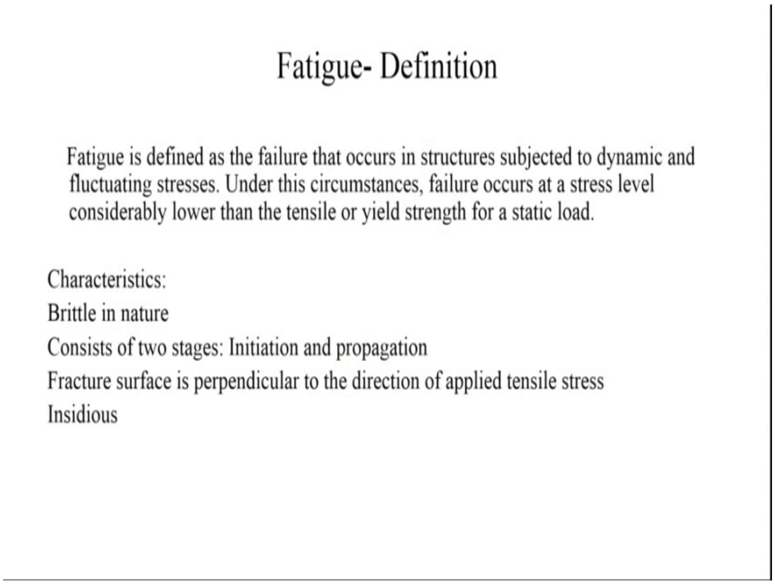


Now, fatigue is defined as a failure that occurs in the structure which is subjected to dynamic and fluctuating stresses. So, under this circumstances usually it is observed that failure occurs at a stress level considerably lower than that of tensile or sometimes yield strength of the material under static load.

If you quickly go through the characteristics of the failure you will see that it is a little different from that of failure of the material under uniaxial tensile loading usually it is brittle in nature, it consist of two stages initiation and propagation. And usually fracture surface is perpendicular to the direction of applied stress and it is usually insidious in nature. So, this kind of very dangerous form of failure of the component in surface.

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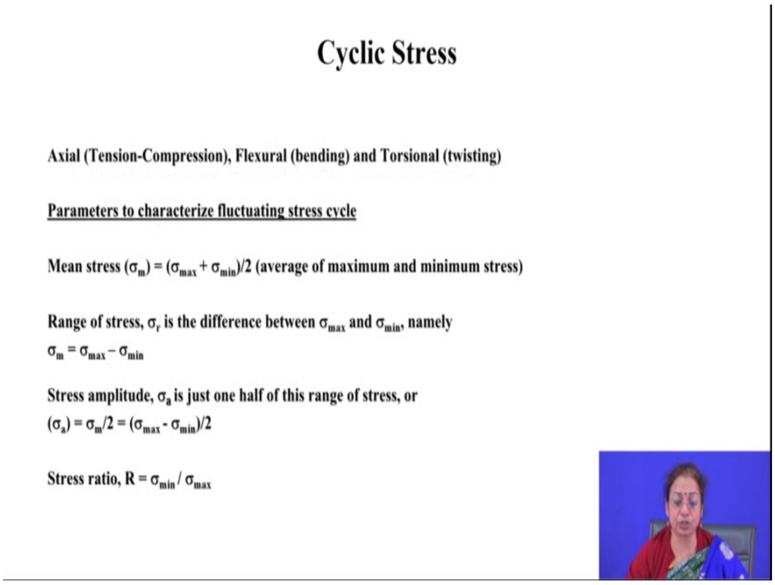


If you just quickly go through the cyclic stress in under uniaxial loading when the component walks then it is very easy to define the stress level. But when the cyclic stress operates on the surface or of on any component you have to define the stress.

So, usually the cyclic stress may be a axial in nature, flexural in nature or torsional in nature. If you just quickly go through the parameters to characterize the fluctuating stress it may be the as follows it may be mean stress which is nothing, but the average of the maximum and minimum stress which is the component is subjected to. It maybe range of stress it is nothing, but the difference between the maximum and minimum stress and it maybe the stress amplitude which is nothing, but mean stress divided by 2.

And it can be stress ratio as well which is the ratio between the minimum stress and maximum stress. So, by this 4 parameters actually cyclic stress is actually represented. So, whenever you talk about cyclic stress you have to talk about any of the parameters which is discussed.

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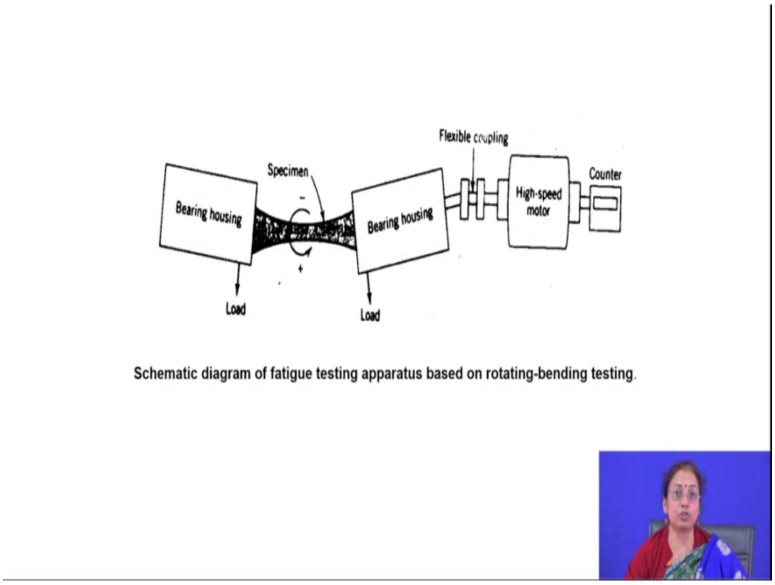

Schematic diagram of fatigue testing apparatus based on rotating-bending testing.

Now, if you quickly go through the way by which the fatigue property is measured it is measured by the typical testing which is called rotating bending testing. So, in this particular test you have the typical tensile specimen which is subjected to continuous rotating and bending operation. So, here when the component is actually subjected to loading you will find that one part of the component is bent actually, so one side is subjected to tensile loading and reverse side is subjected to compressive loading.

So, when you rotate the component you will find that the reverse phenomena occurs the site which you are subjected to compressive loading it actually faces the tensile loading and the other surface faces the compressive loading. So, by this process the same side of component is repeatedly subjected to the compressive and tensile loading and number of cycles to failure is actually recorded with the help of a counter and you can define the number of cycles to failure and for a particular stress level.

So, in this particular testing you need to have a large numbers of samples you go on changing the axial that cyclic stress with different values having different values and then find out the number of times or number of cycles to failure under each cyclic loading operation under each mean stress or under each stress ratio the number of cycles to failure.

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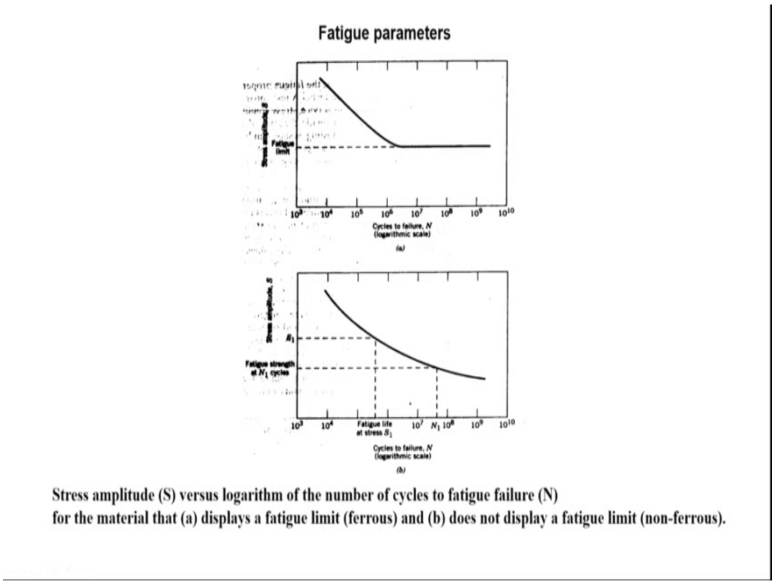


And then you represent the fatigue properties in terms of the cyclic cycles to failure like as a function of stress amplitude or may be specially stress amplitude is commonly applied as a parameter to define the cyclic stress.

So, if you just quickly go through the number of cycles to failure as a function of stress amplitude you will having different kind of behaviour in ferrous and non ferrous material. This is a schematic representation of the fatigue behaviour of ferrous material this is for non ferrous material you will find that in ferrous material when the stress level is below the fatigue limit there is below a certain value of the stress amplitude there is no failure at all. So, we call it as fatigue limit.

So, fatigue limit is usually taken as a safe limit or safe cyclic stress where the component can be applied very nicely, but when the stress level that stress amplitude increases above the fatigue limit there is a chance of failure. So, you have to use the component at a particular at a cycle which is much lower than that of designated cycles to failure of the component under this particular stress amplitude.

From the other hand if you quickly go through the behaviour fatigue behaviour of the non ferrous materials it does not have any safe fatigue limit, but usually it is observed that as you go on decreasing the stress amplitude the cycles to failure actually increases. So, here you have to always define the typical stress amplitude or stress at which there is number or you have to say the number of cycles to failure at a particular stress amplitude.

So, whenever you say about the stress limit of the component then you have to always define the number of cycles to failure. So, you use the component at a stress cycle at a cycle much lower than that of the fatigue limit of the component. So, these are the two important way by which you basically define the fatigue properties of the ferrous as well as non ferrous materials.

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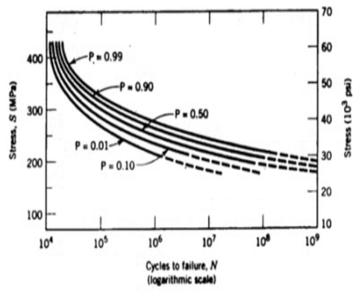


Fatigue S-N probability of failure curves for a 7075-T6 Al alloys.
P denotes the probability of failure

The other way by which you can also basically define or designate the fatigue properties of the material it is nothing, but the probability to a failure. So, where the stress amplitude is actually or its number of cycles to failure is actually taken is slotted as a function of stress amplitude and you just go on defining the probability to failure.

So, you will find that when the probability to failure is 0.99 then naturally the cycles to failure is much lower than that of probability of failure when the stress amplitude is lower. So, like that you can also define the fatigue behaviour of the component that is the probabilities of failure. So, when probability of failure is negligible. So, you can use the particular material at that particular stress limit in a very safe fashion in that stress amplitude at a safe fashion.

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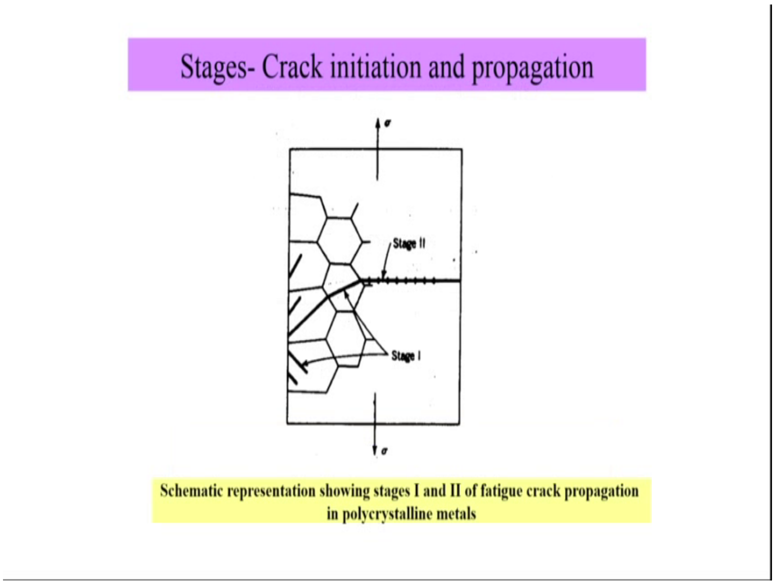


Now if you quickly go through the stages in fatigue, you will find that fatigue usually process in 2 stages 3 stages you can say; stage I is the crack initiation and stage II and stage III are the crack propagation stages. So, crack initiation actually stage you can say there is no stage I people call people call is as crack initiation and crack propagation stages and crack propagation consists of 2 stages stage I and stage II.

If you quickly go through the reason behind the crack initiation you will find that it is because of the presence of the impurities presence of the imperfections on the surface, defects on the surface the stress concentrations at the surface. So, impurities defects stress concentrations at the surface are responsible for crack initiation. So, as I was mentioning that the fatigue is very much dependent on the surface this is because of the reason that crack initiation or fatigue crack initiation is dependent on the surface imperfections value.

So, if you prepare a surface which is free from any flaws which is free from any imperfections, impurities which is free from any stress concentration point, then you can always improve the fatigue life of the component. Now if you quickly go through the crack propagation stage crack propagation again consists of 2 stages; one stage I crack propagation, another one is stage II crack propagation. So, now, if you quickly go through the stage I crack propagation, it basically process at a much slower fashion. So, rate of crack propagation in stage I is very slow and this is nothing, but the propagation of the crack along the direction of the crystallography close packed direction of the material and it proceeds up to 2 or 3 grains right from the surface. So, stage I crack propagation is much slow and if you can and it is also controllable.

So, this is the another reason that fatigue is surface dependent property. So, if by anywhere by surface hardening you can reduce the kinetics further then you can always improve the fatigue life of the component because, this is controllable stage. On the other hand, when the crack length actually increases the it exits the critical crack length for the failure of the component.

In that case, you the crack proceeds at a much faster rate that is stage II crack propagation it is very difficult to control. So, that stage II crack propagation rate is dependent on the fracture toughness of the component. So, you cannot really buy any surface treatment, you cannot control the stage II or cannot prevent the stage II crack propagation.

So, this is very important to note that if you are interested to minimize or improve the performance of the component under fatigue loading you have to improve the surface very nicely. So, that there is no imperfections, there are no imperfections, there are no inclusions, there are no stress concentration points at the surface or otherwise you harden and tuff in the surface in such a fashion that stage I crack propagation rate reduces to a large extent.

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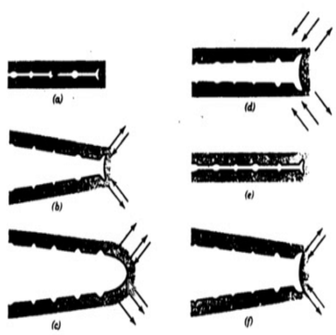


Fatigue crack growth propagation mechanism (stage II) by repetitive crack tip plastic blunting and sharpening; (a) zero or maximum compressive loading, (b) small tensile load, (c) maximum tensile load, (d) small compressive load (e) Zero or maximum compressive load, (f) small tensile load. The loading axis is vertical

Now, quickly go through the stage II crack propagation you will see that stage II crack propagation mechanism is by repetitive crack tip plastic make a blunting and sharpening mechanism. So, if one such stage I crack propagation I mean that creates the crack having the crack length near to that of critical crack length in whenever it is subjected to repetitive compressive and tensile loading whenever it is subjected to tensile loading. So, there is crack widening and subsequently plastic bunting phenomena and when it is subjected to compressive loading then again there is closer of cracking and subsequently again closer of cracking and then again widening of cracking.

So, stage II crack propagation consists of 3 stages; one is crack widening, during tensile loading there is widening of the crack, there is plastic planting and during compressive loading there is again closer of the crack and by that process the crack advances by wants unit step. So, advancement of crack occurs in the compressive component of the loading. So, when is the component is subjected to compressive loading and then again there is widening phenomenon. So, you can see that typical crack propagation or crack length enhancement occurs during the tensile component of the loading.

So, it is very important that when you just apply the compressive loading there is closer phenomena. So, compressive stress is not really so harmful for the crack propagation of the crack, but rather tensile stress very harmful and most of the cases the crack propagation occurs during the tensile stage of the during the tensile component of the loading.

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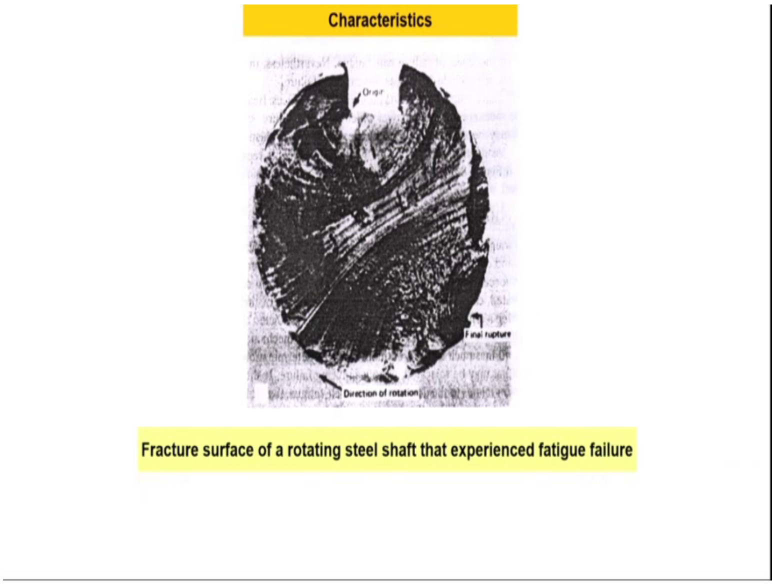


Now, if you quickly go through the characteristics of the fatigue failure it is very important that you know the characteristics of the failure of the component. So, that you can understand that what is the reason and also you can get preventive measures. So, that the component does not fail in surface due to that particular failure.

So, the characteristics of failed surface of fatigue failed component is nothing, but there are lot of beach mark small small bands on the surface. And this is like see beach marks when the that air blows on the see beach till find there is blowing marks on the each kind of. So, because of this particular appearance it is called beach mark and there is also the crack initiation points which is observe and final crack final cracking points is also visible. So, there are three important features one is crack initiation points observed, beach marks observed and the failure points are also zone of failure is also observed in the fail surface.

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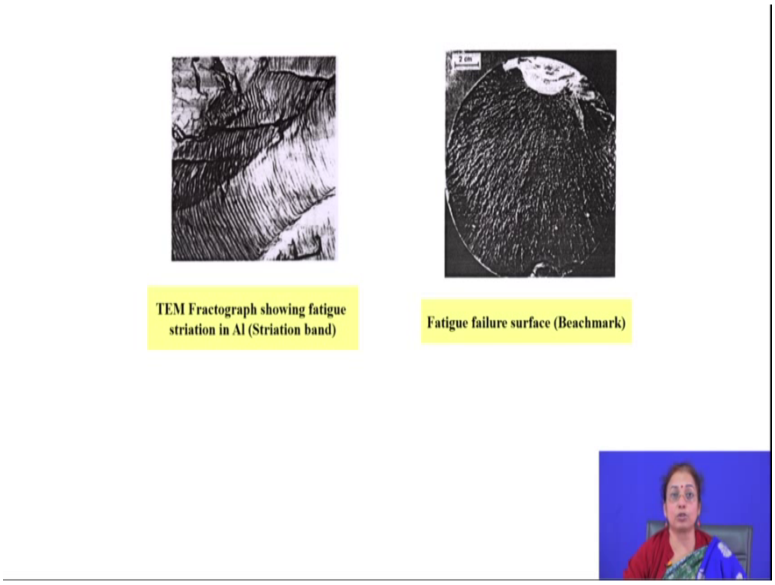


Now, if you quickly go through the beach mark very at a very high magnification you will find that the particularly when you go to TEM observation you will find that there is very fine striation band in the beach mark. And the this striation were striation band length is basically nothing, but the unit length that the crack propagates during the tensile loading of the component.

So, this is typical repetitive phenomena and it is very much dependent on the component of the amount of load the component is subjected to the magnitude of load the component is subjected to and it is also dependent on the microstructure and composition of the component.

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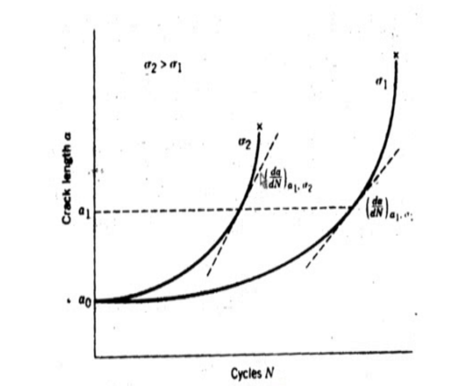


Crack length versus number of cycles at stress level $\sigma_1$ and $\sigma_2$ for fatigue studies

Now, if you quickly go through the that crack length as a function of number of cycles to failure you will find that the rate of crack length propagation with number of cycles to failure actually is very much dependent on the amount of the stress amplitude the component is subjected to.

So, as a stress amplitude increases you will find that as you find that the there is a higher value of the cyclic stress amplitude, value as it increases you will find the rate of crack propagation also increases. So, rate of crack propagation or maybe fatigue life of the component is very much dependent on the stress amplitude value I mean to a large extent.

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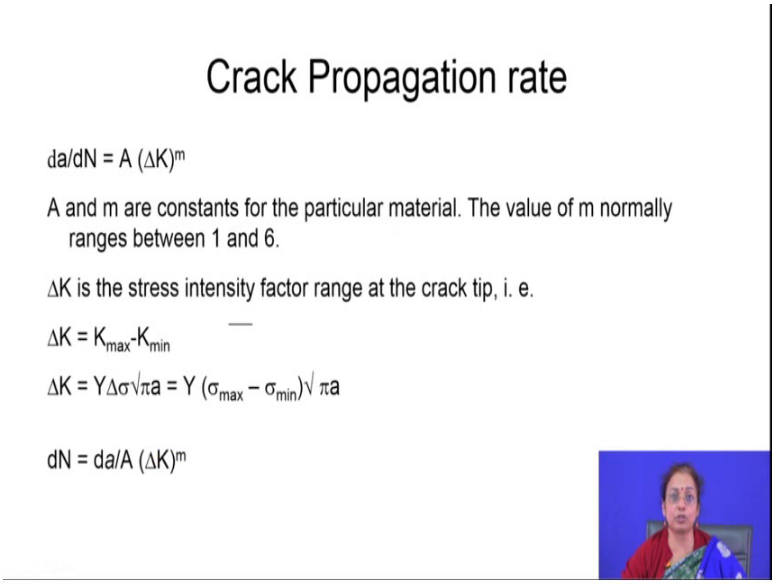


So, if you can reduce the stress amplitude by that process you can reduce the crack propagation rate as well. If you just quickly go through the parameters which actually control the crack propagation rate where a is the crack length and N is the number of cycles to failure. So, da dN can be stated as the typical constant and this is del K is nothing, but the stress intensity factor range to the power m and m is a constant again, the value of m depends on it is very usually 0.26 for the metallic materials.

And del K is the stress intensity factor range which is nothing, but K max minus K min and which is again dependent on the yield strength that Young's modulus of the material then there this is stress range and also the this is the crack length. So, finally if you derive at the term of come to the dN da equal to 1 over A del K to the power m.

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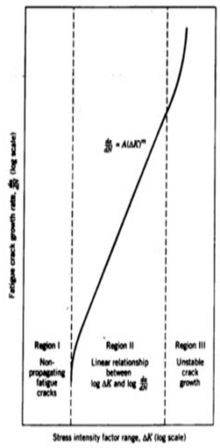


Schematic representation of logarithm fatigue crack propagation rate (da/dN)
Versus logarithm stress intensity factor range, ΔK.

If you just go on measuring these are go on plotting the fatigue crack growth rate as a function of stress intensity factor log float you will find that there are 3 regions; one is the region I where there is non propagating fatigue cracks, region II where there is relation linear relationship between the log del K and log da dN and unstable crack growth where it is very difficult to control the crack propagation rate. So, usually the material is say for it is waited to use the material in the region I where there is no there is non propagating fatigue cracks the fatigue cracks cannot propagate.

So, this is a very safe plot or it is very use useful plot to determine the usefulness of through determine the actually is service to dictate the fatigue stress intensity range of the to dictate the stress range or maybe you can say that fatigue limit fatigue limit of the component where the component should be used.

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Now, if you quickly go through the now in summery you can say that it is very important that you just go on. Concentrating on the surface in order to improve the fatigue life of the component, but in most of the cases particularly if you talk about the component when it is in service if you have to design the component for improved fatigue life usually it is done by proper designing. So, where the basic phenomena or the key point is that you have to avoid the typically stress intensity points where there is chance of stress concentration.

So, this is done by proper designing of the component usually you should avoid the sub points of corners you make it a little bit smoother. So, where there is chance of change in the curvature so by that process you can improve the fatigue life. You can also improve the fatigue life by proper surface treatment. So, surface treatment if you talk about the importance surface treatment techniques which most of the people apply is try to avoid the point of stress concentration you reduce the roughness of the component.

And also you reduce the imperfections on the surface and reduce the stress level on the surface which is done by proper polishing operation, which is also done by typical electro polishing operation and also use that polishing operation where which does not create much stress on the surface.

And you can take care of the stage I crack propagation by typical surface hardening operation. So, when you talk about the surface hardening operation you have to think of the toughness as well. So, usually there are several surface hardening treatment processes available. Some of the surface treatment processes they basically take care of hardness enhancement they do not bother about toughness for example, if you think of titanium nitride coating on titanium or think of chromium nitride coating on the steel in that case you will find that though hardness is increased, but the layer is not really tough.

But if you are interested to improve the stage I crack propagation failure if you are interested to improve the or minimize the stage I crack propagation rate you have to think of the toughness as well along with the surface hardness.

So, you should think of that particular difficult hard facing processes where you improve the toughness as well as hardness both. Another way by improving the surface or fatigue life of the component is by introduction of the residual compressive stress on the surface. You will find that if you just quickly go through the stages in crack propagation particularly in stage II crack propagation you saw that stage II crack propagation consists of repetitive crack winding, plastic blunting and then closer of the crack.

So, closer of the crack usually occurs when the compressive stresses acting on the component. So, compressive stress is beneficial in improving the fatigue life of the component. So, if you by any technique introduces the compressive residual stress on the surface by that process to improve the fatigue life of the component.

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## Mechanical surface enhancement techniques

**Shot peening (SP)**

**Laser shock peening (LSP)**

**Low plasticity burnishing (LPB) and**

**Deep cold rolling (DCR)**

Usually compressive residual stress is applied by different ways like shot peening, laser shot peening, low plasticity burnishing operation, deep cold rolling processes. So, those techniques are widely applied for introducing residual compressive stress on the surface. So, in shot peening operation you go on impacting thin shots made of steel or ceramic materials or sometimes make these are all spherical balls actually they are impacted on the surface, they are thrown on the surface at a certain velocity.

So, by that process you basically introduces lot of compressive residual stress on the surface. But the main problem of the shot peening is that by this process you basically introduces nano deformation on the surface or sometimes it is micro deformation as well. So, whenever you do shot peening operation after that you have to be careful about the appearance of the surface. That it is a very good technique because by shot peening you basically take care of the fatigue property as well as you can clean the surface to a large extent.

So, usually if you apply the shot peening process after carburization particularly or may be flame hardening induction hardening operation. Then usually while flame hardening induction hardening or carbonization process there is formation of very thin oxide layer on the surface is not so clean. So, if you do apply shot peening operation it cleans a surface to a large extent. And in addition to that there is also introduction of compressive residual stress on the surface. So, this process is very much beneficial in improving the fatigue life of the component.

Laser shock peening is another process, which is quite interesting where high powered high energy density pulse laser beam is allowed to eradiate the surface of the component. And when it is eradiating on the surface of the component there is ablation of the material from the surface and the energy density is so high that ablated gaseous species they converts into plasma. And that plasma actually apply special on the surface of the component and that pressure causes the compressive residual stress to get introduced on to the component. So, this is called laser shot peening.

So, the operation can be conducted in air or it can also be conducted in water or may be by application of very thin black painting on the surface. So, if the surface is covered with water or surface is covered with a black painting then in that case you will basically minimizes the probability of the ablation of the material from the surface. So, instead of ablation of the material from the surface there is a actually evaporation and plasma formation from the media may be water or maybe the ink. So, that evaporated material forms plasma and that plasma applies pressure on the surface.

So, this is very interesting technique and lot of work need to be conducted in this area because this is not really quiet widely used technique its not really commercially applied or acceptable technique because of lack of knowledge on the effect of the process parameters on the shot peening hardness and also shot peening micro structure.

So, low plasticity burnishing and the deep cold rolling there another two processes where basically you go on applying pressure on the surface to a large extent in order to improve the in order to introduce the compressive residual stress on the surface. So, by this process also you can introduce compressive residual stress on the surface in addition to that you basically improve the hardness of the surface also to a large extent by the process of strain hardening.

So, these all mechanical surface treatments are very interesting and important in order to improve the fatigue life of the component by introduction of compressive residual stress on the surface. If you are interested to clean the surface you can go for typical electro polishing operation, you can go for plasma training operation, you can go for typical simple polishing operation mechanical polishing operation.

So, by that process you can get rid of discontinuities on the surface or any other impurities is present on the surface that also will reduce the probability of the crack initiation. And you can also improve the fatigue life of the component by the particular the stage I crack propagation rate minimization can be achieved by surface hardening operation. So, surface different surface hardening treatments are available which can be applied for improving the service life of the component under fatigue.

So, these are for example, carburization of the low carbon steel and subsequent tempering operation this is very good treatment for improving the fatigue life of the component. So, usually we will find that when you do carburize nitrating operation when you do carburization or when you do nitriding a very thin harden layer is formed and that layer actually is as harder than that of pure metal. So, it increases the hardness also a fatigue limit of the components. So, these are different ways you can improve the fatigue property of the component.

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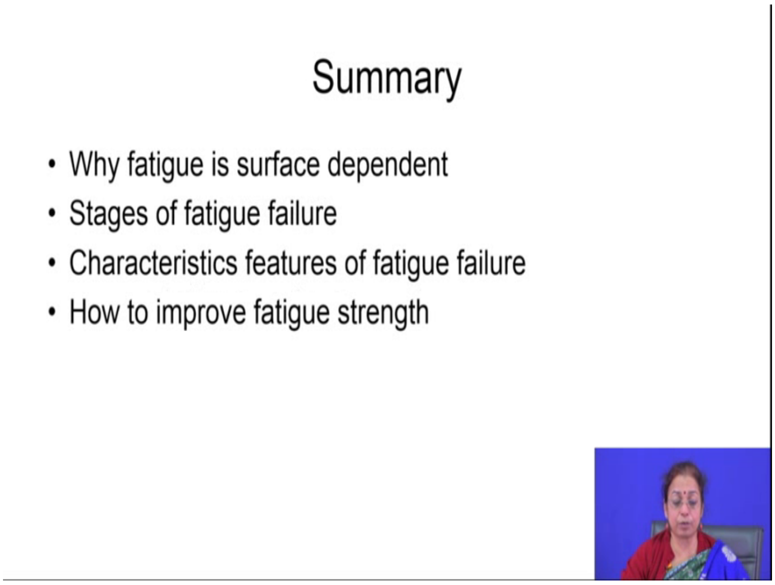


Now, in summery we can say that why say fatigue is surface dependent that is discuss because it is surface dependent property mainly because of the fact that it initiates from the surface and also a few layers from the surface a few the after few day from the surface the fatigue failure can be controlled. If precautions are taken particularly by the application of residual compressive stress or by application of different hardening technique and also fatigue crack propagation stages controllable as I mentioned and also the layer has to be tough.

So, because of these two reasons the fatigue failure is actually surface depended failure. We also discussed about stages of fatigue failure like what I state the stages stage I fatigue failure and stage II fatigue failure. So, in stage I there is crack initiation and stage II there is propagation. Stage II again consists of two different stages like stage I and stage II, stage I there is crack propagation stage I rate is very slow and stage II it is quite fast in nature.

We discussed about the characteristics features of the fatigue failure usually beach marks that crack initiation sides and crack propagation sides are three important characteristics features of the fatigue failure. So, it is very important to know the characteristics features of the fatigue failure. Because usually in service failure occurs by a large numbers of reasons.

So, if it is not known the if the characteristics features is not known then it is very difficult to know what is the reason behind the failure and also the recommend the certain surface treatment or the taken precautionary measure so that the failure does not occur in practice. So, usually in fatigue failure we found that the characteristics features are beach marks and then strength band these are the two characteristics features of the fatigue failure.

And we also learn on how to improve the fatigue strength it is usually improved by introducing the compressive residual stress on the surface may be achieved by typical shot peening laser shot peening and different other low plasticity burnishing operation ultra sound burnishing ultra sound peening operation. It can also be improved by hardening operation and the hardening techniques which are applied for fatigue strength improvement, depends on the kind of material you are looking for if it is difficult medium carbon steel you can apply flame hardening induction hardening operation and subsequent to that you can go for tempering operation if it is low carbon steel then you can go for carburizing operation.

If it is low carbon low alloy steel you can go for typical nitriding operation, if it is non ferrous materials you can go for different hard facing operation by any of the hard facing techniques like typically well lower laying, thermal spraying, plasma spraying those treatments can be applied for the fatigue strength enhancement.

But whenever you apply any technique, surface treatment technique for improvement of the fatigue strength you have to be careful about the surface impurities you have to be careful about the toughness of the surface and you have to also be careful about the design of the surface. You should avoid the sharp corners you should avoid the imperfections on the surface, you should avoid the that coating which gives rise to very hard surface, but quit brittle.

Because if it is brittle in nature there is chance of failure of the component and you can also improve it by introduction of compressive residuals stress of the component which is very easy and quick technique to improve the fatigue strength of the material.

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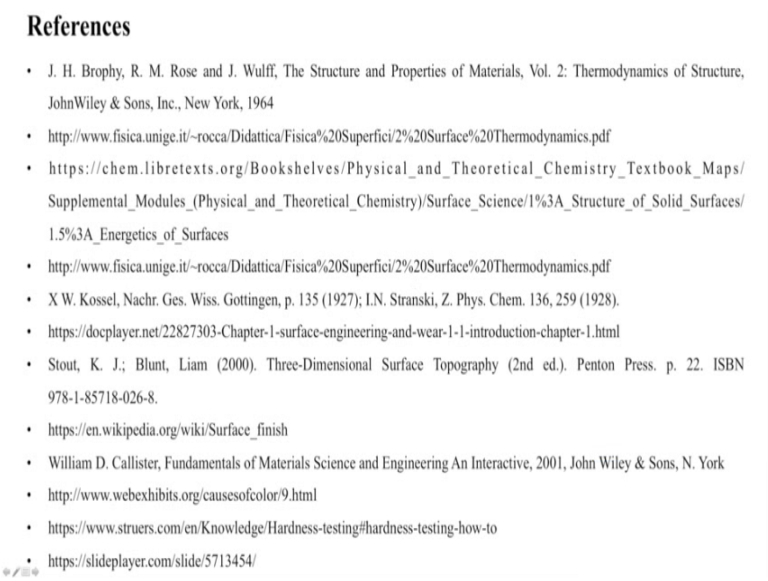


Thank you very much.