Engineering Fracture Mechanics
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Lecture No. # 07
Crack Growth and Fracture Mechanisms

In the last class, I have listed various crack growth mechanisms and also fracture mechanisms. And of this, we had seen in some detail, a model for growth of a fatigue crack. In fact, one of the students, came to me and asked, does the crack, initially propagate at 45 degrees. You should not come to such kind of a conclusion.

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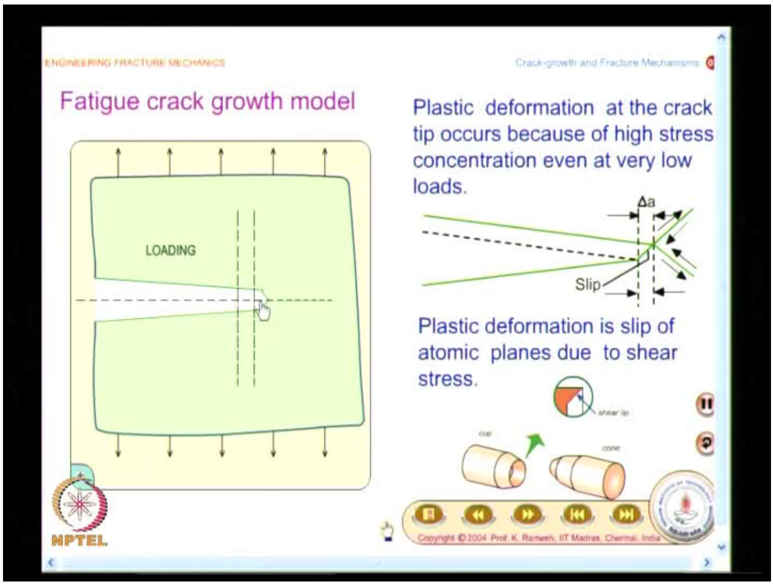

So, I thought that, I would clarify this doubt, before we proceed with the lecture. We will look at what we learned in the fatigue crack growth model. What was mentioned? Because of very high stresses near the vicinity of the crack-tip, you will have plastic deformation; and what is the role of plastic deformation? When you have plastic deformation, it is nothing, but slip of atomic planes due to shear stress. And we had seen in some detail, that in the case of a simple tension test, you have a cup and cone fracture, and I pointed out that, you have a shear lip and this happens at 45 degrees. And what you will have to keep in mind is, all this happens at a microscopic scale, it is very highly enlarged for conceptual appreciation.

So, when I have a crack, I have a slip that takes place. And we have a model of how does a fatigue crack grow as an animation, and this is purely done based on the kind of processes that are involved in advancement of the crack. So, here you have a microscopic model, is bundled with a macroscopic appearance. What you see here, happens that are microscopic level; imagine, that you will have 4 or 5 striations in a span of about 2 microns.

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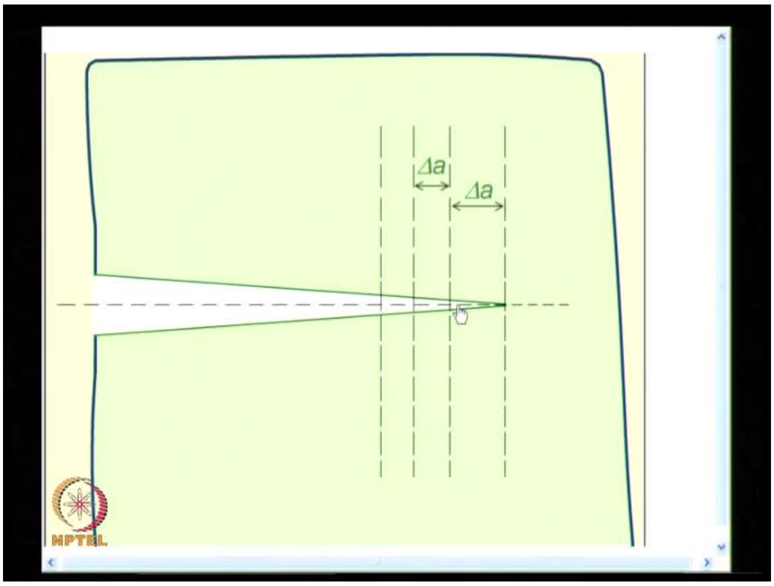

So, this is submicron level, but this is highly magnified. When you see the picture in high magnification, you see the kind of detail that you look at. When I have slip that is shown as a slanted line at 45 degrees.

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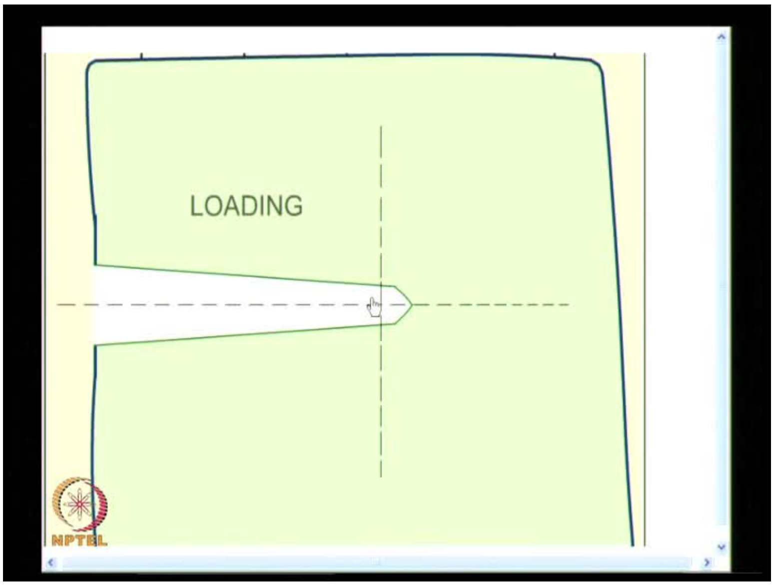

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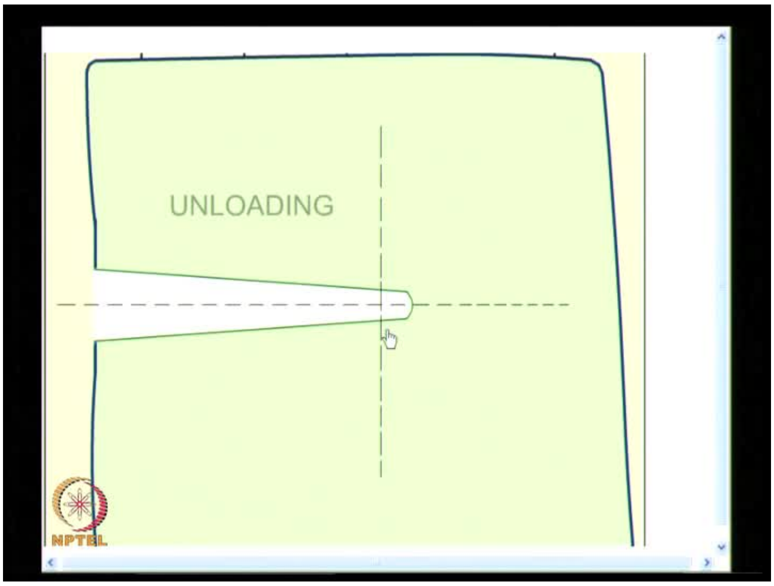

So, you have, while the crack is loaded, it gets blunt; during unloading, it gets sharper. So, this opening and closing leaves the mark on the material, which appear as striations.

So, what you will have to look at is, all of these happen at a microscopic level. The crack by itself advances only along the straight line, but how does the crack advances? So, you are trying to visualize, what could be the possibility in looking at this kind of a process that is what we are really aiming at. So, you have to visualize the crack advances along this line, but how it advances from a point like this to another point? You have a model.

See, as we understand the material more and more, you also find, development of newer models; and this model, really gives you an appreciation that in every cycle of fatigue, there is incremental advancement of crack, and there is also an impression created in the micro structure; so this model, you can accept it.

So, do not think that crack initially propagates at 45 degrees on a ductile material. In fact, towards the end of the course, we would look at several theories, which would give you, at what angle, the crack will propagate for a given loading condition - that is the macroscopic calculation; at a microscopic level, what happens is, what we are discussing.

So, do not confuse these two issues, because you are all engineers, trained in engineering drawing, where lot of emphasize is given for visualization. So, you have to look at that, this happens at a microscopic level, and you are able to see, that when you have a loading and unloading, you are able to see that the crack advances incrementally, and you also look at, because of plastic deformation blunting occurs, that is what is attempted to be shown in this animation, the crack tip blunts, then it becomes sharp. So, this happens repeatedly, the crack advances along this line. It does not go at 45 degrees; do not carry that impression.

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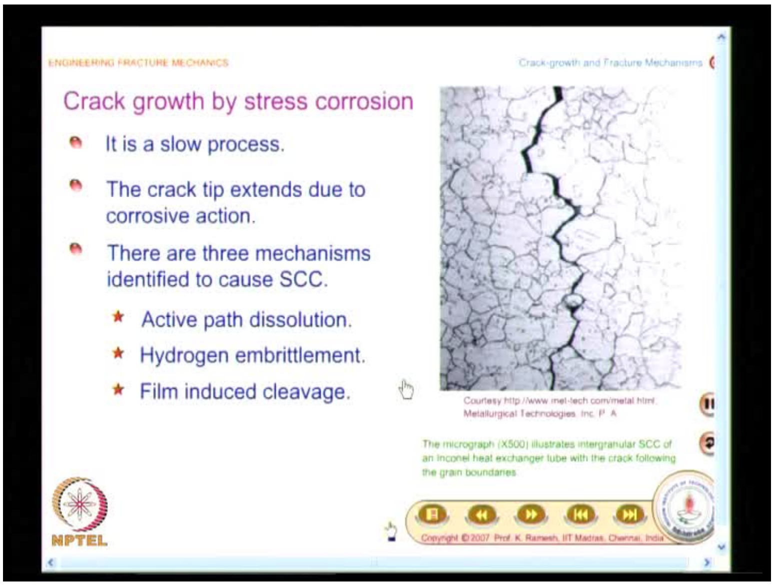

Let us continue our discussion on stress corrosion cracking, and we have looked at, in the last class, crack grows by a stress corrosion, and we saw that, it was an inter-granular crack growth, that is, what you see in this micrograph. And this could advance by any of the 3 mechanisms; 1 is active path dissolution; the second possibility is Hydrogen embrittlement; and third possibility is film induced cleavage. We would see, one after another these mechanisms, these are again descriptive. So, you need to take proper notes of these points.

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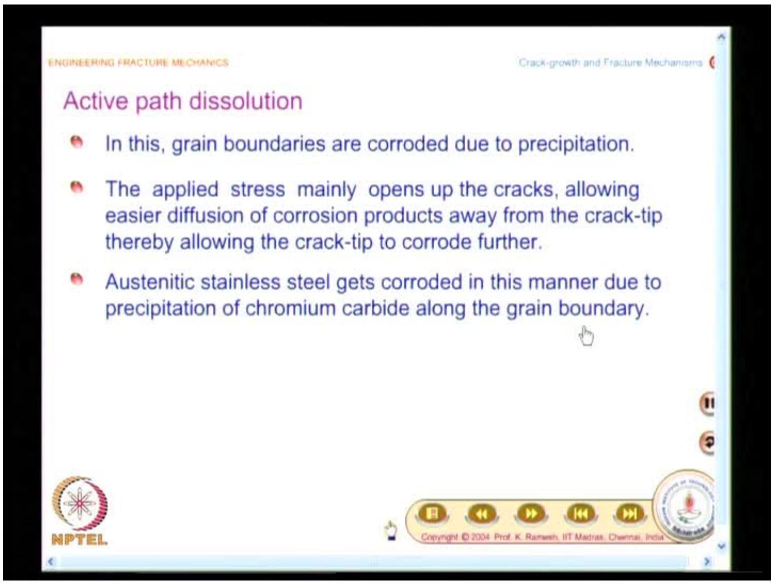

What happens here? In the case of active path dissolution, the grain boundaries are corroded due to precipitation. So, this is the mechanism .What really happens is, the applied stress mainly opens up the cracks, allowing easier diffusion of corrosion products away from the crack-tip. Thereby, allowing the crack-tip to corrode further. So, it is a successive process. In the case of fatigue, repeated loading makes the crack to advance in the case of stress corrosion cracking. By active path dissolution, you find the crack advances because of corrosion. Sustained stress in conjunction with corrosive environment, you find crack advances. And certain kind of material, gets affected by this process, you, find here, austenitic stainless steel gets corroded in this manner, and what happens in this? We have seen the grain boundaries are corroded due to precipitation; in the case of austenitic stainless steel, you find precipitation of chromium carbide, along the grain boundary.

So, by enlarge, you find in SCC, the crack proceeds along the grain boundary, in a zigzag fashion. You will see that, as zigzag fashion at a microscopic level; at a macroscopic level it may give a different picture.

So, do not confuse what happens at microscopic level, with what you see in a macroscopic level, you should be able to visualize as you are all trained as engineers.

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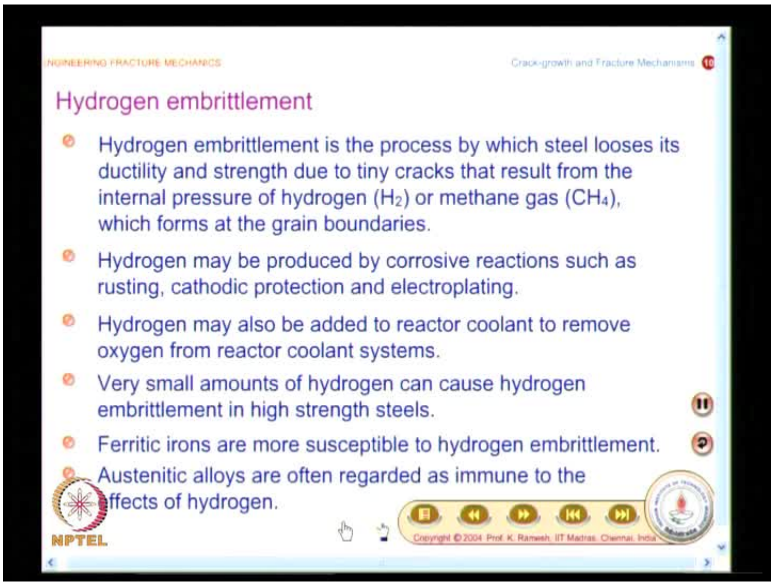

The next process is Hydrogen embrittlement. This is another possibility, by which the cracks can grow due to stress corrosion cracking, and what you find is, hydrogen embrittlement is the process by which steel looses its ductility and strength. What happens? Tiny cracks that result from the internal pressure of hydrogen or methane gas causes loss in ductility and strength, and where do these form? Again, the grain boundaries are affected.

So, what is distinct in SCC is, grain boundaries are affected by various mechanisms. It is getting affected due to precipitation, in active path dissolution; in hydrogen embrittlement, you find tiny cracks that form due to internal pressure of hydrogen. And where do this hydrogen come from? This may be produced by corrosive reactions such as rusting, which is very common place; cathodic protection as well as electroplating. Normally, you do these to prevent corrosion, they have a deleterious effect. And with the use of nuclear reactors for power generation, you need to take care of them and for your own requirement, hydrogen is added to the reactor coolant to remove oxygen; though, it is used to remove oxygen, it adds up to hydrogen embrittlement.

So, you get one benefit, you get a disadvantage because of using that; duality always exist, there is nothing like one is always good or one is always bad; you always as a mixture of these two. And what you will have to notice is, very small amounts of hydrogen can cause hydrogen embrittlement. It is not that you require a very high volume of hydrogen gas to go and give your problem, small quantities traces here and there, can cause embrittlement. And if you notice, ferritic ions are susceptible to hydrogen embrittlement. On the other hand, austenitic alloys are often regarded as immune to the effects of hydrogen. In fact, an observation like this, is advantageous; because if you know your corrosive environment, there is a possibility of crack growth by active path dissolution, then use an appropriate quality of steel. On the other hand, if you are going to have predominantly hydrogen embrittlement, go for austenitic steels.

So, you have a via media by selecting an appropriate material for your structure, you are able to overcome or minimize such problems. I suppose, you had time to take down the points that are listed. And what you have to keep in mind is, the hydrogen does not come from outside, it may be because of corrosive reaction such as, rusting or cathodic protection or hydrogen that is intentionally added in reactor coolant, they remove oxygen, can also give you problems.

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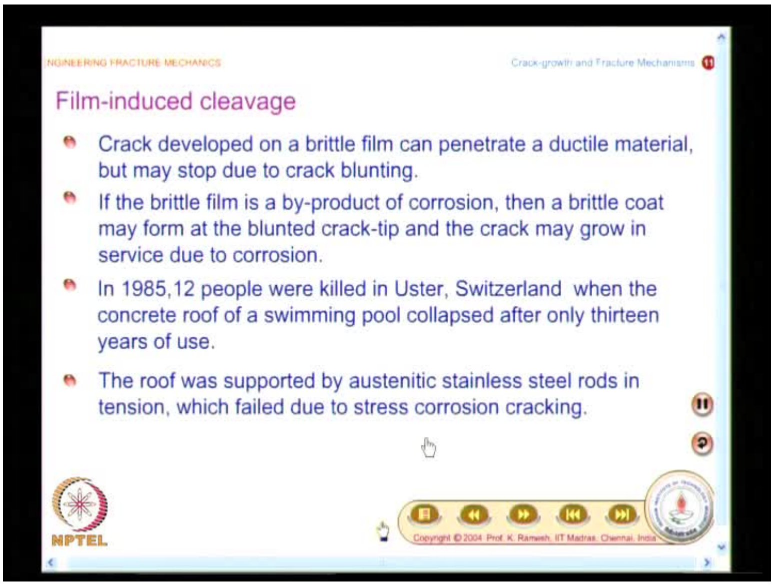

The other way, SCC can developed is Film-induced cleavage. In this, crack developed on a brittle film, can penetrate a ductile material but may stop due to crack blunting, and this is what I said, blunting of a crack which happen because of plastic deformation is beneficial in fracture mechanics. And you know, many protective coating, you put to prevent corrosive environment; the protective coatings are in general, brittle. And crack starts from the surface and penetrated. And what happens? Once, you have a crack, you can have a brittle film formed; if the brittle film is a by-product of corrosion, then a brittle coat may form at the blunted crack-tip, and the crack may grow in service, due to corrosion. See, if you look at, success of engineering has always been in looking at failures and identify the cause for the failure and try to modify or improve your design or use of material to prevent such failures in future.

So, what happen was in 1985, there was an accident in Switzerland, in a swimming pool, the roof collapsed after only 13 years of use; there were 12 people killed; it is very nice, they value the human life’s and they take this as a challenge, to look at what was the cause for this kind of an accident. And when they studied? The roof was supported by austenitic stainless steel rods in tension. The postmortem revealed, they failed due to stress corrosion cracking. What is a common impression of a stainless steel? When you have a corrosive environment, you put a stainless steel, it will not get corroded; if you put a mild steel, it will get corroded, you will have rusting so on and so forth.

So, in a normal corrosive environment, if you put a stainless steel, it will not get corroded but what has happen in this case? The stainless steel rods were in tension, they were supporting loads. So, what you find is, combination of a load plus corrosive environment has precipitated crack growth, due to stress corrosion cracking. And here again, you find austenitic stainless steel is susceptible to this.

So, you take a proper category of steel, then you can avoid or minimize this problem and let us look at what happens in a swimming pool, it is a very highly corrosive environment, that you may not realize; you all enjoy swimming and you know in foreign countries because the temperatures be sub-zero, they need to have swimming pools heated and to prevent disease, they add chlorine to the water.

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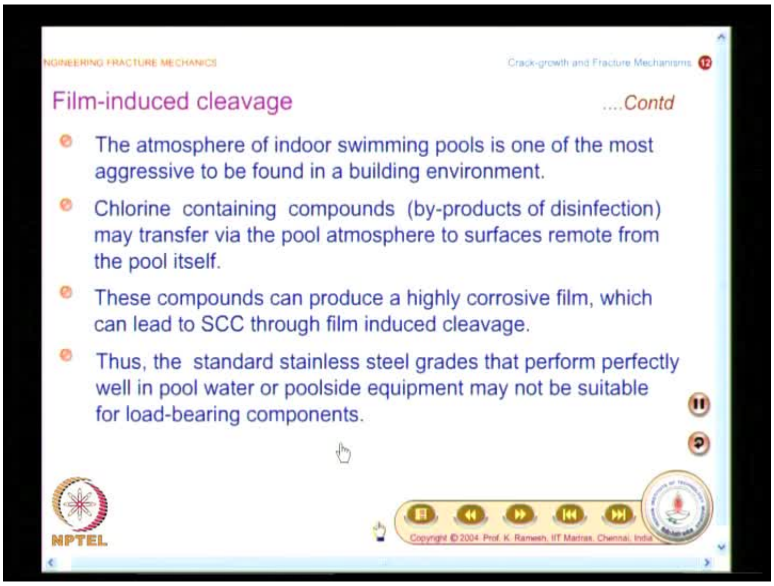

So, this creates a very nice atmosphere for corrosion and if you look at from structural analysis point of view, the atmosphere of indoor swimming pools is one of the most aggressive to be found in a building environment. See, first thing is even recognizing, there could be problem in such places, you have to use special material to handle anyone of the structures that you have in a swimming pool, you have come across several swimming pool side way equipment, made of stainless steel; they do not support load, they are just to give you grip and then, get into the swimming pool and coming out, nothing will happen to that. But if you have a roof, which is supporting load and also in corrosive environment that causes failure, we have to distinguish the difference between the two.

So, what you will have to look at is, the chlorine containing compounds, which are used for disinfection, may transfer via the pool atmosphere to surfaces remote from the pool itself. So, that is what happen, when you have a roof supported by stainless steel rods. So, they were exposed to chlorine containing compounds; these compounds can produce a highly corrosive film, which can lead to SCC through film induced cleavage. As, I mentioned earlier, the standard stainless steel grades, that perform perfectly well in pool water or poolside equipment, may not be suitable for load bearing components. See, you should not exploit a material beyond its intended purpose, you have developed stainless steel to resist corrosion, it can be used for certain kind of application, for load bearing the suggestion is do not go for austenitic stainless steel in a swimming pool, either you have to protect it, from corrosive environment by some kind of a protective coating or insulated in some manner and we would also see what are the ways that we could avoid or minimize stress corrosion cracking? And, this is what you find. What are the methods that could be used to prevent stress corrosion cracking?

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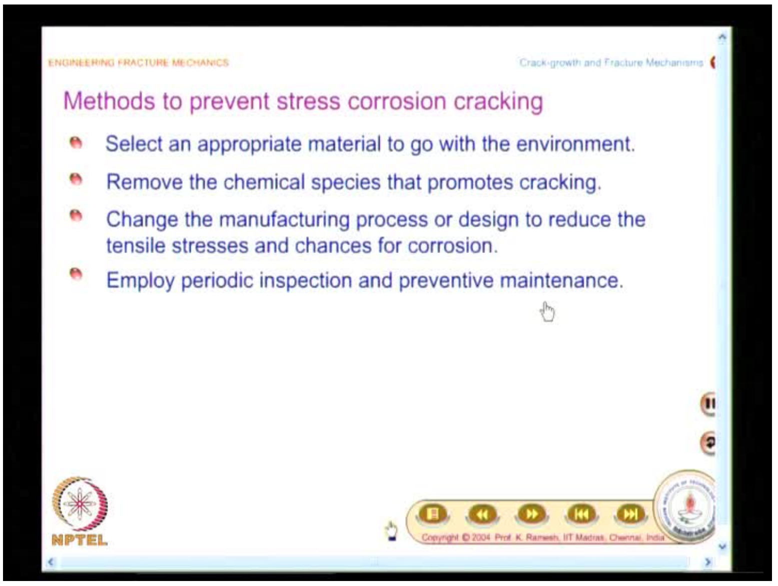

So, the first step is, select an appropriate material to go with the environment; and the second step is, remove the chemical species that promotes cracking. These are all doable. And the third step is, we have already seen, in the case of active path dissolution; tensile stresses causes the correct environment for the crack to grow.

So, you look at the manufacturing process, as well as the design to reduce the tensile stresses and chances for corrosion, because the combination of stresses and corrosion will lead to stress corrosion cracking. So, you address both; in the first two, you have looked at appropriate material; second one is the chemical species that promotes cracking; the third one, you look at minimizing or eliminating the existence of tensile stresses in your design structure.

This is very important; with all this, go for periodic inspection and preventive maintenance. This is very important, the moment you come for damage tolerant design approach, you have to do periodic inspection; there is no escape from that they go together.

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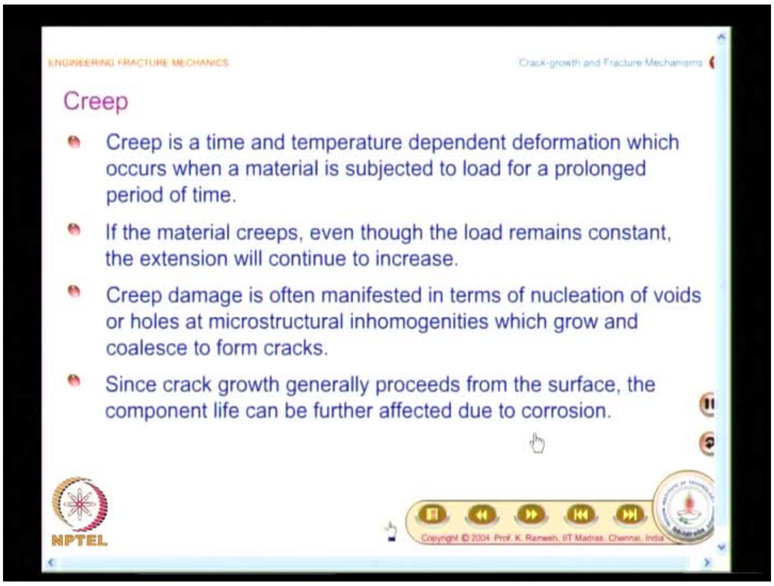

Then, we move on to the next model of crack growth. What is Creep? It is a time and temperature dependent deformation, which occurs when a material is subjected to load for a prolonged period of time. See, one of the common examples that people would use to explain creep is, you find the tar put on the road, if it spills out of the container that this kept, over a period of time it will spread, without apparent external load, it will keep on creeping slowly, it will move, this you see at room temperature.

A similar phenomena occurs in the case of metals at high operating temperatures. If the material creeps, even though the load remains constant, the extension will continue to increase; that is what I mentioned that, you come across in the case of a tar, this happens in the case of metals at high temperatures and how does a creep crack growths?

Nucleation of voids or holes at microstructural inhomogenities, grow and coalesce to form cracks. So, the way a creep damage grows is different; the way your stress corrosion cracking growth is different. Similarly, a growth of a crack by fatigue is different, people have analyzed and have form models, to explain what is observed in practice. So, in the case of a creep, it is essentially nucleation of voids or holes at microstructural inhomogenities, which grow and coalesce to form cracks.

So, the physical process is different. In many examples, you will find, crack growth generally, proceeds from the surface. This is a very common thing, you know, you have a stamping of the seal, on the surface of the component after is fabricated, even that could form as a sight for crack to grow. So, when you have crack that has grown from the surface, corrosive environment will precipitated further. So, that is what is mentioned here, the crack proceeds from the surface and the component life is further affected due to corrosion.

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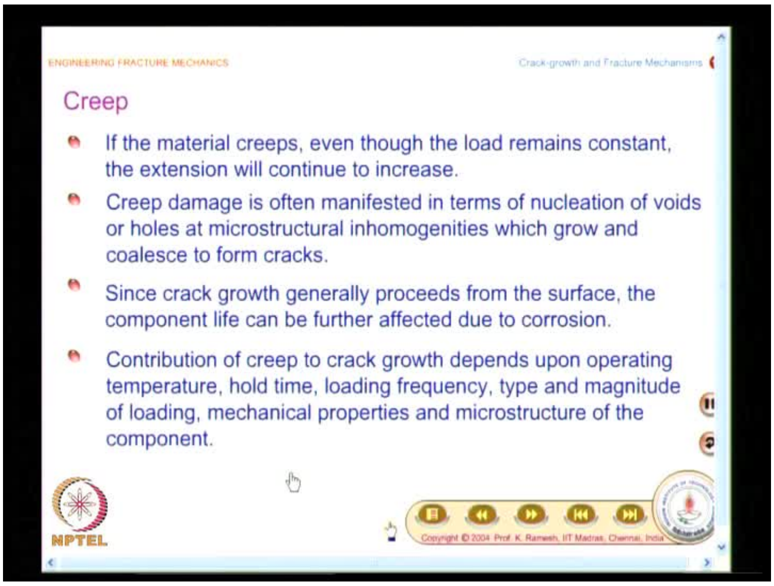

As I mentioned earlier, operating temperature is very important and you have many other aspects of the service condition, contribute to creep. So, you have to look at the operating temperature, hold time, loading frequency, type and magnitude of loading, mechanical properties and microstructure of the component. So, when you find there are so many parameters that influence; it also provides you a possibility, to minimize crack growth by creep by addressing some of these intelligently; by understanding, what is the process by which, creep crack grows, you try to minimize it.

You know, so far, we have seen fatigue separately, stress corrosion cracking separately, and creep, but in practice, you will find the combination of this, they do not exist in isolation. And now, we look up what is corrosion fatigue, if failure is due to combined action of fatigue and SCC, then it is corrosion fatigue.

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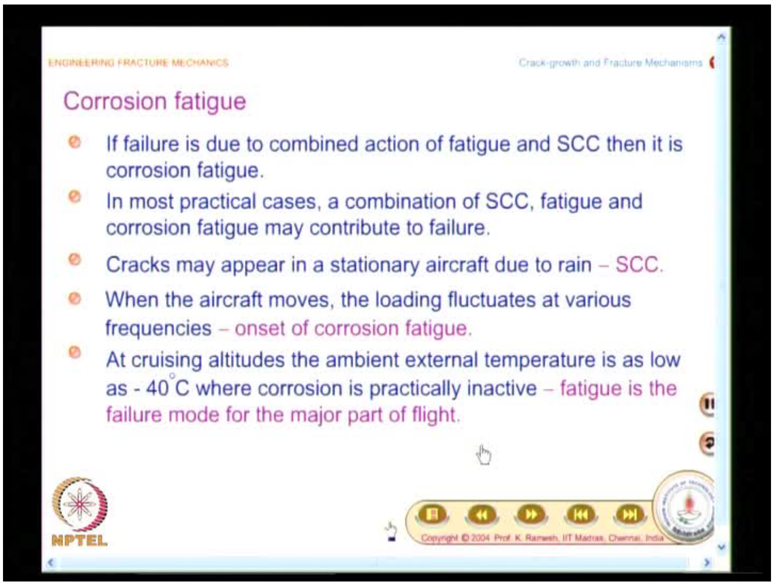

So, in many practical cases, you always find a combination of SCC, fatigue and corrosion fatigue, and they would contribute to failure, and we look at an example, then you'll understand, how such a combination exists. So, take the case of an aircraft; cracks may appear in a stationary aircraft due to rain, and here the crack grows, because of stress corrosion cracking. Then what happens? You move the aircraft in the tar mark, so you have loading fluctuations and this causes onset of corrosion fatigue, and it is one of the very important problem to study the fluctuation of loads in randomization studies, they really look at, what way the terrain is and how the random loading is taking place, and so on and so forth. It is one of the very important problem, that they study the loading fluctuations, and what we look at here is combination of loading fluctuation with existence of a crack, will lead to onset of corrosion fatigue. And what happens? Then the aircraft flies into the air and at cruising altitudes, the ambient external temperature is as low as minus 40 degree centigrade, where corrosion is practically inactive, fatigue is the failure mode for the major part of flight, it is a very nice example.

You know, you look at, you find because of rain, stress corrosion cracking takes place, then because of taxing in the tar mark, you find there are load fluctuations induced on the aircraft. So, you find answer tough corrosion in a fatigue, which is continued in flight, as fatigue crack growth.

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And another crack growth mechanism, is liquid metal embrittlement, corrosive degradation of metals in the presence of a certain liquid metals such as mercury, zinc, lead, and cadmium. And like what we had seen in the case of hydrogen embrittlement, there are also we saw, very small amounts of hydrogen, can cause problem. Here also you find, very small amounts of Liquid metal, can cause embrittlement, and where do they come from? They may be introduced due to manufacturing processes such as brazing, soldering, welding, heat treatment, or hot working. See, these are basic manufacturing processes; see, this is the reason people realized the performance of a structure depends, both on the manufacturing methodology and the design. So, that is why, now, people are going for integrated manufacturing and design, it is not only the final dimensions of the structure dictate, how it is going to perform? How the structure has been fabricated? What are the manufacturing processes that has gone into it? Also has an influence on the performance of the structure.

So, you will have to equally address the manufacturing issues. And very similar to SCC, in much the same way that a localized corrosion event is needed to initiate SCC. In the case of LME, local chemical attack is usually a precursor. So, in the case of stress corrosion cracking, corrosion event precipitates that. In the case of liquid metal embrittlement, a chemical attack is a precursor. And there is a typical characteristic of LME, what it shows is, it shows a rapid transition from slow to rapid crack growth. This is a very significant signal of that the growth is precipitated by LME, and how you can minimize this? You can do it by proper surface treatments.

So, by doing this, they can help to enhance resistance to LME. So, by looking at these processes, we also learned in what way, you could minimize crack growth by these mechanisms.

So, that is very important. See, in the case of fatigue, if we have a very smooth surface, you will delay crack initiation in fatigue. It is one of the very important research, people do in fatigue and in the case of stress corrosion cracking, select the suitable material and minimize the corrosive environment. In the case of LME, go for a suitable surface treatment. So, you have a via media to minimize or delay the crack growth. And whenever you go for a surface treatment, you will have to be very careful. This should be conducted with extreme caution since, damage to the surface layer may induce cracking. You know, whenever you put a surface coating, even a small crack in the surface coating, over a period of time, if unnoticed, can precipitate corrosion from that. So, after putting the coating, you have to inspect it and periodically repair those patches, it is very important.

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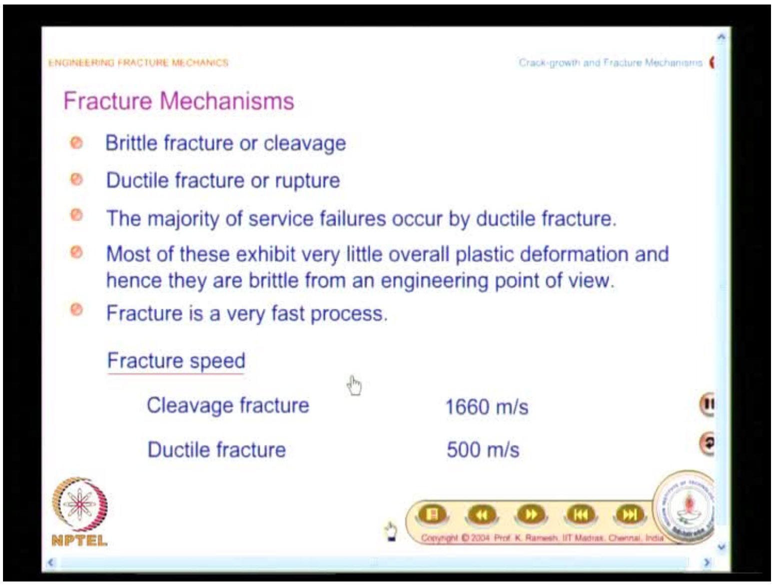

Now, we move on to fracture mechanisms. We have already noticed, that there are 2 important fracture mechanisms; one is brittle fracture; another is ductile fracture. Brittle fracture is known as cleavage, ductile fracture is also known as rupture. And we will see, how the Fracture Mechanisms are different from crack growth mechanisms, you will have to make a distinction, how these happen in contrast to crack growth? Though, we have two fracture mechanisms, the majority of service failures, occur by ductile fracture in the local region near the crack-tip is plastically deformed. The structure as a whole, still behaves in a brittle fashion, but if you go and look at the mechanisms of fracture, you classify in a certain fashion as brittle and ductile.

So, you have to delineate what we discuss at the microscopic level and what we understand at the macroscopic level. We are now looking at the microscopic level; at the microscopic level, the fracture can be classified as brittle as well as ductile. But both the structure, behaves in a brittle fashion from a macroscopic point of view. And in contrast to crack growth, fracture is a very fast process and this is what I said, both fractures are very fast, cleavage fracture the crack travels at a speed of 1060 meters per second; ductile fracture, it travels at a speed of 500 meters per second. You know, if you look at a racing car, that travels around 100 meters per second, that itself with very high speed and imagine, a crack travels at 500 meters per second, it is really very fast.

It is only in attention to detail, you find one fails in a brittle fashion, another is a ductile fracture. And we will also look at the mechanisms, and those mechanisms will give an explanation, why a cleavage fracture is very fast? And why a ductile fracture is relatively slow? But you will have to keep in mind, both are very fast processes in comparison to crack growth.

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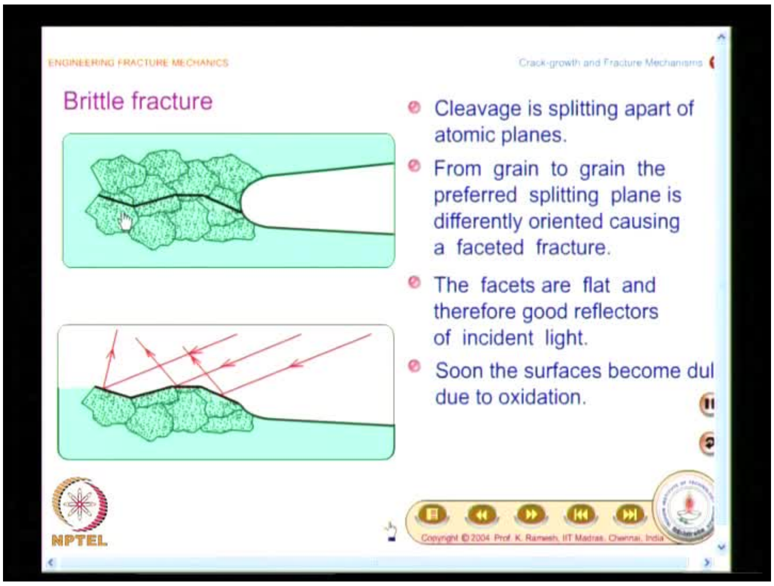

And what is a cleavage fracture? So, what you find is, in the case of cleavage, it is splitting apart of atomic planes, and here again, you have a magnified picture of the grains near the crack-tip. So you will have to understand, that this is a very highly magnified picture, and what is shown as a black line here is, splitting apart of atomic planes. See, each one has a crystal and their planes are oriented differently from grain to grain. So, the splitting planes also will differ from grain to grain, and they are differently oriented which causes faceted fracture. You make a neat sketch of it, and what happens is the crack advances each time, through one full grain. So, that is why it is very fast, the crack advancement is grain by grain. And when you move from one grain to another grain, the orientation of the V plane is different, and you just observe the animation now, you will find that, it goes very fast.

So, you have a crack grown like this; at a macroscopic level, you will find the crack has grown straight; at the microscopic level you will see all these variations. And there are certain characteristic features of the fracture surface. The facets are flat, and therefore, good reflectors of incident light. So, you will find the surface is very shiny, in the case of a brittle fracture. In fact, if you take prospects, if it fails, it would be brittle in nature, you will have very nice polished surfaces. On the other hand, if you take aluminum or steel, you will have a ductile fracture. Though, the surfaces initially are shiny, in the case of metals, the surfaces become dull, due to oxidation. So, what you find here is, the crack advances grain by grain and the weak planes are different; so, you find a faceted type of crack. That is the characteristic of it, and because it moves grain by grain, the process is very fast. And you also have 2 classification of this kind of fractures; one is a transgranular, that is what we had seen just now, and it says that most metals fail by transgranular fracture.

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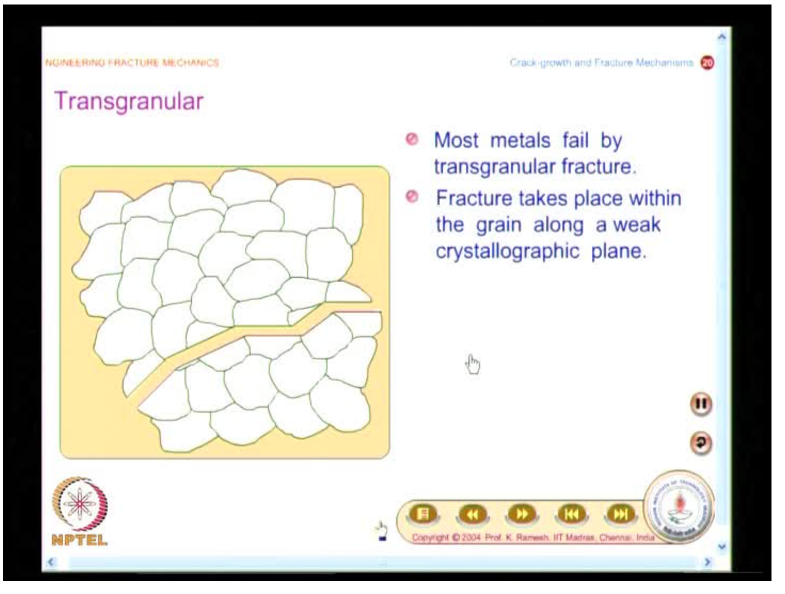

So, this is the model you have grains, and you have a cracks, oriented at different directions in each of the grains. And you classify, if a failure has happen like this, as transgranular. You also made a schematic of this, what is important is, you have these cracks cutting across the grains, and this is the common failure observed in most metals. And you have another process, we have already seen that in the case of stress corrosion cracking, where you had the crack growth along the grains. So, that is called intergranular fracture. In the case of metals, intergranular fracture is only an exception, rather than the rule under monotonic loading.

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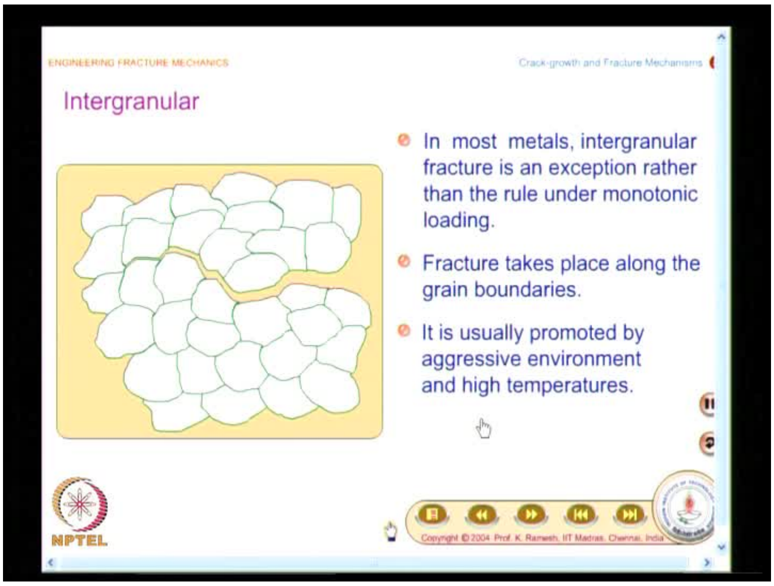

So you will have to understand under monotonic loading, it is only an exception. And in the case of intergranular, fracture takes place along the grain boundaries. And this is, usually promoted by aggressive environment and high temperatures. We have already seen in some of these, in the context of crack growth. In the case of fracture also, aggressive environment and high temperatures induces intergranular type of fracture.

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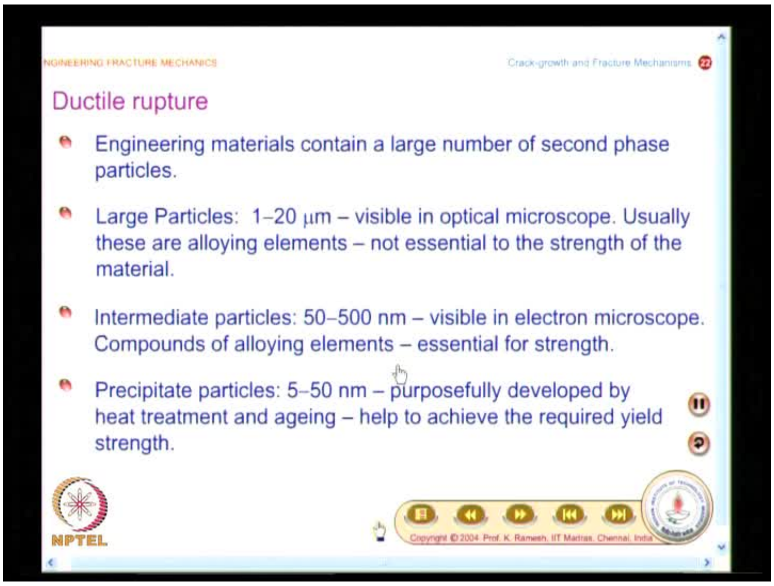

Then we move on to, what is ductile rupture? You know, you will have to understand what an engineering materials contain. They contain a large number of second phase particles, these are all understanding from metallurgy, say unless, you go into, how alloying is done and what kind of issues, you will not be able to appreciate this and recognizing the kind of various particles, helps you to understand, what are the processors, by which ductile rupture takes place.

So, you could have large particles which are of size 1 to 20 micrometers. When I say large particles, they are visible in optical microscope, and what are they? They are usually alloying elements, not essential to the strength of the material, but they are present, it is unavoidable. Then you have intermediate particles, the size range is 50 to 500 nanometers. They are visible in electron microscope. The large particles are visible in optical microscope, the intermediate particles are visible only in an electron microscope. And they are compounds of alloying elements, they are very essential for strength, you want to have them; that is why, you add alloying elements.

In the process, you have large particles; ultimately, you want this. So, when I have large and intermediate, I should also have small particles, and they are classified as precipitate particles, which are 5 to 50 nanometers - very small. They are purposefully developed by heat treatment and ageing. And what is their role? They help to achieve the required yield strength. See, all these, in the domain of metallurgist, you know material scientist. They develop high strength alloys and they also want to have combination of high strength alloys and high toughness. So, they have to find out, what kind of processes that would help them to do it. So, they find suitable heat treatment and ageing can help to achieve the required yield strength. And we have to see under loads, how do these particles behave? Because we all know near the crack-tip, you have very high values of stresses that can give you plastic deformation. How do the large intermediate and precipitate particles respond to this plastic deformation?

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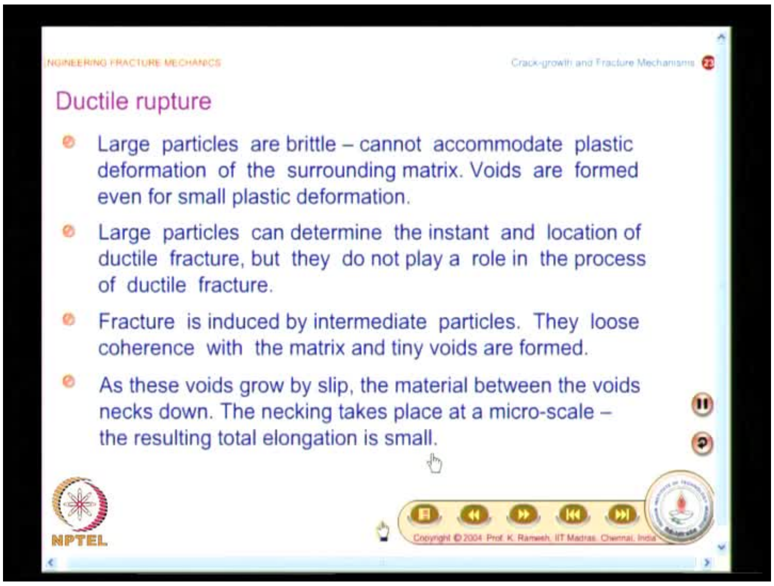

Large particles are brittle, they cannot accommodate plastic deformation of the surrounding matrix. In view of this, voids are formed. And what way the large particles play a role is, they determine the instant and location of ductile fracture. And what is reported is, they do not play a role in the process of ductile fracture, they determine the instant and the location. Then, what happens to intermediate particles? The intermediate particles loose coherence with the matrix and tiny voids are formed. And in essence, fracture is induced by intermediate particles.

And what you have is, you have these tiny voids, and these voids grow by slip; that is why, we spent time on slip, we have learned from a tension test that you have shear lip, and you find these voids grow by slip, and the material between the voids, necks down, this is called micro-necking. The necking takes place at a micro-scale, and the resulting total elongation is small.

See, we are now discussing micro-scale activity, because we need to give an explanation, why the surface is rough, why it is slow and so on and so forth. This is possible only when you look at the micro-scale; at the micro-scale, you find voids are formed, the voids grow; the voids grow by, necking of the material in between to them, by micro-necking and the crack proceeds.

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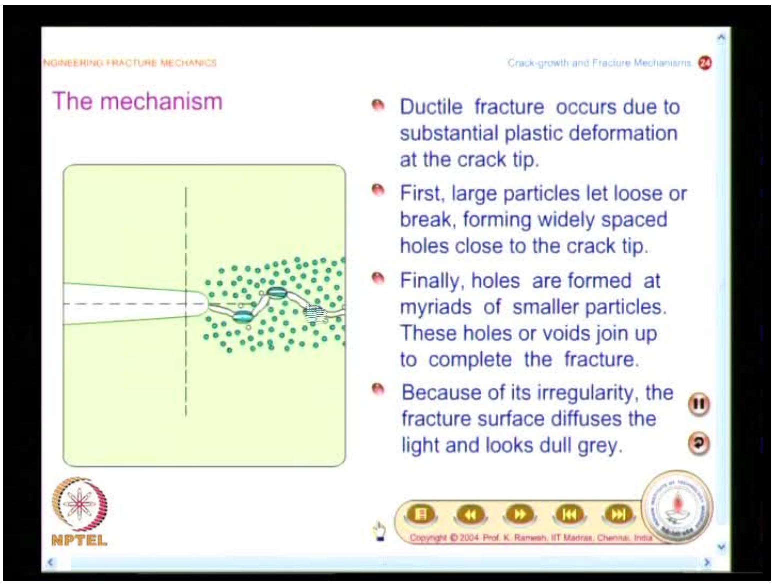

Now, let us look at the animation, explaining the phenomenon of ductile fracture. We have seen already that ductile fracture occurs due to substantial plastic deformation at the crack tip, and what you have is, first the large particles, let loose or break, forming widely spaced holes close to the crack tip. In fact, you could look at the animation simultaneously, but you would also spend time and looking at the animation exclusively later.

Now, let us look at the steps. After the large particles let loose or break, holes are formed at myriads of smaller particles. And what happens is, these holes are voids, join up to complete the fracture. And what do you find here is, the holes are joined and you find the crack proceeds, at a microscopic level in a zigzag fashion; and a macroscopic level, it is proceeding straight as what is shown by the arrow. And because of the irregularity, the fracture surface diffuses the light and looks dull grey.

So, what we will look at now is, we will have a closer look at the animation; this shows the last part of it, where voids are joined due to micro-necking, and you have a crack propagation, the process starts here. Initially, the large particles break, then you have myriads of holes formed, they fail by micro-necking and the crack moves forward. And you see, when you have this micro-necking followed by crack propagation, because you have particles are removed, you find the surface is not smooth, it has valleys and mounts.

In fact, you would be able to see that, at appropriate magnification in a scanning electron microscope. You know. One of the habits that you have to develop is, look at, also the books and gain more information. In fact, if you go and look at the book by broek, you would have micrographs showing breaking of large particles in an aluminum alloy, and followed by scanning electron microscope photograph of the surface, showing valleys and mounts, which explains why the surface has been rough in a ductile fracture.

We will again look at the animation. This will give you some kind of a clarity, on appreciating the processes involved. So, the large particles break, followed by intermediate particles getting removed and forming holes, which is followed by micro-necking.

So, in this class, what we have looked at is, initially, we have explained certain clarifications on the fatigue crack growth model. Later on, we proceeded to look at various ways, stress corrosion cracking can happen. We have looked at active path dissolution, then hydrogen embrittlement. And finally, film induced cleavage, then we moved on to another crack growth mechanism, namely creep. In an actual structure, you will have combination of many of these, for the case of example of an aircraft, we saw that, crack can get initiated by stress corrosion cracking, which proceeds while the aircraft is under taxing as corrosion fatigue. And in the actual flight, the crack propagates by a fatigue mechanism.

So, in reality, many structures will have combination of many of these crack growth mechanisms possible. Finally, we also looked at, what is the crack growth mechanism due to liquid metal embrittlement. Then we moved on to discussing fracture mechanisms, we have looked at brittle fracture, as well as ductile fracture.

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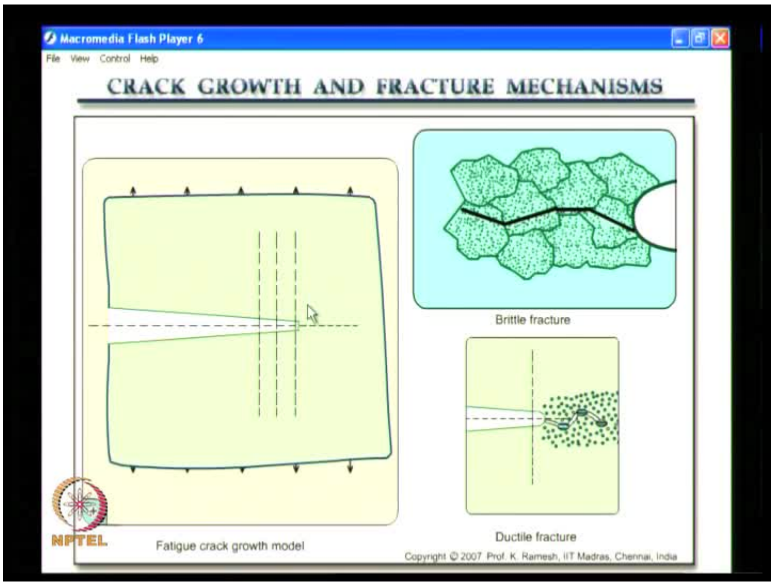

So, in essence, in this chapter, we have looked at in greater detail, what are crack growth and fracture mechanisms? In fact, this slide summarizes, the crack growth mechanism of fatigue, where you could see, for every cycle the crack grows by an incremental amount. In contrast, you find in the case of a fracture, first we have taken the brittle fracture; crack moves very fast and it grows grain by grain and you have the ductile fracture depicted here. The processes involved in ductile fracture are different and in a sense, it move slowly in comparison to brittle fracture, but if we compare it with crack growth both the fracture mechanisms are ultra-fast processes. Thank you.