Mechanical Behaviour of Materials

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Module - 11
Lecture - 60
Fatigue - I

Hello, I am Professor S. Sankaran in the department of Metallurgical and Materials Engineering.

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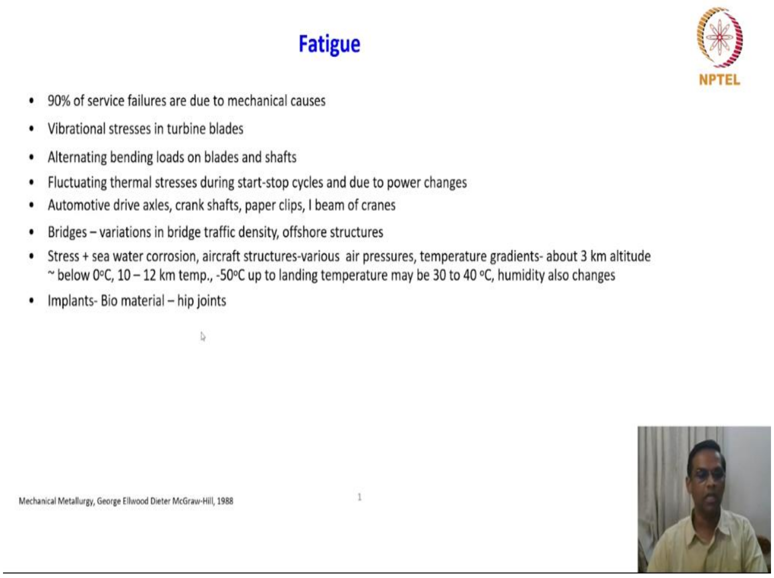

Hello everyone, welcome to this lecture. And today we will pay our attention to the topic on fatigue. Though we have seen this phenomenon along with the fracture mechanics, in fact, we looked at elaborately on the crack growth aspects in terms of Paris law; and we also looked at the fatigue threshold, crack growth and environmental effect and various crack closure mechanisms; Wheeler.

In fact, all the design related aspects of fatigue, we have already seen along with the fracture mechanics; but in this lecture, at least I want to look at the other aspects whatever we have not yet touched upon. In fact, we will start with the very historical background and basic definition of fatigue and so on, just so that you have a complete information about this topic. So, 90% of service failures are due to mechanical causes; that is why we are interested in fatigue.

What you have to understand here is, though the typical tensile test gives an idea about a yield stress of a material or yield strength of material. And when material is subjected to cyclic loading or multiaxial loading, the material will fail much below the yield strength or yield stress. That is why we in fact study all the mechanical behaviour in detail, like for example three, the high temperature definition and biaxial loading, triaxial loading, and then with environment, without environment.

So, all these aspects, the material is going to respond to the external loads or type of external loads very differently. That is why we study all these different aspects of mechanical behaviour, like tensile impact the fatigue, fracture and so on. So, vibrational stresses in turbine blades. For example: a typical example by which the failure takes place through fatigue.

In fact, we have seen this as a; in the fracture mechanics lesson, one of the blades we have shown is the turbine blades, where the critic fatigue crack growth was shown. Alternating bending loads on the blades and shafts; this is most of the rotating body whether in any engineering setup or even the vehicles, automotive vehicles; these are all quite routine components which are subjected to alternating bending loads.

Fluctuating thermal stresses during start-stop cycling and due to power changes. So, this is also another source of cycling load, not necessarily mechanical, but here we are talking about thermal fatigue. Automotive drive axles, crank shafts, paper clips; very day to day examples; I beam of cranes. And bridges; where you see the variations in the bridge traffic density, offshore structures.

And stress plus seawater corrosion; aircraft structures, various air pressures; temperature gradients, about three kilometre altitude below 0 degree centigrade temperature will be experienced, and ten to twelve kilometre temperature, -50°C temperature will be experienced; and up to the landing temperature maybe 30 to 40 °C; humidity also changes. So, the aircraft is one classical example where you have all type of environment; first of all, cyclic loading plus stress corrosion cracking environment and then temperature difference depending upon the altitude.

So, that is why, in fact, we emphasise the crack growth problem and the crack nucleation problem. We elaborately discussed in the fracture mechanics, because of this aspect. And even implants in a biomaterial, most of the biomaterial; a classical one is hip joints; they are all subjected to fatigue loading. So, this we know.

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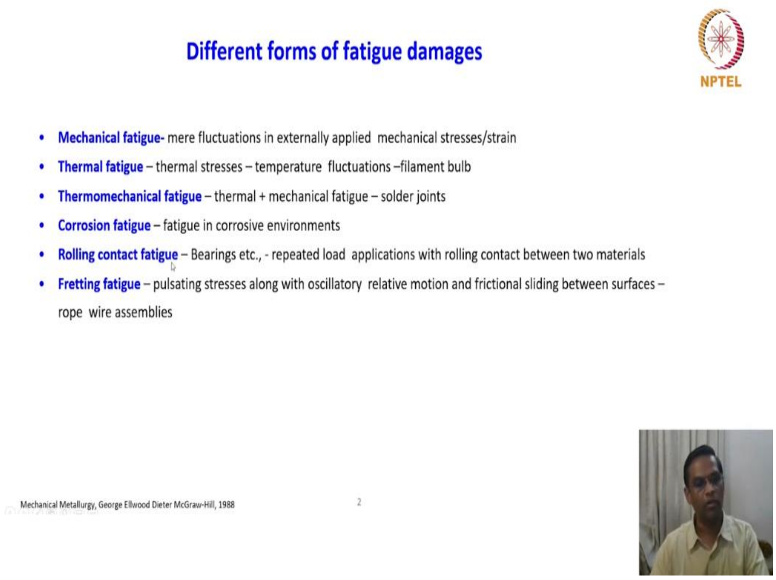

And we will look at what are the different forms of fatigue damages. And the one which we generally talk about is mechanical fatigue where mere fluctuations in the externally applied mechanical stresses or strain is considered. And thermal fatigue where thermal stresses, temperature fluctuations only considered. Example is filament bulb. And there is something called thermomechanical fatigue, where thermal plus mechanical fatigue, they are combined together.

That means, mechanical fatigue happening at very different high temperatures. A typical example is shoulder joints. Corrosion fatigue: Fatigue in corrosion environments; that is very important. And rolling contact fatigue, where example in bearings, etcetera, the repeated load applications with rolling contact between two materials. So, rolling contact fatigue is also important on some of the rays on the top surface; very important applications.

And then, fretting fatigue: Pulsating stresses along with oscillatory relative motion and frictional sliding between surfaces. For example, rope in the wire assemblies. There an inner core wire will be there; and then, there will be a shell or cover. They will just move against one surface against the other surface or inner surface; so, that will create a kind of fatigue loading. So, you see that primarily you have about six types of or different forms of fatigue damages. Here we can just look at it.

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If you look at the historical background, the fatigue, the word comes from the Latin word fatigare; means, to tire. So, like human beings get tired after some heavy work, workload, like material also get tired. That is the kind of meaning. And if you look at the definition, fatigue is a term which applies to changes in properties which can occur in a metallic material due to the repeated application of stresses or strains, although usually this term applies especially to those which lead to cracking or failure.

We have to understand that fatigue is a failure mechanism. In a fracture mechanics, we described fatigue as a crack growth mechanism. So, that is why it is completely come under the fracture, not this deformation. Fatigue and fracture mechanics are closely related. They are in fact 90% overlapped, because fracture mechanics considers fatigue as one of the primary crack growth mechanisms.

So, similarly, here also, we will bring in fracture mechanics class concepts wherever it is required; we will see. And fatigue is recognised problem with the advent of rotating and reciprocating machines during industrial revolution in 1800. And in last four decades, mechanical, microstructural, environmental factors on cyclic deformation has been investigated, because of the optical and electron microscopy development.

People started looking at the PSBs called persisted slip bands, striations, crack closure, short and long cracks, variable amplitude spectrum loads, corrosion, low and high temperatures, multiaxial state of stress, notch fatigue, life prediction methods, non-metallic materials, composites, thin films, nano materials, bulk metallic glasses. So, because of all these developments, the fatigue has been focused, has taken into different branches, because of the material development and also the characterisation techniques and also the needs, the special needs, the special environment and so on.

So, the fatigue is going in all this fields. So, it is an underpinning phenomenon. Whatever the material changes, whatever the technology changes, you have to study this phenomenon; without that in engineering, you cannot do any, save the life of the component, without understanding this phenomenon. So, that is very important.

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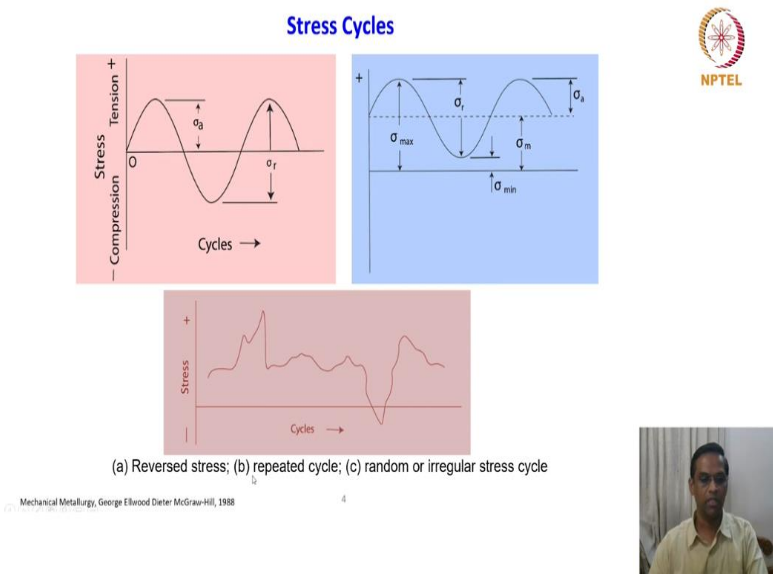

So, now we will look at what are the stress cycles, the basic idea about this stress cycles. What you see here is a stress versus a cycle plot. So, you have the sinusoidal cyclic stress is shown here. This is a tension axis and this is a compression axis. So, this distance what you are seeing is a σ_a. That is a, you can say amplitude or alternating stress; you can call it σ_a. And this is σ_r; it is completely a reversible cyclic, completely reverse cycle.

So, this is one way of subjecting the cyclic loading. So, in this type of loading, what you have to understand is, the magnitude of the tension and compression is equal. So, there is no net effect. We will see what is that, what is the (()) (11:28). So, on the other hand, what is seen in the first one; if you look at this, it is entirely quite different. What is the major difference? The complete cycle is happening only in the tension region.

So, it is always tension tension, but only the magnitude varies here. So, this is a σ_{max} and this is a mean stress σ_{min}. You can see that σ_{min}. And this is σ complete reversed cycle, and this is a σ_a, alternating stress. So, this is σ_{min} and this is σ_{max}. So, that is how it is shown. So, you can choose any one of this kind of loading to study the fatigue phenomenon.

But what about this figure? What does it show? In fact, most of the, in real time situation, the stresses will be of this kind, like any critical engineering component will be subjected to, they will be experiencing this kind of a stress cycle. For example, typically the aircraft wing, when it flies at the high altitude, because of the gusts, right? So, this wing will be subjected to this kind of arbitrate loading.

So, you can see that, though there is no constant amplitude here, suddenly it spikes kind of a overload. This is an overload here; again something like that. So, in reality, it will be very complex. So, that is why, whatever we do in the laboratory in the form of fatigue test, it will give some idea, it will never replace the reality. So, what are the complicated cycles we can; I mean, if you are interested in studying the material behaviour under cyclic loading of very complex cycle nature, so, you can create one and then try to evaluate the life of the component of the material and so on. So, that is the idea. So, this already I have told. This is reverse stress and repeated cycle, and this is random or irregular stress cycle.

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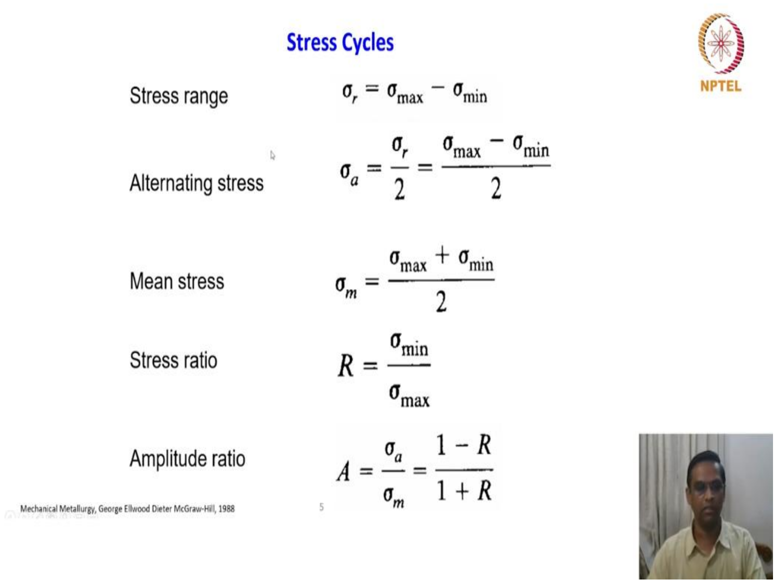

And then, we will now look at some of the basic definitions. Stress range: $\sigma_r = \sigma_{max} - \sigma_{min}$. So, I just said, completely reverse stress will have this stress range σ_r. And alternating stress $\sigma_a = \sigma_r/2$, where $(\sigma_{max} - \sigma_{min}) / 2$. So, this is one another definition. There is something called mean stress. Mean stress is $\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$.

And the stress ratio, very important parameter in fatigue; R is equal to $\sigma_{min} / \sigma_{max}$. So, this is called stress ratio. And there is also another parameter called amplitude ratio, which is designated as $A = \sigma_a / \sigma_m$, which is equal to $(1 - R) / (1 + R)$. So, this is some of the parameters which being used in the fatigue chapter or fatigue literature. You will come across all this terminology.

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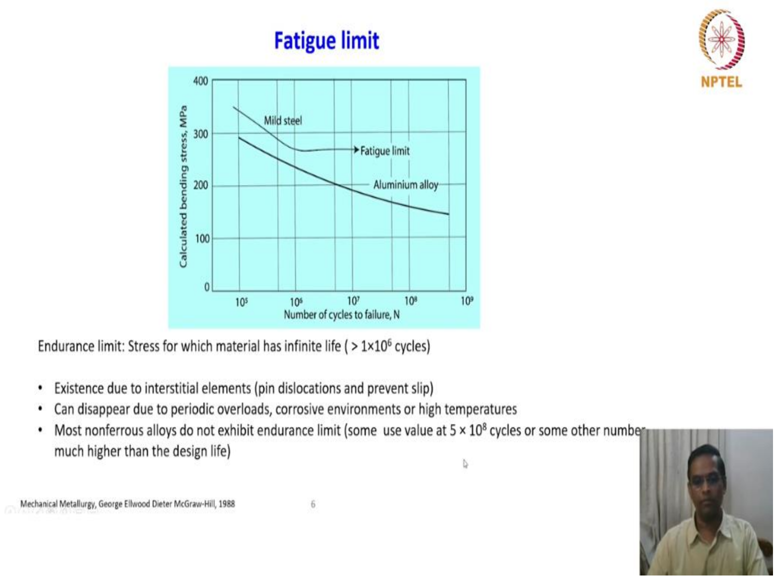

And one important parameter which is a characteristic of a material similar to yield stress is the fatigue limit of the material. So, typically, the fatigue limit is; you can see in the stress versus number of cycles to failure plot. For example, if you see the mild steel, the life keeps on increasing as the stress comes down, which is quite obvious; but after that, it reaches a saturation here.

So, this is around 10^7 number of cycles typically characterised as a fatigue limit. But if you look at the aluminium alloy, the stress keeps on decreasing; and with the decreasing cycle, the number of cycles to failure keep on increasing, but it is not reaching a saturation; it just goes down. And then, we will see why it happens. It is related to a microstructure. You know the phenomenon behind it. We will discuss that.

And this fatigue limit is also called as endurance limit. Stress for which material has infinite life, which is generally considered as more than 10^6 cycle, but in modern days, it is not just 10^6, it is 10^8 and beyond. In fact, if you look at the literature, people talk about very high-cycle fatigue. Very high-cycle means, it goes beyond 10^8 and 10^9 and 10^{12} and so on.

So, we will look at those details. The endurance limit existence is due to interstitial atoms; pinning of dislocations and which prevents the slip. That is one of the reasons people report. And this limit can disappear due to periodic overloads, corrosive environments or high temperatures. So, what we are talking about is the room temperature deformation here; but when it comes to overloads which we have seen in the last chapter, and corrosive environment, high temperature, this may not exist; the endurance limit cannot exist.

Most nonferrous alloys do not exhibit endurance limit. And hence, they use the value of 5 x 10^8 cycles or some other number much higher than the design life. As I just mentioned, fatigue limit is the design parameter, like yields. So, the material does not exhibit a fatigue limit or endurance limit and one can consider 10^8 number of cycles; the corresponding stress is considered as the fatigue limit.

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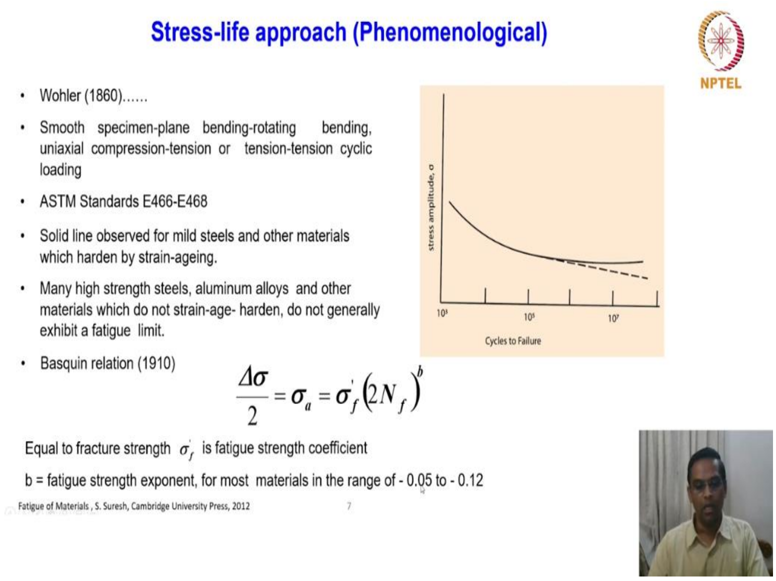

So, this way of finding out the S-N curve, that is the stress versus number of cycles to failure is called stress-life approach. So, that is how you should look at it. This is also called stress controlled fatigue or high-cycle fatigue. There are different names depending upon high-cycle fatigue, because normally the material reaches endurance limit and beyond, more very huge number of cycles.

So, the name comes from that kind of number of cycles. But technically, it is a stress controlled fatigue test. So, the stress amplitude is controlled and look at the life of the component. So, it is called stress-life approach. So, that is what is shown here; it is the same graph like what we have seen there before. And Wohler reported quite a bit of aspects about this fatigue in 1860.

And he conducted a lot of experiments on smooth specimen plane bending-rotating bending, uniaxial compression-tension, tension-tension cyclic loading. So, you can have any combination of this loading pattern to take this S-N curve. And there are standards now available, very well established standards, ASTM standards; E466 or E468 in a quite nicely exhibit the code for conducting this kind of test.

And the solid line is again for mild steel and other materials which harden by strain-ageing. See, most of the material which undergo the strain-ageing, you know; you have the background to understand this terminology now; they will exhibit a typical fatigue limit. Many high strength steels, aluminium alloys and other materials which do not strain-age or harden, do not generally exhibit a fatigue limit. So, this is one clue.

So, it is closely related to the microstructure, but it is also characteristic of a material; what we have just looked at (()) (21:13) material or (()) (21:14) and so on. And then, you can bring in some other microstructural aspect also; very many high strength steels we have, which have non (()) (21:26) micro structures, also will not undergo strain-ageing or strain-hardening or work-hardening significantly.

They also will not exhibit the fatigue, sharp fatigue limit. So, that point you have to remember. So, this stress-life approach is normally represented by this equation called Basquin relation;

$$\frac{\Delta\sigma}{2} = \sigma_a = \sigma_f^{'}(2N_f)^b$$

This is very important relation. So, equal to the fracture strength; $\sigma_f^{'}$ is a fracture strength or it is a fatigue strength coefficient; you can call it equivalent to the fracture strength what we have known in fracture mechanics. $\sigma_f^{'}$ is the fatigue strength coefficient. b is the fatigue strength exponent for the most materials in the range of - 0.5 to - 0.12; that is something we have to remember.

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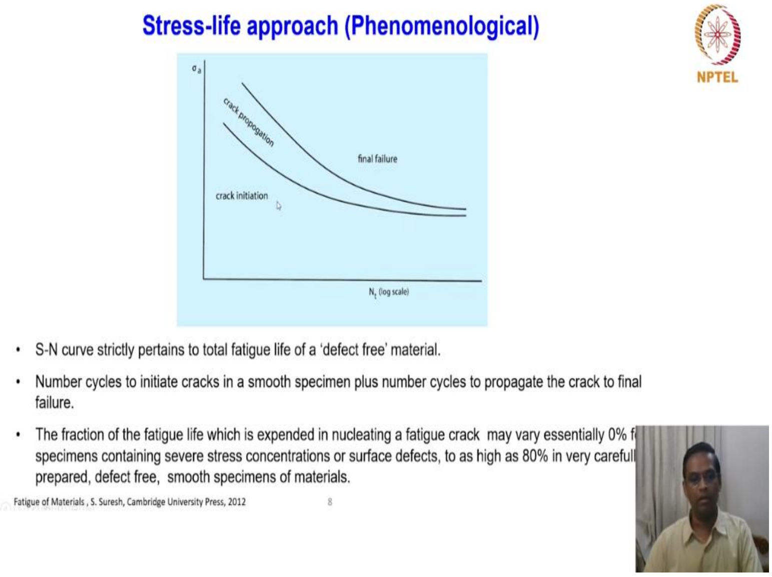

And like we have seen in the previous chapter, the fatigue life which we talked about is not, the total life is not; I would say the total life has got several components. It is not just represented by one factor. That is what I was trying to say. So, the total life contains a crack initiation period and the crack propagation period; and then, final failure. So, this is how the endurance limit curve has to be understood like this.

And of course, the gap between the final failure and the crack propagation keeps on decreasing as you move close to the endurance limit. And also close to the, when you approach the endurance limit, the life spent on the crack initiation is much higher. This also we have seen in the fracture mechanics chapter. As you come down in the stress, the time required to nucleate a crack or initiate the crack is much higher.

That is a major part of the life. And the crack propagation is much less. So, the S-N curve strictly pertains to total fatigue life of a defect free material. We assume that it is a defect free. Number of cycles to indicate cracks in a smooth specimen plus number of cycles to propagate the crack to the final failure. So, that is what is shown here. The fraction of fatigue life which is expended in nucleating a fatigue crack may vary essentially 0% per specimen containing severe stress concentration or surface defects to as high as 80% in a very carefully prepared defect free smooth specimens of materials.

So, what you have to understand from this statement is, for a fatigue tests, you need to prepare very careful surface; the surface should not have any defect. In fact, some people do electropolishing. Electropolishing also will create some surface defect. Some people adopt some etching technique to dissolve all the grooves which are generated by the turning operation by fabricating the turn by; the specimen is being turned.

So, this grooves all will get dissolved by the chemical etching. Then surface becomes smooth. There are several methods by which you can produce smooth specimen. Then you can see that 80% of the life will be exactly spent on the crack initiation. So, this is about the general aspects of the stress-life approach.

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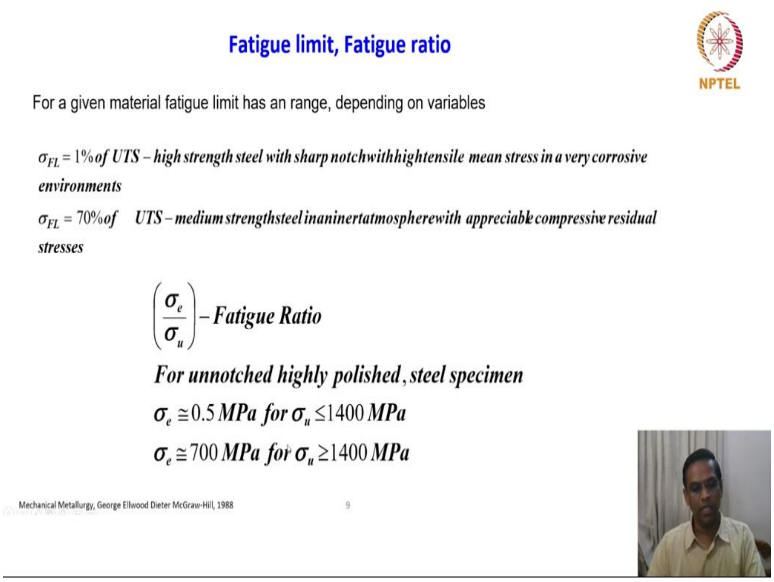

For a given material, fatigue limit has a range depending upon variables. σ_{FL} is 1% of UTS. Very high strength steels with a sharp notch with high tensile mean stress in a very corrosive environment. This is some kind of a thumb rule people have reported in the literature. σ_{FL} is 70% of UTS, which is medium strength steel in an inert atmosphere with appreciable compressive residual stresses.

So, this is all some thumb rules in a kind of a shop floor kind of environment people use. I just want to give some reference for that. So, there is something called fatigue ratio, which is σ_e/σ_u, that is ultimate tensile strength. For unnotched highly polished steel specimen, σ_e is equal to 0.5 MPa for specimen which is having σ_u less than or equal to 1400 MPA. Where σ_e is of 700 MPA, then you have to have the ultimate tensile strength should be greater than or equal to 1400 MPA. So, this is some kind of a thumb rule.

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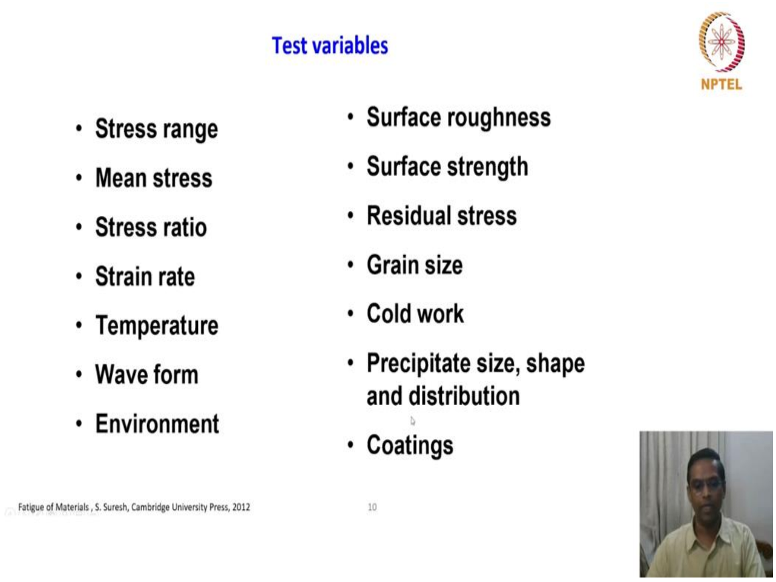

And what are the test variables? One primary variable which we talked about the surface roughness and also stress range. So, under these two headings, we can have several variables. One is stress range; and then, another is a mean stress; stress ratio r; strain rate; temperature; wave form. So, you have about six important test variables are possible. So, you need to select or fix each one of them for each fatigue tests.

And very importantly, finally, environment; this is again a variable. And if you look at the surface, surface roughness is one term; surface strength; residual stress; grain size; cold work; precipitate size, shape and distribution. So, look at the number of test variables. Now, we are going to affect the test results. It is quite a lot of variables. So, obviously, what do you expect in this kind of a tests? You will have lot of scatter.

That is why fatigue testing is inherently statistical in nature; fatigue data itself is a statistical data. Unless you have this statistical way of analysis the fatigue data, it is very difficult to arrive at a concrete or a meaningful conclusion. So, this is one important aspect you have to remember. Of course, the coating also one of the parameters which decides the fatigue life.

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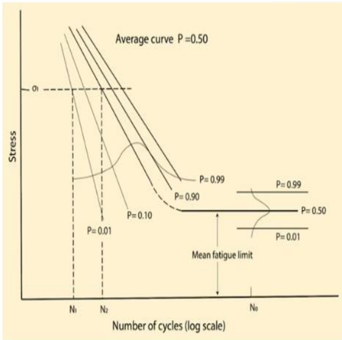
Statistical Nature of Fatigue



Representation of fatigue data on a probability basis

Mechanical Metallurgy, George Ellwood Dieter McGraw-Hill, 1988

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So, like it is just said, fatigue data, inherently it is statistical in nature. So, let us look at what are the statistical aspects of fatigue. So, what you are seeing here is very interesting plot. So, this is a stress versus number of cycles to failure plots. And when you see that, it is actually a three-dimensional plot drawn in a two-dimension. You can see, this profile goes and comes down. This is a three-dimensional profile.

And what you want to look at here is, what you are seeing is probability. The probability of the material failure is plotted. And you can see that this is a 1% probability, 10% probability and this is 50% probability and this is 90% and this is 100%. So, what you have to appreciate here is, suppose all these terms also will exhibit a kind of endurance limit. So, for example, if you take this curve, it will land up in this endurance limit.

And this 50% probability is coming in the centre; and about 10% probability is here. So, here itself, you have a distribution of data you have to predict the endurance limit. So, you may have the test which; your test may involve a stress level belong to this; and then it may fail within this if it is a higher stress. And if it is a lower stress, it may end up here. So, even this endurance limit from 10% to 100%, we need to have arrive at a mean fatigue limit.

So, that is how; even to create this kind of a plot in a true sense, you require a large number of samples. So, it is not like I will take my tensile test, one sample; I will test it; I will find out all the parameters; then I will take another specimen to test it again to look at the range of yield strength, ultimate strength so on. So, but in fatigue, it is not that. If you want to really create a complete statistical analysis like this, you require huge number of samples.

It is not that. And how much time it is going to? We are talking about each test is going up to 10^8 or 10^9 number of cycles. And then, we are talking about here what the range of fatigue limit. So, one really has to spend lot of time and energy to obtain these kinds of a true fatigue data. So, now you understand the significance of the statistical nature of fatigue. So, that is the intention here. So, this is the fatigue data represented on the probability basis.