Mechanical Behavior of Materials
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Lecture No 50
Fracture Mechanics - II

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(Video Time: 00:18)

Hello, welcome to this lecture again, in the last lecture we very quickly looked at the overview of fractal mechanics and in fact I moved little fast because most of them were already you know we know we have sufficient background we have spent quite a bit of time on the deformation and little bit of fracture indirectly on creep and so on. I just rushed it up but nevertheless to we will continue to concentrate on concepts which is new and we will spend sufficient time on that.

So, in order to you know keep the continuity of the discussion first we would like to finish some of the crack growth mechanism concepts. So we will look at them one, even this particular lecture I am pretty sure that you all have enough background on this, most of them are known to you if you are a material science student. But we will try to connect these crack growth mechanisms to fracture mechanics and the related concepts one by one.

So, the slide which you are seeing is we are trying to address the crack and fracture surface what you see here is a CT-specimen which is broken under the which is tested for this fracture toughness measurements you can see that clearly this is a shear lips or here which is normally 45^{o} after the crack drop we will look at the detail. A crack by itself is only a partial failure due to service and environmental conditions a crack can grow and become critical.

So, like I mentioned in the overview lecture, a crack has got two phases one is growth phase and is fracture phase. And if the crack reaches a critical length then only you try to grow, this is what we are going to prove through the fracture mechanics. So, due to the service and environmental condition a crack can grow and become critical. So, this can happen during the service depending upon the environment. A critical crack can lead to a fracture resulting in material separation. Crack growth is a slow process, whereas fracture is an ultra fast process.

In fact, we will look at the quantitative data on this particular ultra fast process in a later part of the lecture. We will have a look at it. Stable fracture is sometimes reported for plates in plain stress. However stable fracture is followed immediately by unstable fracture. So, this is also reported we look at it what is stable fracture, what is unstable fracture? Unstable fracture you can just readily visualize it is a very fast ultra fast process.

What is stable fracture? We will we have to qualify these statements in the course. So, crack growth mechanisms can be classified into several and one of them is fatigue. Fatigue is considered one of the crack growth mechanisms which involves cyclic loading. And the stress corrosion cracking is also considered as crack growth mechanisms. A sustained static stress under the aggressive environment and creep is also classified as a crack growth mechanism.

A sustained static stress under high temperature, corrosion fatigue/creep fatigue they are also crack growth mechanisms. Liquid metal embrittlement we will see what it is and then finally fracture mechanisms which is either a brittle fracture or cleavage, ductile fracture or rupture. So, these are all very important growth mechanisms which we have to consider. We will just look at them one by one.

So, what is shown in this slide is the fatigue crack growth model. What you can see this animation already is showing this plate or the specimen is being pulled in tension and then it is loading unloading cycle is shown here. You can see that loading slowly it goes up you can see the crack grows. And if you look at this crack tip how it grows you can see a pattern of you know the pattern in which it moves.

So, let us look at the details. Plastic deformation at the crack tip occurs because of high stress concentration even at very low loads. So, here the details of this the crack tip reaction is shown here. So, what is shown here is the multiple slip and the crack tip depending upon the slip availability I mean the slip plane availability and orientation. You have better understanding now on how the plastic deformation takes place. And this Δa is the increment in the crack extension length.

And then plastic deformation is slip of atomic planes due to shear stress and then you can see that it is a cup and cone fracture. You can see that the cup has always the crack grows and then after that it fracture at the end. So, it is always like a shear lip which is having 45^o angle it is called shear lip. So, if you look at this crack tip little closely you can you can witness that how the crack growth model is and we saved here.

It is quite interesting to note that the crack when the unloading takes place and then loading takes place when it closes and then the crack become sharp. Probably I will just replay this animation and then zoom it once again you will be able to appreciate it better. So, you can see that now it is now unloading and then the crack extends in like this because of the plastic deformation and then becomes blunt or because of the plastic zone.

We will see later how this is really true and then because of this you can see that now a becomes the Δa increment has taken place and then this reaction continues opening and then closing when the crack opens and then the plastic zone becomes blunt and then it becomes sharp again and then you try to extend this. So, it is a good schematic at least to start with to appreciate the crack growth model, we will see how we can support this state of ideas.

So, this is another schematic which shows what is happening in the tip where you can see that continued slip on complementary slip planes and how the Δa is accomplished. And then finally how the blunting takes place, crack tip blend due to plastic deformation and then again it becomes sharp and then it extends crack tip becomes sharp due to unloading the process will be repeated for subsequent load cycles.

So, this is how it is modeled and we look at the little more detail about this crack. In the fatigue loading; one of the signature fracture surfaces indication of or a formation of striations. Striations are very tiny, closely spaced ridges that identify the tip of the crack at some point in time. So, you can see that these are all called striations and you can see that very closely spaced ridges are there and then this is a this is an indication of a overload, you can see here also there is a step and this is overload and then it moves and it comes like that. You can see that that continues like that. These ridges are formed due to repeated blunting and sharpening of crack front due to fatigue loading. So, this is one hypothesis what we have just shown in the previous slide.

If it continues or if you assume that crack growth takes place then these kinds of fridges are all supporting that kind of an idea that is how we have to look at it. These are all visible only at high magnification and seen on the crack surface obviously these are all under the microscope you can see that the scale is 2μ here. So, all those striations are the most characteristic microscopic evidence of a fatigue fracture, they are not always present on fatigue crack surfaces.

So, it is also very difficult to see them I mean not 100% you will be able to see it but most of the fatigue fracture you will be able to see them. So, you can see this is also a fatigue fracture but then you are not seeing the kind of striations which is shown in the previous slide. So, that is what we are saying it is not necessarily it has to show striations. Then there is something called beachmarks or also signature of crack growth and fracture.

Beachmarks are microscopically visible marks which are formed when the fatigue crack growth is interrupted and then how do we sketch them. So, this is one schematic which the crack initiates from this point and then and you see that these lines are the crack is growing like this and then finally it is a rupture as you know it is a shear lip which is the 45^{o}. So, origin of the crack is shown here and this particular zone is called fatigue zone and this is called rupture zone that is a crack growth zone or rupture zone.

And concave marks known as clam shells or stop marks or beach marks. There are different names given to this kind of signature of the crack growth and these are also known as you know clam shell or crack stop lines but you should not confuse this with the striations. How do you distinguish this with striations that is something you have to see. This will not be present if the part is operated continuously or with only brief interruptions in service. But this to realize this kind of style I mean beachmarks it has to undergo a lot of surface time then it is easy to visualize.

Beachmarks must not be confused with striations although they frequently are present on the same crack surface, there may be many thousands of microscopic striations between each pair of macroscopic beachmarks. So, what it means is the beachmarks are basically a macroscopic scale as compared to the striations which are microscopic scale. So, that is how we should understand this.

So, next one what you would like to see is stress corrosion cracking (SCC). Stress corrosion cracking is the tracking induced from the combined influence of tensile stress and corrosive environment as the name itself indicates. The required tensile stresses may be in the form of directly applied stress or in the form of residual stresses like oversized pins used in assembly. So, this stress and environmental combination causes this but that stress need not be an applied stress alone.

But it could be a residual stress. The origin of a residual stresses are quite a bit we will see it in the later but in this particular case the oversized pin which is given for the assembly a tight fit also will leave a lot of residual stress behind in the structure. The exact alloy composition microstructure and heat-treatment can have a marked effect on SCC performance. This is quite obvious. Because depending upon the alloy composition and the processing will be decided and process will decide the microstructure and then that microstructure will decide the performance and properties.

So crack growth by stress corrosion is shown in this micrograph. It is a slow process. The crack tip extents due to corrosive action. There are three mechanisms identified to cause SCC. Active path dissolution, hydrogen impediment and film induced cleavage. So, these are the three types of mechanisms which are identified for the SCC. So, what you are seeing here is this is a material failed due to stress corrosion cracking and what is that you are seeing the crack just percolated through just passed through the grain boundaries.

So, it is kind of intragranular fracture. So, we will see the details little bit. Active path dissolution in this grain boundaries are corroded due to precipitation. The applied stress mainly opens up the cracks, along allowing easier diffusion of corrosion products away from the crack-tip thereby allowing the crack-tip to corrode further. Austenitic stainless steels get corroded in this manner due to precipitation of chromium carbide along the grain bond this is a classical example.

In austenitic stainless steel chromium carbide precipitation along the boundary is a problem especially under the aggressive environment this is a well-known issue. The other important issue is the hydrogen embrittlement. Hydrogen embrittlement is the process by which steel loses its ductility and strength due to tiny cracks that result from the internal pressure of hydrogen or methane gas which forms at the grain boundary.

So, this is a very important phenomenon hydrogen embrittlement it is quite industrially really a threatening one. Hydrogen may be produced by corrosive reactions such as rusting, cathodic production and electroplating. Hydrogen may also be added to reactor coolant to remove the oxygen from the reactor coolant systems. Very small amounts of hydrogen can cause hydrogen embrittlement in high strength steels.

So, this is a reason this is why I said it is industrially quite sensitive and dangerous because you do not require a large amount of hydrogen to pass this embrittlement even a very small amounts can cause this embrittlement. Ferritic irons are more susceptible to hydrogen embrittlement. Austenitic alloys are often regarded as immune to the effect of hydrogen. So, this is one aspect of hydrogen embrittlement. But there are several aspects to it but just we are briefly discussing it here as the mechanism of crack growth.

Finally the film-induced cleavage which is a crack developed on the brittle film can penetrate a ductile material, but may stop due to crack blunting. If the brittle film is a by-product of corrosion, then the brittle coat may form at the blunted crack-tip and the crack may grow in service due to corrosion. This is one way of describing the mechanisms. In 1985, 12 people were killed in Uster, Switzerland when the concrete roof of a swimming pool collapsed after only 13 years of use.

So, this is again people learnt after the failure. So, because of the roof was supported by austenitic stainless steel rods in tension, which failed due to stress corrosion cracking. You see in the previous slide we said that austenitic stainless steel is immune to hydrogen embrittlement. But then it has got some other problem because you know it can very easily susceptible to stress corrosion cracking because when it is you know in the aggressive environment even austenitic stainless steel fails to perform.

So, we need an alternative solution to overcome this problem. So, that is how you have to look at it. The atmosphere of indoor swimming pools is one of the most aggressive to be found in the building environment. Chlorine containing compounds which is a by-product of disinfection may transfer via the pool atmosphere to the surface surfaces remote from the pool itself. These compounds can produce highly corrosive film, which can lead to SCC through film-induced cleavage.

Thus, the standard stainless steel grades that perform perfectly well in pool water or poolside equipment may not be suitable for load-bearing components. So when the load and aggressive environment come together then you need very different type of material, not just stainless steel or something like that. So, that is a message. How to prevent this? There are several methods proposed. Select an appropriate material to go with the environment. Remove the chemical species that promotes cracking.

So, what does it mean? You have to do a proper alloy design. You have to look at which are the elements that will promote corrosion or in a corrosion signs people talk about which anodic reaction, cathodic reaction that you have to look at it. Change the manufacturing process or design to reduce the tensile stresses and chances for corrosion. Employ periodic inspection and preventive maintenance. These are all some of the general guidelines for preventing the stress corrosion cracking which is good.

Next is creep is also considered a crack growth mechanisms. So, we have already seen these mechanisms I mean this particular phenomenon we have seen it extensively and here we are discussing just to because it is a crack growth mechanism right. If the material creeps, even though the load remains constant, the extension will continue to increase. Creep damage is often manifested in terms of nucleation of voids or holes at microstructural inhomogeneities which grow and coalesce to form cracks.

Since crack growth generally proceeds from the surface, the component life can be further affected due to corrosion and contribution of cream to crack growth depends upon operating temperature, hold time, loading frequency, type and magnitude of loading, mechanical properties microstructure of the component and so on. So, this all we already know just for the completion you know it is here the other crack growth mechanism is corrosion fatigue.

If failure is due to combined action of fatigue and SCC then it is corrosion fatigue that means cyclic loading in the aggressive environment. In most practical cases, a combination of SCC, fatigue and corrosion fatigue may contribute to failure. Cracks may appear in a stationary aircraft due to rain that is stress corrosion cracking. When the aircraft moves, the loading fluctuates at various frequencies onset of corrosion fatigue.

At cruising altitudes, the ambient external temperature is as low as -40 ^{o}C where corrosion is practically inactive, fatigue is the failure mode for the major part of flight. See you may wonder why we are discussing so many mechanisms or so many classifications of mechanisms. It is something like this, you may have some knowledge about the materials tensile properties or impact properties.

Then based on that assumptions you can consider them for some application where such strength levels are put in use. But when it combines with the other parameters like aggressive environment or a tensile versus cyclic loading then also the property will be changed. Because the material will in a fatigue loading the material will fail much below the yield strength which is predicted by the simple tensile test that is why people do fatigue. A creep also definitely will fail much different load than what is predicted by the tensile behaviour.

So, similarly even corrosion fatigue will be very different from the normal fatigue without an aggressive environment. Yet a cyclic loading less aggressive movement will be very different from cyclic loading plus just corrosion cracking plus corrosion. So, there are different combination of phenomenon come together your material will behave very differently and studying or estimating their life by just one methodology or one phenomenon is not going to help. So, that is something you have to appreciate that is why all these crack growth mechanisms are discussed.

Even though it is very descriptive and it is more conceptual ideas you have to pick up from this text that is what that is the intention we are discussing all this. So, the next one is liquid metal embrittlement, what is that? Corrosive degradation of metals in the presence of certain liquid metals such as mercury, zinc, lead and cadmium. This is quite important, very small amounts of liquid metal can cause embrittlemen, which may be introduced due to manufacturing process such as brazing, soldering, welding, heat treatment or hot working.

In much the same way that a localized corrosion event is needed to initiate stress corrosion cracking. Local chemical attack is usually a precursor for liquid metal embrittlement. Liquid metal embrittlement shows a very strong effect of stress intensity and a rapid transition from slow to rapid crack growth. Surface treatments may be utilized to enhance resistance to liquid metal embrittlement. However, this should be conducted with extreme caution since the damage to this surface layer may induce cracking.

So, even the surface treatment has to be looked at very differently. So, now we come to fracture mechanism. We know what fracture mechanism is now brittle fracture which is also called cleavage, ductile fracture or rupture. The majority of the service failures occur by ductile fracture most of these exhibit very little overall plastic deformation and hence they are brittle from an engineering point of view. Fracture is a very fast process.

So, we will what is the fracture speed? The cleavage fracture speed is 1660 m/s. A ductile fracture is 500 m/s. So, it is you know a significantly different values you are getting for a cleavage fracture and ductile fracture when it comes to fracture propagation. So, we can look at the severity. So, look at the brittle fracture little more closely. Cleavage is splitting of atomic planes from grain to grain the preferred splitting plane is differently oriented causing a faceted fracture.

The facets are flat and therefore good reflectors of incident light. Soon the surfaces become dull due to oxidation. So, these are some of the features of brittle fracture when you look at the microscope. So, there is a transgranular fracture that means the most metal failed by trandgrsnular fracture. Fracture takes place within the grain along a weak crystallographic planes. So, all the grains are you know just cut through transgranular fracture.

And then you can have another type of brittle fracture called intergranular. Intergranular fracture is an exception rather than the rule under monotonic loading. Fracture takes place along the grain boundaries. It is usually promoted by aggressive environment and high temperatures. This we have already seen one example in a SCC failure. We have shown that the crack just crossed through the grain boundaries.

Then the ductile rupture; engineering materials contain a large number of second phase particles. Large particles which is 1-200 μm visible in optical microscope. Usually, these are alloying elements not essential to strength of the material. And there are particles which is in the range of 50-500 nm can be visualized under electron microscope, they are basically compounds of alloying elements, essential for strength. And further there are precipitates of size 5-50 nm purposefully developed by heat treatment and aging help to achieve the required yield strength.

So, all these are very basic ideas which we already know. So, I am just skipping them in the interest of time we have looked at all this earlier and large particles are brittle cannot accommodate plastic deformation of the surrounding matrix. Voids are formed even for small plastic deformation. Large particles can determine the instant and location of the ductile fracture, but they do not play a role in the process of ductile fracture.

Fracture is induced by intermediate particles. They lose coherence with the matrix and tiny voids are formed. So, if you can look at all these features in a typical ductile fracture, the small small dimples will be formed because of the particle from the matrix that is what it is shown here they lose the coherence with the matrix. As these voids grow by slip, the material between the voids necks down. The necking takes place at the micro-scale the resulting total elongation is small.

So, this is one kind of description how the ductile rupture phase, basically the fracture surface description. So, the one schematic shows about these particle mediated ductile fracture. This is a crack you can see the crack tip you have the two types of particles are there coarse one and the small one. And ductile fracture occurs due to substantial plastic deformation of the crack-tip. First, the large particles let loose and break forming widely spaced holes close to the crack-tip.

So, this is what it is shown here and finally holes are formed at the myriads of smaller particles. These holes and voids join up to complete the fracture like what is shown here in the schematic. You can see that you know small voids form and then and the crack grows. Because of its irregularity, the fracture surface diffuses the light and looks very dull. So, I can just zoom in to appreciate what we are discussing.

So, now you see that yeah this particle crumble then it creates a void and then some small particles go out that also creates a void and then it all join up and it becomes a crack. So, you can see that very clearly in this animation. So, this is very important, yeah. You can see that it is an actual micrograph, cracked particle in an Al-alloy, you can see that they are all broken. They are coarse particles and their small particles are also visible some of them are visible.

And this is a fracture in Al-Cu-Mg-alloy. It is a SEM image and this is a TEM image and this is what I wanted to just stop here. What we have just seen in this lecture again I rushed up a little bit, because most of the concepts are already known to you and just to have a continuity and the main point I want you to remember in this lecture is we have predominantly seen a crack which is having a growth phase and a fracture phase.

So, that is something we have to keep in mind. So, now we will discuss the detailed, you know concepts which is causing cracks and how it propagates and so on. We will discuss in the next lecture, thank you. **(Video Ends: 35:39)**