Engineering Fracture Mechanics
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Module No. # 01
Lecture No. # 06
Fatigue Crack Growth Model

In the last class, we have looked at Typical Photoelastic Fringes. When the crack is subjected to mode 1 mode 2 or combination of mode 1 and mode 2, we will see them again and I have asked you to make a neat sketch of these fringes; particularly

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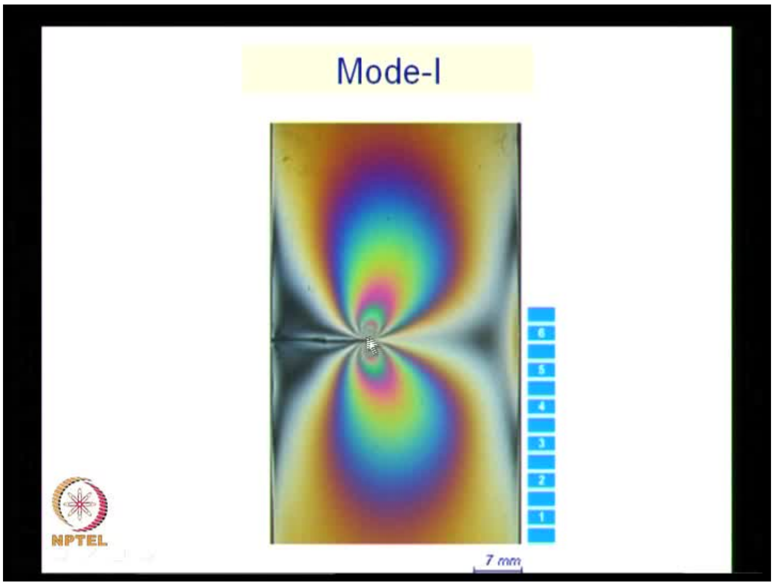

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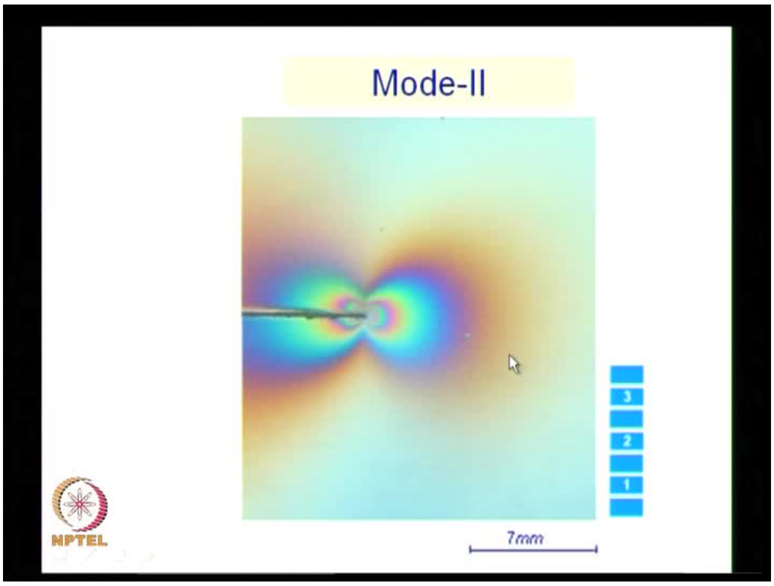

I want you to pay attention on the geometric features of these fringes, in your notes if you have not completed some portion you could see this and edit those pictures suitably and these are all the fringes that you see for mode 1 loading, these are the fringes you come across for mode 2, so if you have an exposure to this it is easy for you to identify by looking at these fringes, whether mode one loading exists or mode two loading exists.

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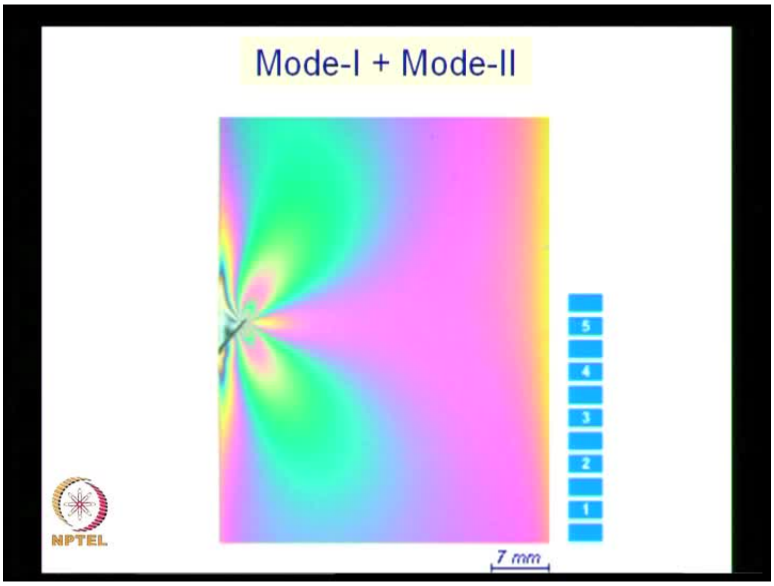

I have already mention that these are contours of sigma 1 minus sigma 2, so when you develop stress field equations it is possible to verify the accuracy of those equations by comparing it with experimental result; in fact, we would do that in the development of fracture mechanics this is very, very essential and people have improved their analytical solution by comparing it with photoelastic fringes and photoelasticity can give you mode 1, mode 2 or combination of mode 1 and mode 2.

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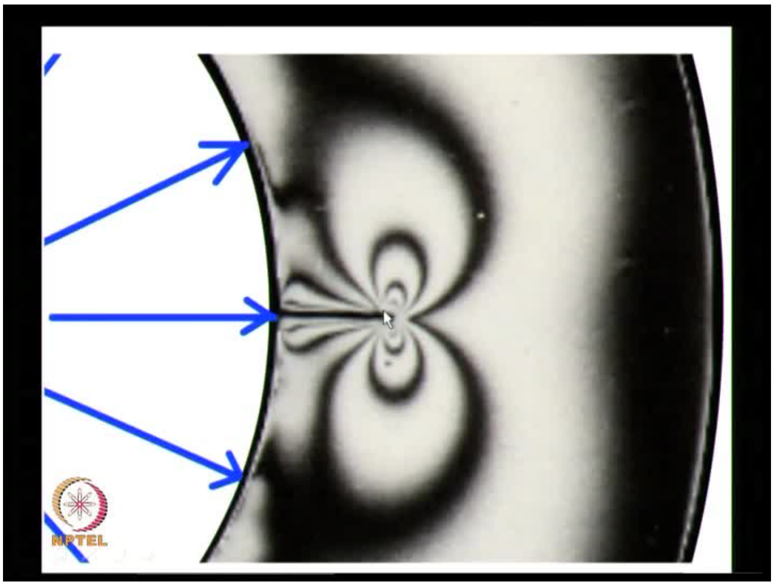

It cannot give you mode 3 fringes because that is out of plane and in the case of mixed mode which is the combination of mode 1 and mode 2; first observation is fringes are not symmetrical about the crack axis and they are also tilted to different angles in the top as well as the bottom, then we graduated and looked at the kind of fringe field in a simulated pressure vessel, you have actually a annular ring subjected to internal pressure.

I drew your attention that, the first fringe what you see here is backward tilted, second is also slightly backward tilted and the third fringe is forward tilted and fourth fringe is almost straight and near the tip of the track you really do not have data and this observation is quite important for an experimental list.

See, we have been looking at when you have a crack and the immediate vicinity of the crack the stresses would be very, very high and you will have plastic deformation, you really do not have mathematical equations to fully capture, what happens exactly at the crack-tip from an experimental point of view, you will not able to go close and collect data, you have to collect data only from a region away from near vicinity of the crack-tip and in this you find several geometric features, which really give a clue for you to incorporate, how many terms in your analytical expression that need to be use to extract and process data from experiment to calculate the stress intensity factor.

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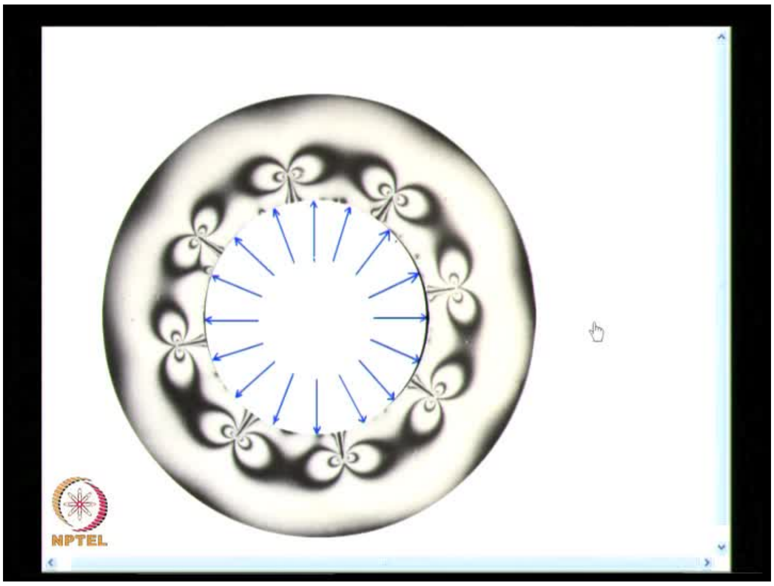

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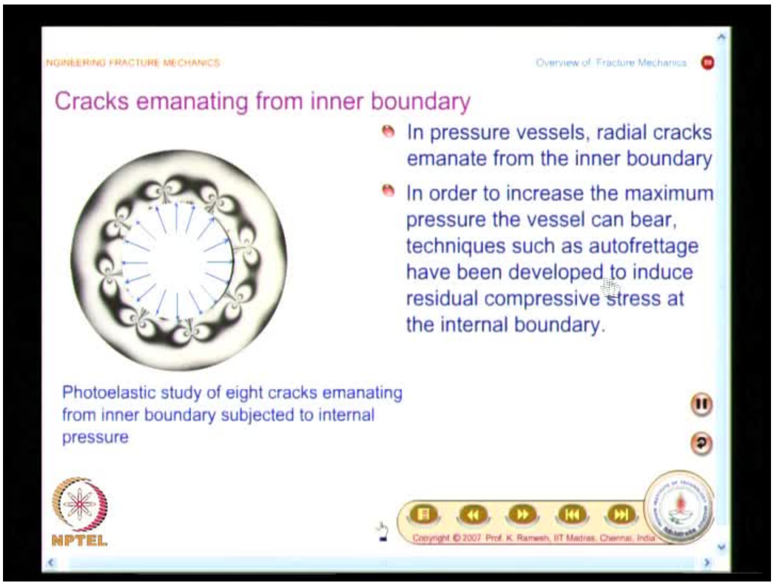

Because, when you are really looking at practical problems they are all finite geometry analytical solution, provide only for infinite geometry or you have series of repeated cracks such nice problems only you have expressions for stress intensity factor, for any other problem when you have a crack lying in a stress concentration zone or in a finite geometry you have to depend on either a numerical technique or an experimental technique; in the case of an experimental technique you will have to use appropriate equations to process the data that becomes very important and we have also looked at in the last class a series of cracks, radial cracks emanating from the inner boundary and from your understanding of solid mechanics, because it is subjected to hoop stress it is essentially in mode 1 loading and you observed that, there is no major interaction of these cracks when you have multiple cracks, if they are far apart they are not really interacting and you also saw that fringes depict a typical mode 1 loading situation and in pressure vessel technology, they want to increase the pressure carrying capacity of the vessel and you all know that inner boundary is very heavily stressed.

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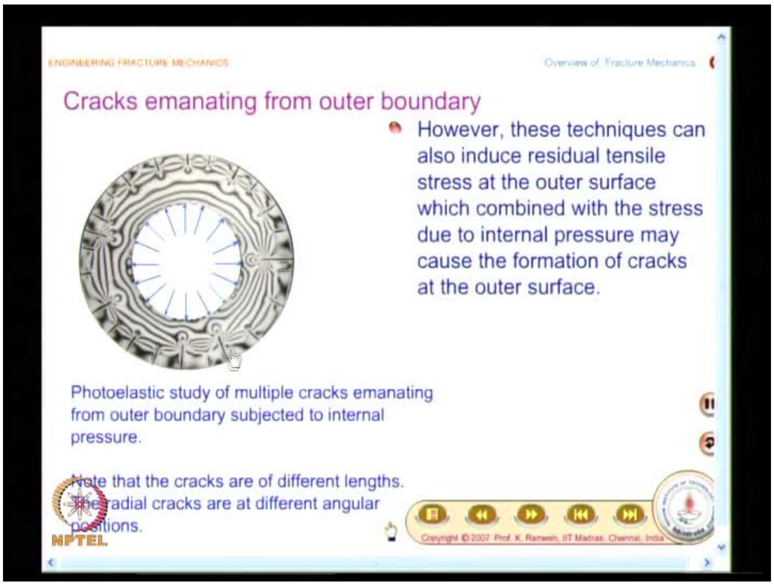

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So, there is a possibility of cracks emanating from the inner boundary, suppose I want this to with stand a higher pressure there have been techniques, such as autofrettage have been developed, which induce residual compressive stress at the internal boundary, so if I have a residual compressive stress at the internal boundary, the possibility of cracks to grow from the inner boundary will be diminish but, what does this autofrettage do? It will generate residual tensile stresses on the outer boundary, so when you pressurize the vessel this is in combination with the residual tensile stress on the outer boundary, can lead to cracks emanating from the outer boundary and you have an example, where several cracks are put on the outer boundary and you have cracks of different links and also they do not follow a periodicity, this is randomly done to observe is there any major interaction between the cracks and from your understanding of solid mechanics, you can easily say that, these cracks also experience mode 1 type of loading, but do you see anything different in the fringe patterns, in all the fringe patterns where fringes are well develop.

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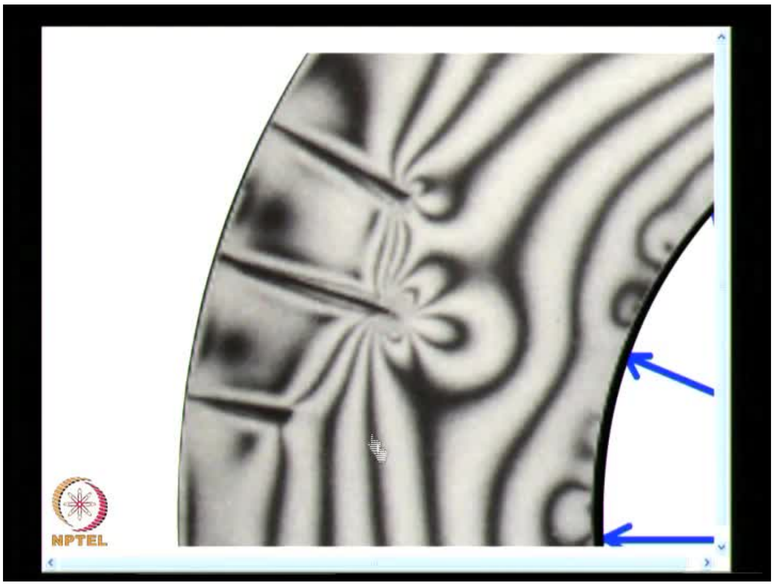

You find a frontal loop, I will magnify it and show, so what you find here is these are the features that we saw in a short crack, you have fringes forward tilted they are symmetrical about the crack axis, but this crack exist in a pressure vessel and stresses are very high in this region, so the crack-tip is in a stress concentration zone and the crack is also very long and what you find, you have a prominent frontal loop you have many such loops available in addition to the forward tilted loops; in fact, if I go and use an analytical expression to process experimental data the analytical.

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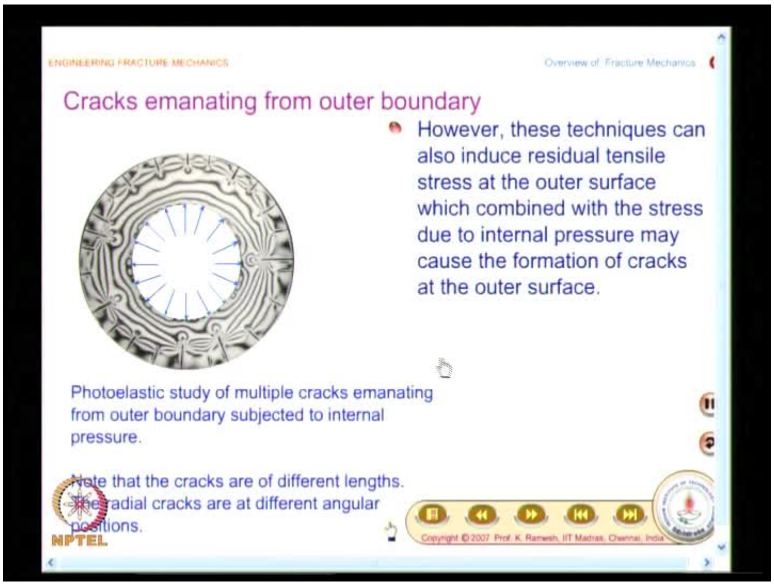

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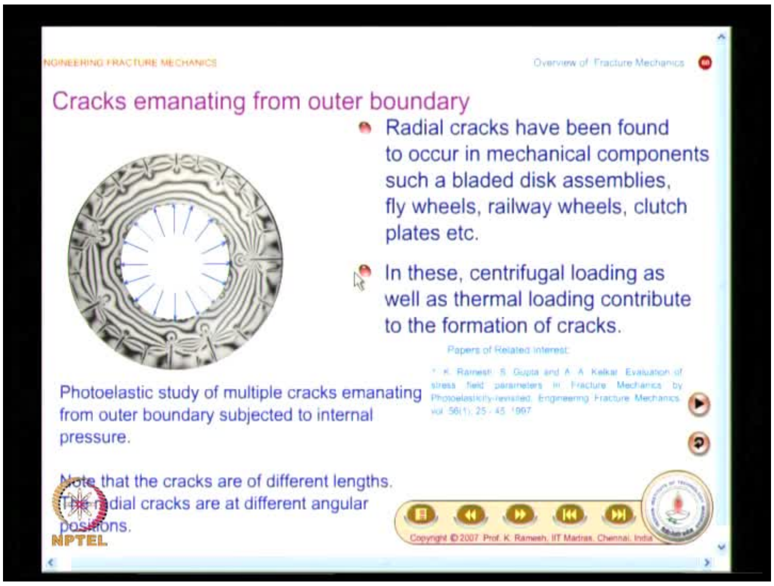

Expression should have sufficient number of terms to represent this phenomenon, it should be able to capture this aspect from the experiment only, then I can use it for data reduction based on experimental information, this is very, very important and this is what is summarized here, that the autofrettage techniques can also induce residual tensile stress at outer surface which combine with the stress due to internal pressure may cause the formation of cracks at the outer surface, this is what we have just now discussed and the problem of an annular plate with the radial cracks, you come across in many engineering applications, radial cracks have been found occur in mechanical components such as bladed disk assemblies, fly wheels, railway wheels, clutch plates, etcetera. So, there are many practical problems which come under this category, because they are all finite body problem experimental results are very valuable in those cases.

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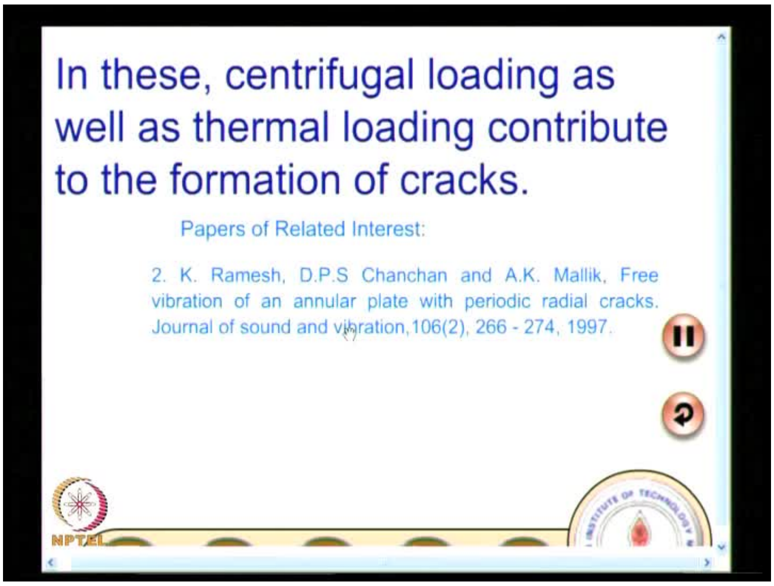

How the cracks are formed, the centrifugal loading as well as thermal loading contribute to the formation of cracks, so it is practically a very important problem; annular plate with radial cracks, emanating from inner boundary or outer boundary, if you understand you could address quite a variety of practical problems in a meaningful way and for further information you could look at some of these references and this was published in way back in 1997 this really brought out the higher order terms in fracture mechanics stress field equations.

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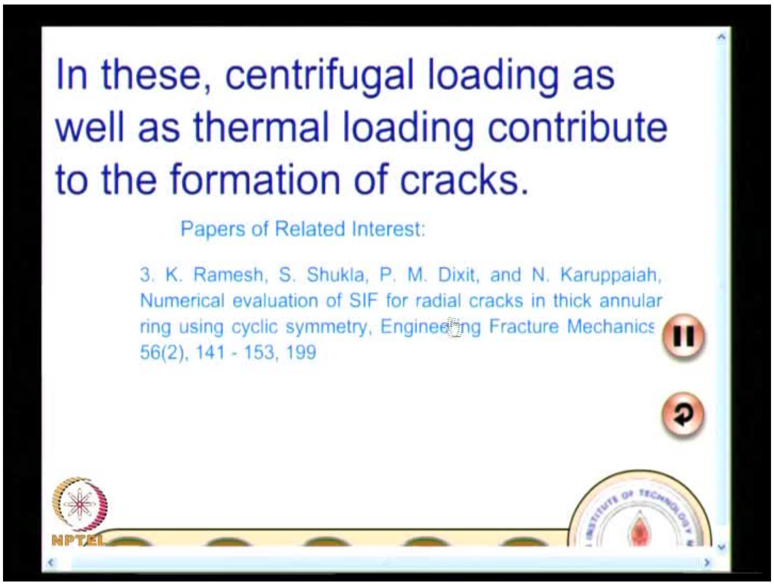

Which need to be utilize for processing photoelastic data, then you have another paper which deals with periodic radial cracks and there are also numerical studies, then for the evaluation of stress intensity factor in thick annular plates using cyclic symmetry.

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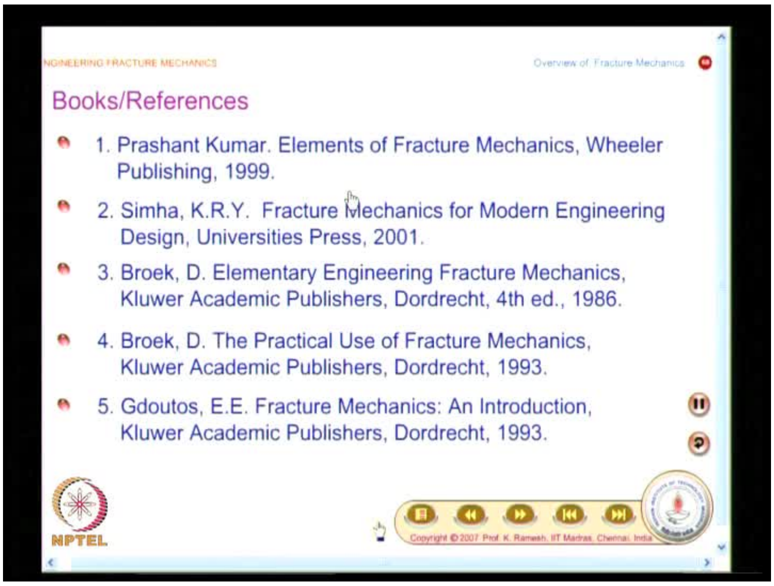

We have come more or less to the end of this overview on fracture mechanics and for you to have a collection of books and references these are summarized hereand is a book by Prashanth Kumar elements of fracture mechanics this was earlier published by wheeler publishing.

Now, it is available throughout Tata Mcgraw hillit is quite a good book for you to purchase, it has a balance of conceptual development and mathematics, it is affordable and I would recommend you to have this as a text book for your convenience and there are many other books, the book by professor Simha from IIT Bangalore, this focuses more on conceptual development and the mathematical rigorous, consciously avoided to drive home the basic tenets of fracture mechanics and you have the very famous book by Broek on elementary engineering fracture mechanics, this was originally published by Kluwer academic publishers.

Now, it is taken over by springer science and business media and there is also another important book by Broek, the practical use of fracture mechanics, so in all these references you write the name of the author, the publisher and year of publication.

That would quicken up your writing of these references, the title even always find out from the internet, then the other the book is by Gdoutos fracture mechanics and introduction and each one of these provide you different flavor of fracture mechanics, what I have attempted to give is a pronglamation of all these books.

Whatever the ideas that they have focused they are presented in a convenient fashion for you, to appreciate both concepts as well as mathematical development, you may be thinking in the overview that, we have been listening more of concepts, but we would soon get into mathematics where you would find the mathematics is quite complex.

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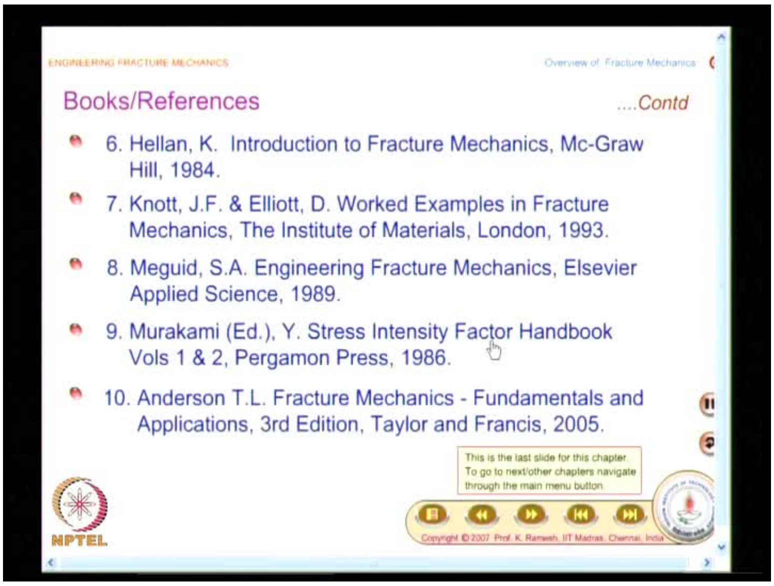

So, we will do that and you also have several other books, these are also listed as a book by Hellan, this is on introduction to fracture mechanics this is highly mathematical and there is a book by Knott, there is a book by Meguid, it is mostly on practical applications and you have a very important handbook on stress intensity factors. Say, if while discussing fracture mechanics we have already seen, you need to find out stress intensity factors for a given geometry, In olden days for stress concentration factors, you had a very famous book by Savi, that provided stress concentration data for a variety of problems, on similar lines Murakami has come out with stress intensity factor handbook it is available in volumes 1 and 2 it is available in our library; whenever you have a problem for which you need to know the stress intensity factor you can have a look at it if you have it then proceed with it, if you do not have it then go for a numerical or experimental approach.

Finally you have a book by Anderson, this is more like an encyclopedia it covers very many topics in fracture mechanics and this is again available in the library it could be use more as a reference, what in my opinion to be a better book as a reference rather than a text book.

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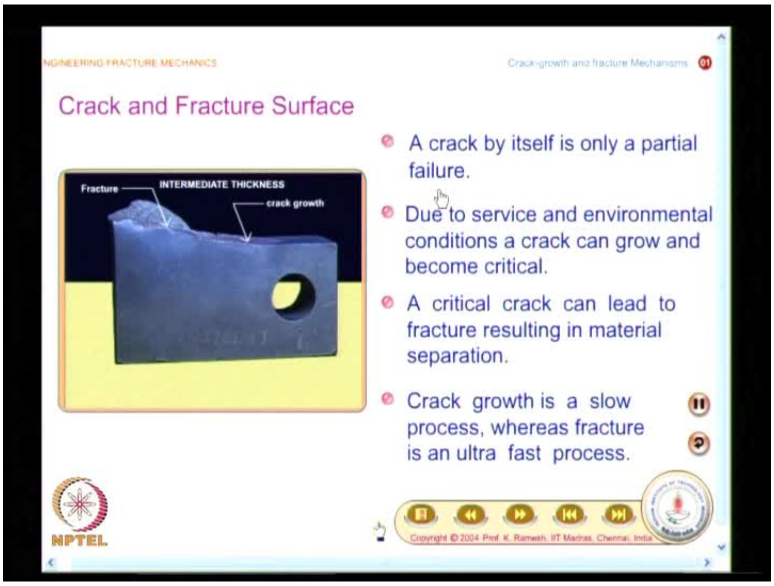

And now, we move on to the next chapter on crack growth and fracture mechanisms, know have understood reasonably well after a very long overview on fracture mechanics a crack by itself is only a partial failure due to service and environmental conditions a crack can grow and become critical, a critical crack can lead to fracture resulting in material separation.

So, that you know this is what we have develop very carefully in overview of fracture mechanics, so you have that knowledgeto start with and we will make a certain distinction between crack growth and fracture, crack growth is a slow process whereas fracture is an ultra-fast process it happens very, very fast.

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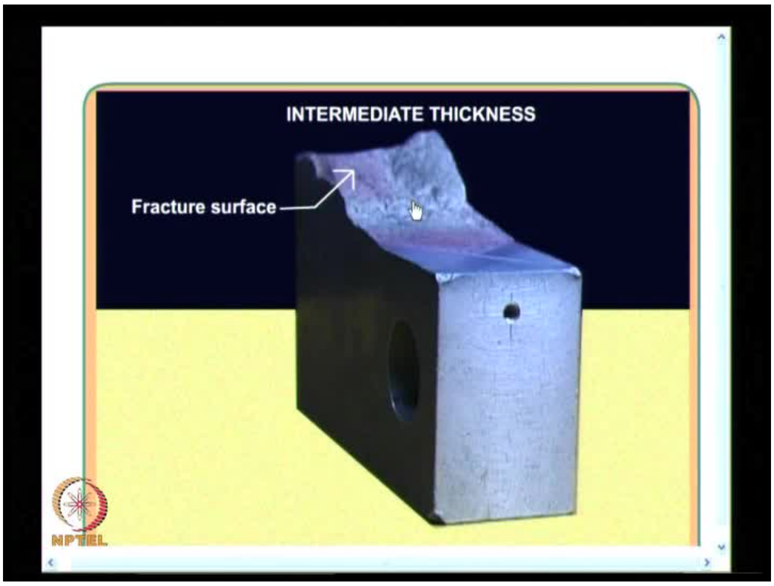

We would have a closer look at this animation and this shows, there is a crack growth phase it followed by fracture and you watch it carefully you have this di penetration technique is used you see the crack growth surface which is in pinkish in color, after the crack has grown you have this material as fracture and if you watch it carefully you would see this is at forty five degrees this is called a shear lip.

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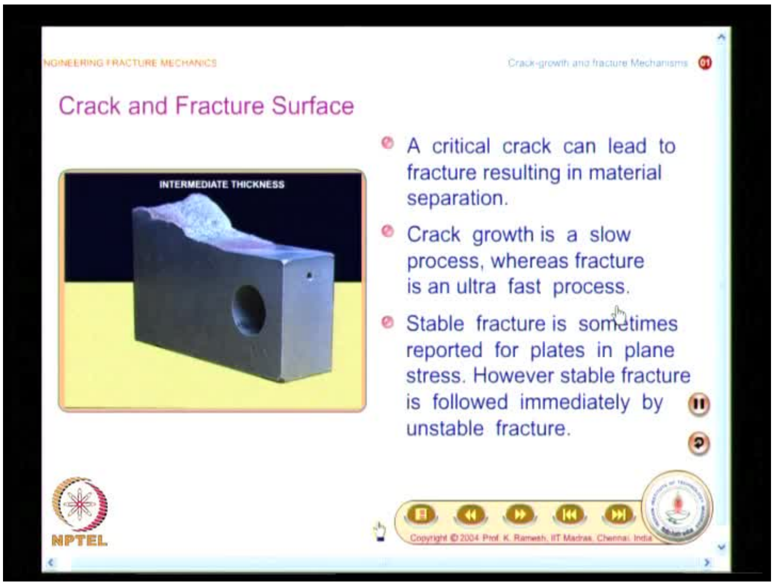

We would see that in detail for us, to appreciate certain mechanisms dealing with crack growth and before I proceed further, I would also like to point out that there is stable fracture possible, we have said crack growth is a slow process whereas fracture is an ultra-fast process, but you also have another the phenomenon, that is observe in the case of plates in plane stress there is stable fracture, however stable fracture is followed immediately by unstable fracture. Now, I am trying to develop a good conceptual foundation for you to appreciate the mathematical development, because you need to know there is crack, there is crack growth and fracture. And fracture also the people have observed stable fracture and when you have actually looked at a broken specimen, you find there is a shear lip and it is worthwhile to spend some time on understanding the shear lip, this is seen in a conventional tension test itself.

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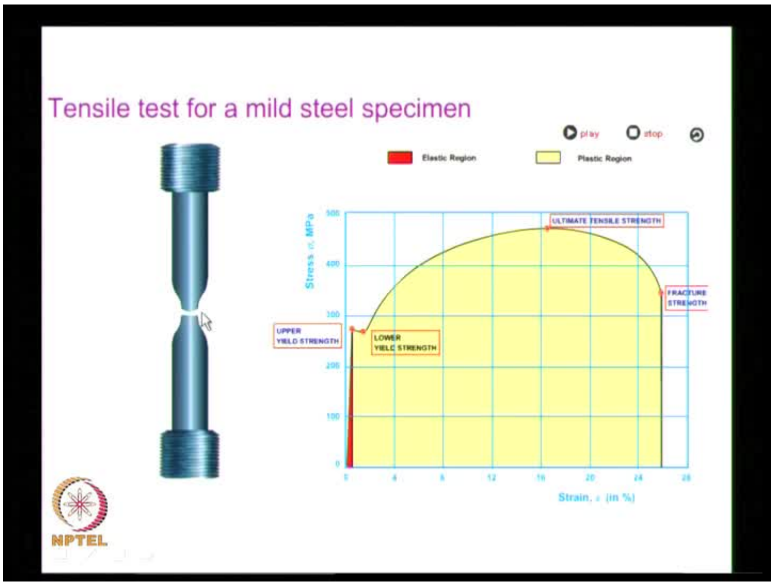

You will have a look at it, let us go back to the conventional tension test, you have a specimen that is pulled and after it has reach the ultimate tensile strength followed by fracture, you find there is necking and the material as separated and what causes necking; how necking can be modeled, there is a there is a very simple model, that I am going to show and in the case of necking.

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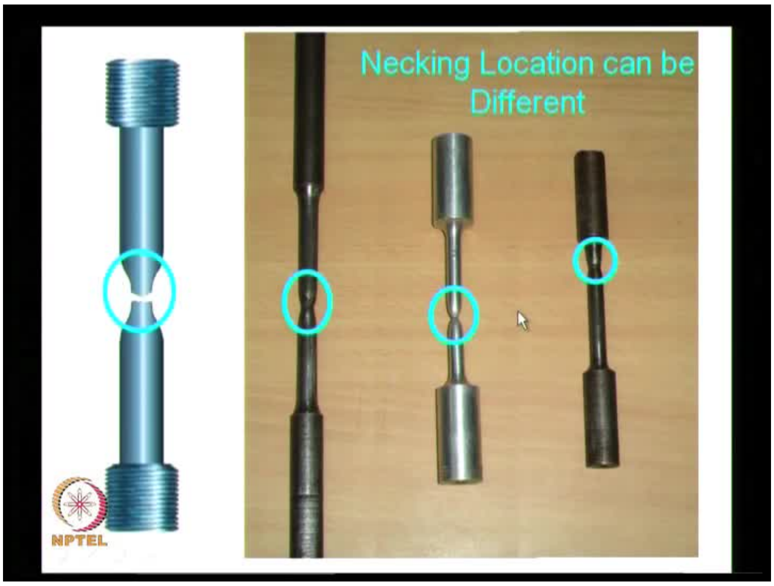

It is actually the internal flaw which dictate along the length of the specimen, where the necking would start and what happens is, you have a internal flaw which precipitates necking and this flaw grows in size that is what you see here, that is shown in red and after sometime you find suddenly on the ends you have a shear failure at 45 degrees.

So, the material separations starts from the center of the specimen and proceeds outward and you have a shear lip on either side, you would see the animation full, so this gives a possible explanation on how necking could be viewed and what this slide shows is in a simulation, it is shown that necking has taken place at the center of the specimen. This need not be and I am going to show you examples from a actual material failure done in a tension test you have one example, you have another example this is of aluminum specimen, there is a third example this is on steel, these are done at various a points in time and what these specimen show is necking location can be different, so you find it is exactly at the center in the case of a simulated test specimen. On the other hand it is more or less at the center in the specimen it is slightly off, whereas this is very close to the reb's, since we have seen what really causes necking, you are in a position to appreciate, because you have internal flaws that dictates where necking would precipitate.

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So, you can understand it can happen along the length of the specimen, my focus is to appreciate the shear lip in the case of a necking also, we would have a look at it and what you have actually is there is a cup and cone fracture, you could see a more or less a flat portion here and it is at 45 degrees and this is all around this is a circular specimen and,. so this forms like a cup and you have a cone. In fact, we would revert back to the shear lip again and again for several conceptual development, when we want to understand different models for either crack growth or fracture this is one view of it, I would like you to make some sketch as much as possible, may not be able to replicate all these finite details at least the appearance of a cone like what you see here and a cup and you can see localized plastic deformation.

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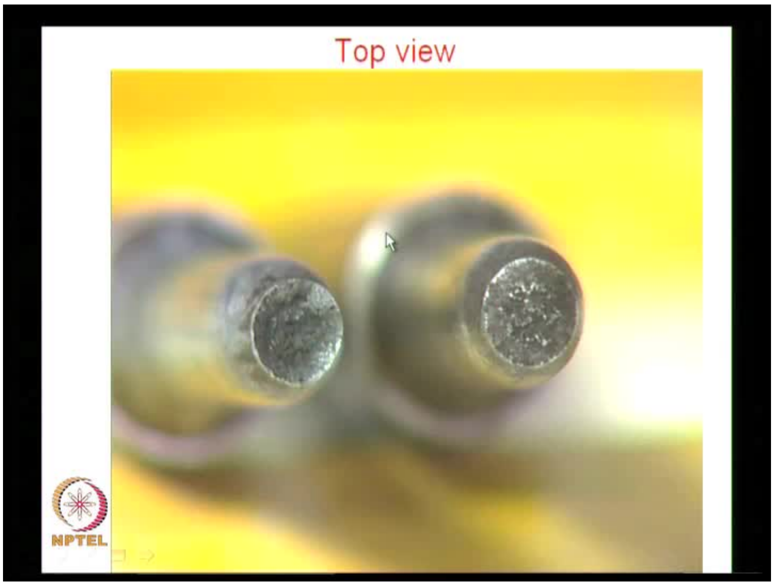

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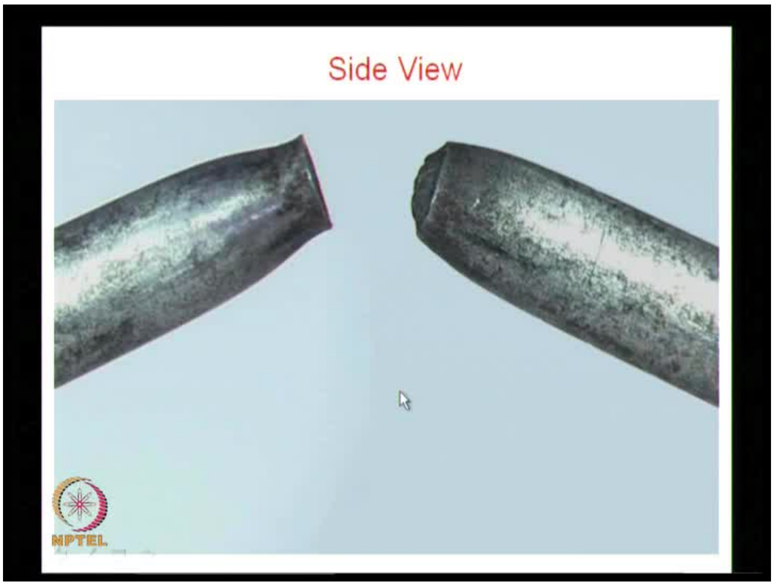

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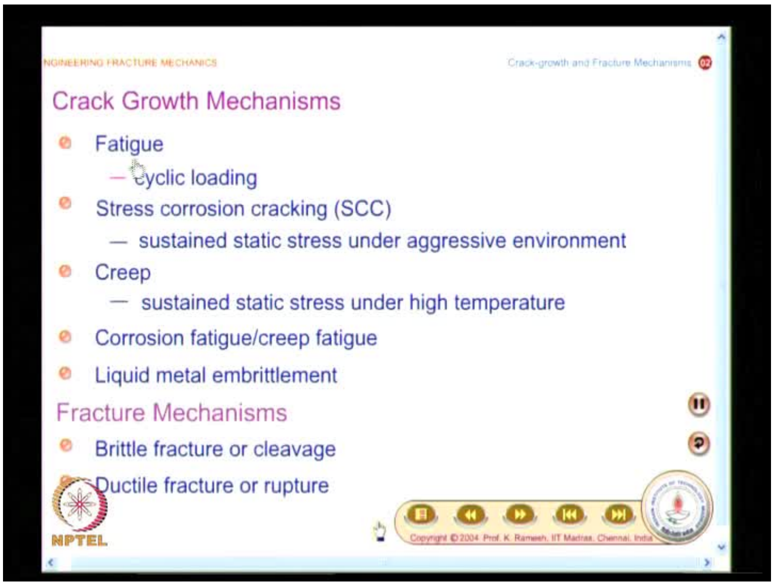

I have different views of the same specimen, you also have a top view, so this shows that you have a cup and you have a cone and there is also a nice side view, so you have the necking region is very clearly seen and this is a cup and cone failure. In fact, this is taken out from the experiments done by various students in the laboratory, whatever the specimens that we are available, we put them together and you get a feel that, there is a cup and cone failure is been observable in the case of a tension test. And you essentially have a shear lip and we would use that for developing a model for fatigue as well as for ductile fracture and we will look at crack growth mechanisms, you will be very familiar with fatigue and fatigue occurs, because of cyclical loading. Whenever people think of crack growth they immediately jump all cracks grow by fatigue, so what you will have to keep in mind is fatigue is one of the mechanisms for crack growth and it is widely prevalent, there is no harm that when you have a crack growth to feel, that you could have been a fatigue crack.

That is quite all right but, that is not the only mechanism; that is what you have to keep in mind, crack can also grow by stress corrosion cracking, which is abbreviated as SCC. What happens in this, you do not have a alternating stress but, you have a sustained static stress but, the specimen as a hole is a under aggressive environment.

So, it is a combination of aggressive environment and sustained static stress, lead to stress corrosion crack, when you can have another phenomena possible, that is creep in this you have sustained static stress under high temperature in practice, what you will find is you will have a combination of this individually, when you study you can look at what happens in fatigue, what happens in SCC, what happens in creep but, in practice you could have a combination of this.

So, you can have, what is known as corrosion fatigue, creep fatigue; it is a combination of corrosion and fatigue you call it as corrosion fatigue, combination of creep and fatigue you call it as creep fatigue and you could also have liquid metal embrittlement.

So, there could be many crack growth mechanisms and we need to understand, I have already mention that you need to know the degradation mechanisms of structures and that is very important for you to develop concepts related to damage tolerant design, unless you understand the degradation mechanisms, you will not be in a position to develop the appropriate methodologies. We have looked at crack growth mechanisms, we will also look at what are the fracture mechanisms, you could have brittle fracture or cleavage fracture, we would see each of them in detail, you have ductile fracture which is also called as rupture, you would see each of this in detail and brittle fracture is very, very fast, ductile fracture is also equally fast from conventional point of view but, compare to brittle fracture it is slow.

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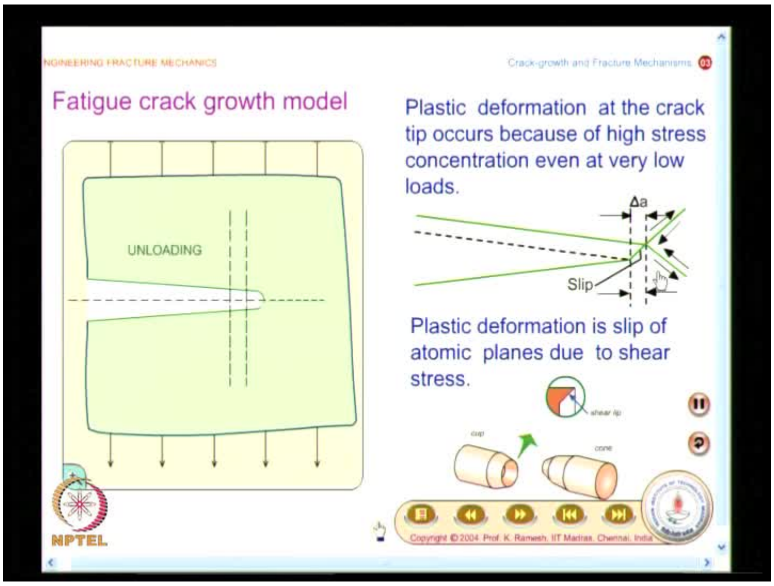

When you look at crack growth, fracture is a very fast process whether it is brittle or ductile, it is only attention to detail that is, all they are both fast processes in relation to brittle fracture; ductile fracture is slightly slow and what we will look at is, first we will try to understand how a crack grows due to fatigue. We will develop a model for this after having looked at the solution by Inglis, you would agree that, there would be excessive plastic deformation present at the crack-tip, because of high stress concentration even at very low loads.

I am going to show a sequence of steps for modeling the fatigue crack growth, after you observe these steps will go to this animation and clarify our self the understanding what causes a crack to grow. So, first pay attention on the concept presented in this portion of the slide and I would like you to make a sketch of this and in order to explain, only I focused on the shear lip in the case of a tension test, you have a cup and cone and what is important here is you have a shear lip at 45 degrees.

So now I have a crack, because load is applied, you will have plastic deformation in the vicinity of the crack-tip, which will cause slip of atomic planes due to shear stress, so what will happen is, this will slip and you will have a extension of crack and such a phenomena can happen in complimentary planes. See, my focus is to show conceptually, there is a possibility of growth of a crack due to fatigue in contrast to a crack zipping through the metal, when it moves very fast it is fracture.

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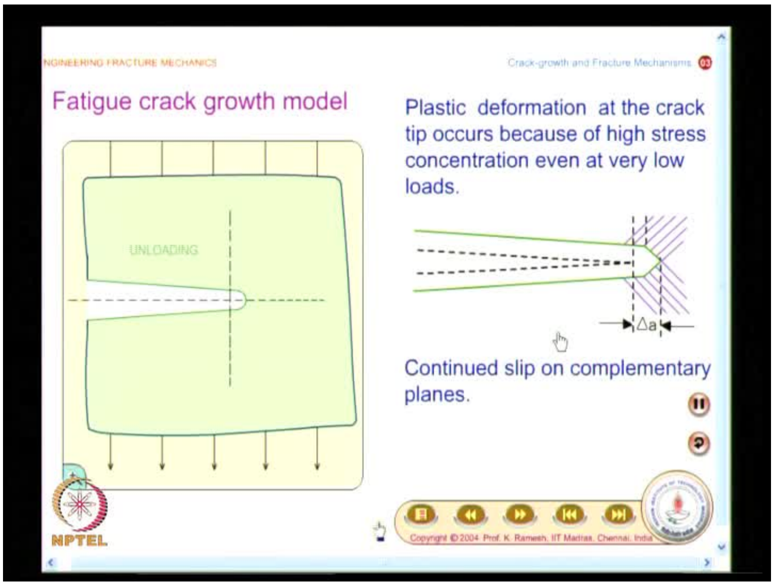

Now, what we will look at is, we look at a reasonably a good model which explains how a crack grows, because of repeated loading. So, the first thing what happens is you have to recognize, there is plastic deformation at the crack-tip and because of this slip of atomic planes occur, so it could happen in complimentary planes and that is what is shown in the next sketch, so what you have here is, because of successive slip you find the crack has taken a shape like this, make a neat sketch of this this will give a this will give you a conceptual appreciation, how a crack grows in the case of fatigue, in contrast to what you come across in fracture.

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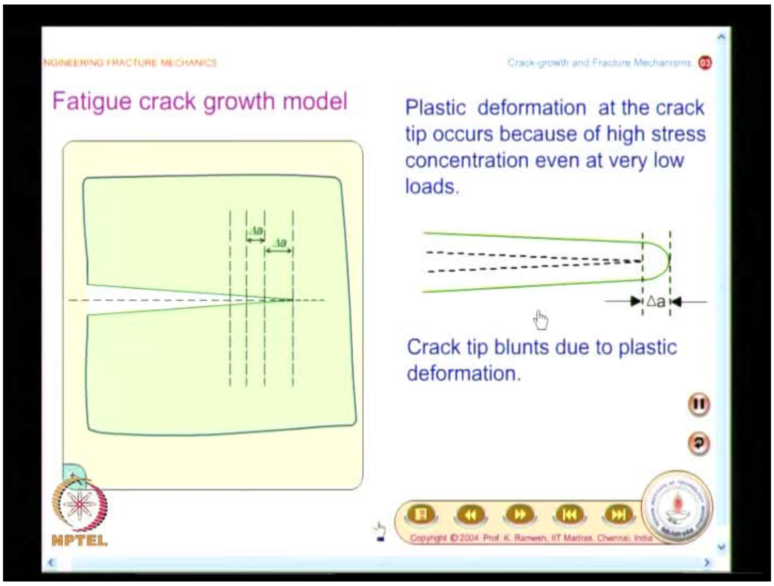

Simultaneously, people who have drawn this they could also have a look at this animation, seeing this 2, 3 times will make your concepts clear, so what you find is the crack which was originally like this, it has taken a shape when you recognize that, there could be slip on complementary planes. Nevertheless, you should recognize you have plastic deformation, so nothing can remain sharp a plastic deformation will deform it, so you can reasonably anticipatethe crack would blunt by itself, so what you find is, you had a sharp crack from the knowledge of Inglis solution, you can anticipate the stresses would be very high, even for very small external loads.

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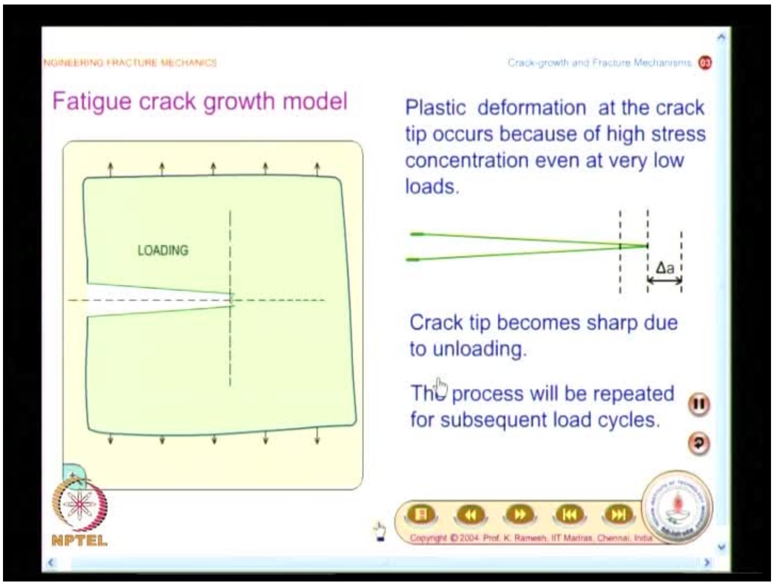

So, there would be plastic deformation this plastic deformation cause a slip and you find slip in complimentary planes, then eventually you find a crack has grown by some distance and it is blunt because of plastic deformation, so all this happens during loading and when the load is removed, when you go through the cycle the crack-tip becomes sharp, because when you have a cyclical loading it moves up and down.

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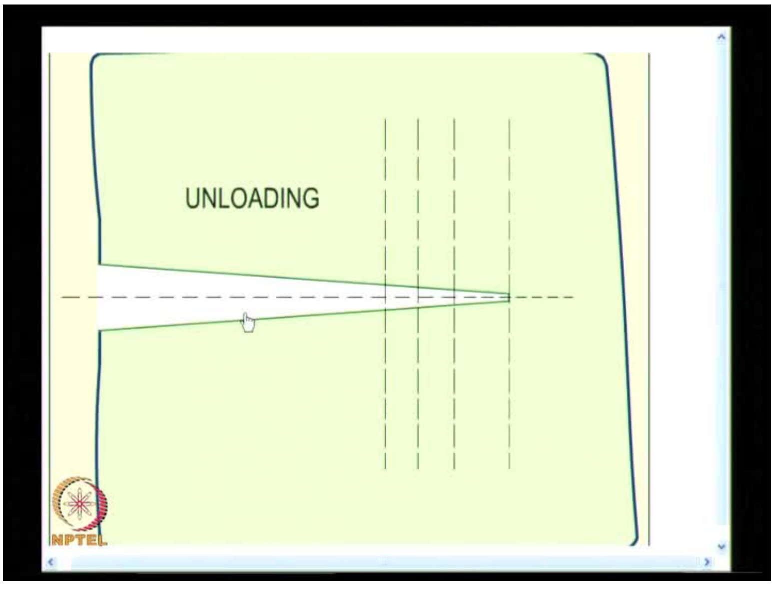

So, when the loading is removed the crack become sharp, then the whole process will be repeated for subsequent load cycles, what I am going to show here is, first see this animation like this then I will magnify, because you could see loading clearly, so during the loading phase, the crack advances at the end of the loading phase, it becomes blunt then it becomes sharp when it is unloaded, so you could see the loading, unloading on this scale of the animation. Suppose, I magnify you will see what happens at the crack-tip, you have to recognize that, this is highly a magnified picture it is a in the level of microns, we have magnified it several times just to illustrate what is the reasonably a good model to appreciate growth of a crack infinity, you could see here during the loading phase the crack advances by slip and slip in complementary planes.

So, it become sharp, then it becomes blunt and when you have unloading the crack has become sharp, then the whole process starts, the whole process starts all over again and what is also attempted to show here is the delta A, what you come across after each cycle would be slightly different after several cycles, because the crack is growing larger stresses also will be very high, so the increment also will become larger and larger as the crack grows this is easy for you to extrapolate.

In fact, in one of the assignment sheets you will go and find out crack growth rate by processing the micrographs. Now, what I am going to draw your attention is the model says, there is crack-tip blunting and then it becomes sharp, when it is unloaded the crack has grown by loading it has become a blunt and when I do the unloading it becomes sharp. Common sense tells this should leave some residue on the actual material, because you say that it is opening closing, opening closing, opening closing it becomes blunt and sharp something should happen. In fact, it is so, people have done postmortem and understood whatever the model that you have in the such model is explainable by looking at what are known as striations we look at that.

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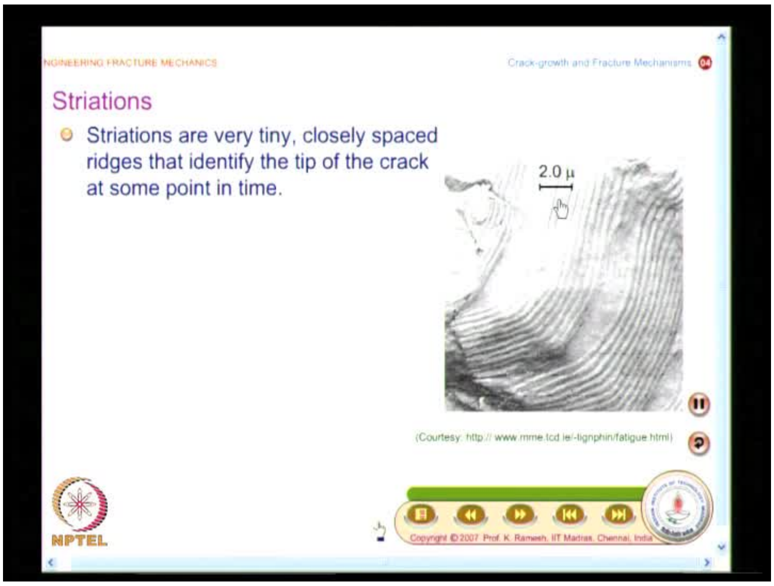

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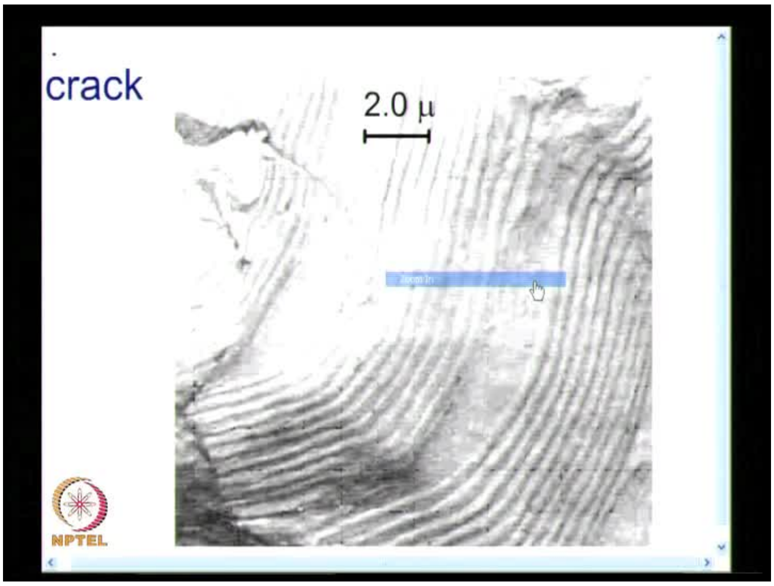

So, what are striations? Striations are very tiny closely spaced ridges that identify the tip of the crack at some point in time and you have a typical striations observed in a specimen, the courtesy is given at the bottom and you should also see the scale it is two microns, this is short distances is two microns, so within two microns we have 1, 2, 3, 4 striations are seen and I will also magnify this picture for clarity and try to make a sketch of it and why these ridges are form these ridges are form, because of repeated opening and closing, that is what we had seen when we had develop the fatigue model, we have a repeated opening and closing, you cannot see them in naked eye you will have to see them only at very high magnifications, so the specimen carries the signature.

In fact you could find out, what is a kind of loading, there may be a over load here repeated over load, so you find that, there is a shift here, there is a very long crack growth all that kind of analysis metallurgies do. Now, we have seen that, there are striations form now you have an explanation from the fatigue crack growth model why striations are form they are explainable.

In all crack surfaces you come across, striations this is one of the important signature at the microscopic level but, it depends on the material also it depends on the composition of the material you cannot go and argue if striations are not seen crack growth has not taken place by and large. In most of the situations you come across striations, there are certain exceptions depending on the composition of the material clear striations may not have been formed, so this is also you have to keep in mind.

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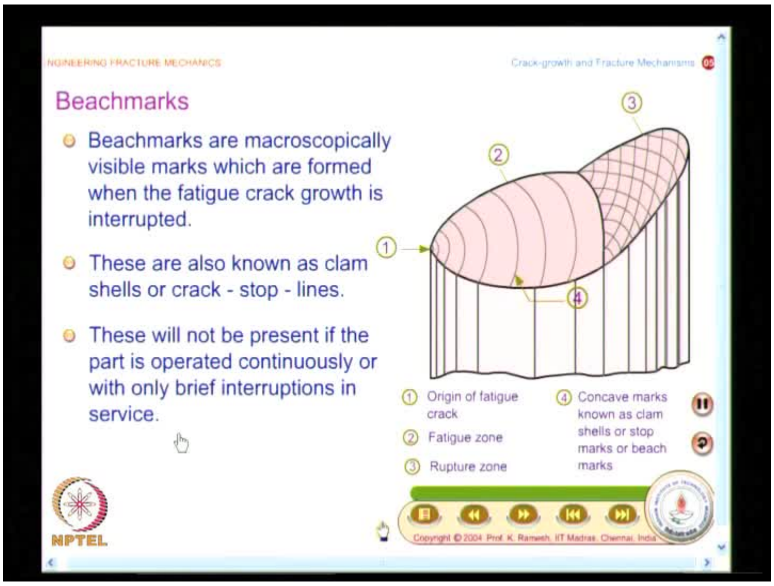

Now, we move on to, what are known as Beachmarks? See in contrast to striations Beachmarks are macroscopically visible, so you should not confuse between a Beachmark and a striations, these Beachmarks are formed when the fatigue crack growth is interrupted; that means, you run the machine for a several hours and stop it for one or two days, then restart and then run it for a several days then stop, so all these the specimen carries a signature, so you can do postmortem, say in the case of trees if they want to find out what is the age of the tree, they would see embedded circles.

So, you can go and do the dating of the tree, some kind of a natural phenomena happens even when a structure is subjected to external loads, we think that it is inert, it is not inert it also has some kind of an intelligence it is expressing itself, that this is the way I have been loaded I carry all this information. So, this is what metallurgies do in their postmortem analysis and normal mechanical engineer, may not even heard the term what is striations but, once we come to take a course in fracture mechanics, you need to have certain rudiments from material science which would help you to appreciate fracture mechanics better.

So, that is the reason why I thought, I would spend some time on explaining what are striations and now we are looking at Beachmarks, I also have a nice picture here again you see a failure by a shear lip this is always shown at 45 degrees, I would like you to make a sketch of it.

So, in this you have origin of a fatigue crack, there is a fatigue zone and there is a rupture zone and in the fatigue zone what you find, I find several concave marks these are known as clam shells. They really stop marks there also having the name Beachmarks; The Beachmarks will not be present if the part is operated continuously or with only brief interruptions in service.

So, you will have to know only when there is stoppage and re-operating of the machine you find distinctive Beachmarks and what are striations in between these Beachmarks; you may have several thousands of them, they would be visible only under a microscope, only under a very high magnification they are visible.

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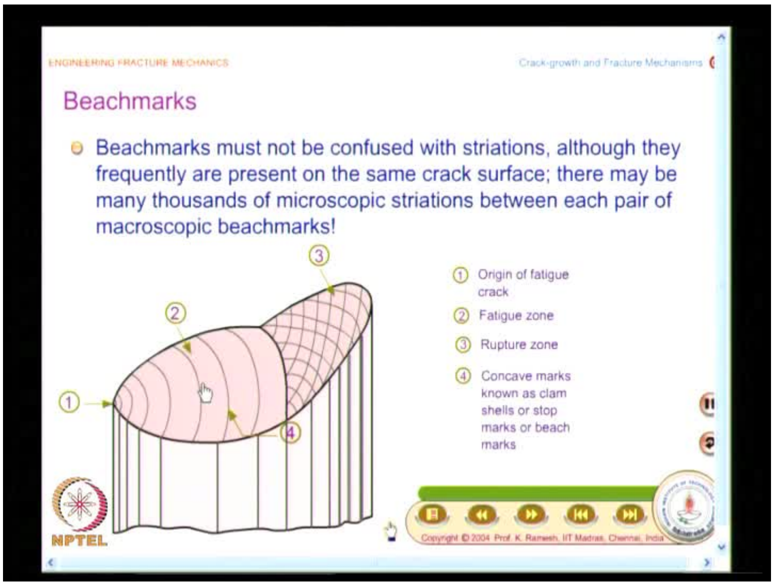

So, you have to make a distinction between what are striations and what are Beachmarks and that is what is again emphasized, Beachmarks must not be confused with striations. Although they are present frequently on the same crack surface, there may be many thousands of microscopic striations between each pair of macroscopic Beachmarks and make a neat sketch of this and make a distinction between striations and Beachmarks.

So, you will have many thousands of striations between the Beachmarks.

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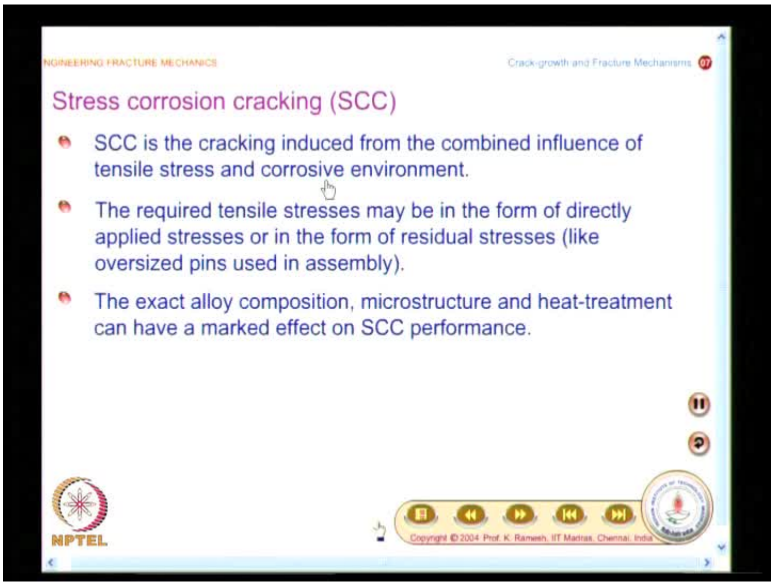

So, this explains what is the mechanism of crack growth by fatigue, now, we move on to Stress Corrosion Cracking abbreviated as SCC and we have already noted SCC is induced from the combined influence of tensile stress and corrosive environment; where do the tensile stress come about, see in many mechanical assemblies you have interference fits, these interference fits also can cause local tensile stress zones or if you have a oversized pin and that is what is summarized here.

The require tensile stresses may be in the form of directly applied stresses or in the form of residual stresses like oversized pins used in assembly and this is usually ignored, see if you go to a company if they make a part by interference they do not even recognize, that interference fit would induce quite a lot of stresses in the vicinity.

They ignore that, when they do the analysis they only take the external loads and they find eventually whatever the component that they have made, they fail in service then they come back to us and we have to tell them you have overlook the residual stresses created by interference.

So, interference fits are very, very important and you have to analyze and handle them carefully you should not over look the role of residual stresses induce, because of interference fit and if you look at SCC, there is also a material angle to it, what is the exact alloy composition, so that also it gives you some kind of a way to come out of SCC.

If I have a SCC problem can I go and play with the alloy composition or can I go and play with the microstructure and also the heat-treatment by such methodologies, you may be able to find out a way out from minimizing the crack growth due to SCC, in fact one of the example which we would see later, would bring out what kind of steels that you should choose for a given application.

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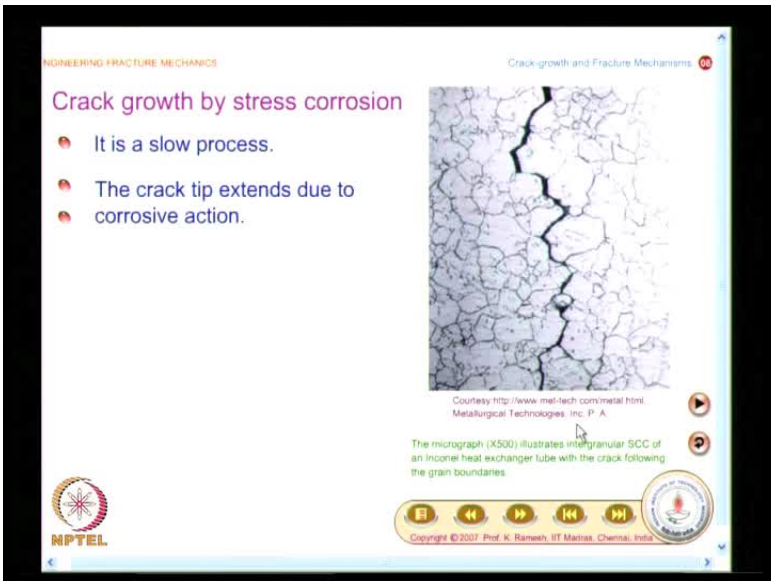

So, definitely the microstructure heat-treatment or alloy composition do play a role and this is again a crack growth and crack growth is a slow process and here you have a very nice magnified picture of an application, it shows intergranular SCC of an inconel heat exchanger tube with the crack following the grain boundaries.

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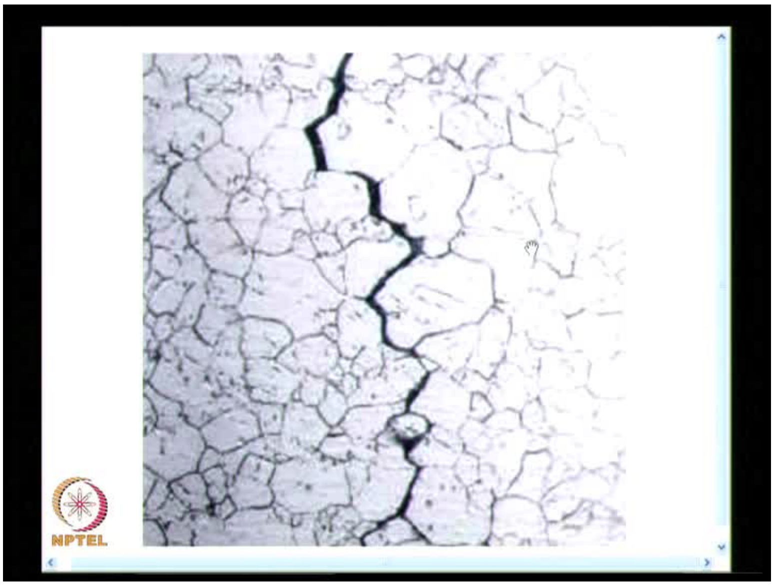

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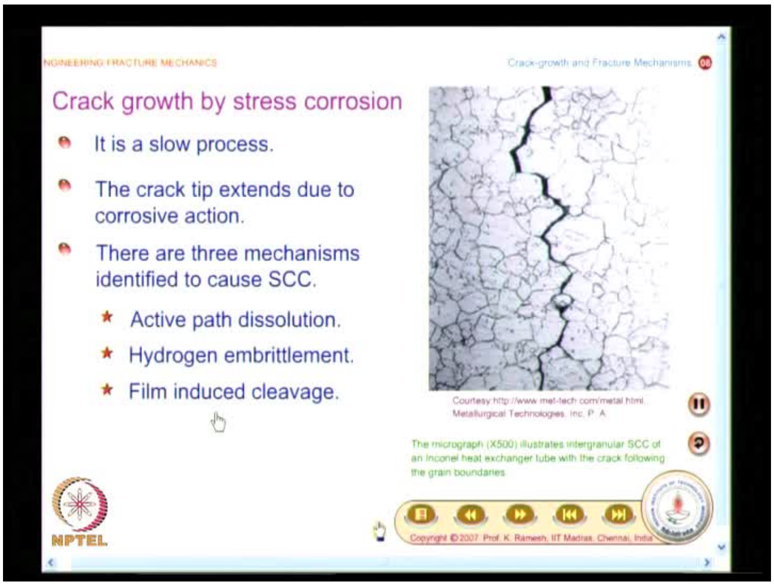

The courtesy is also given this from metallurgical technologies incorporated and I would magnify this picture, you would see different grains on this, this also make a simplified sketch of it; what you see as thick black is actually the crack and where the crack has grown it has essentially grown on the bound of the grains, so it is intergranular crack growth and how does the crack-tip and how does the crack-tip extends, because of the corrosive action the crack-tip extends we saw a different mechanism in fatigue.

There are three mechanisms identify it to cause SCC: one is active path dissolution, second one is hydrogen embrittlement, the third one is film induced cleavage.

In fact we would look at these mechanisms in the next class and what we saw today was the geometric features of the photoelastic fringe, gives you an indication of what kind of loading that exist and I also pointed out, if I have to find out stress intensity factor by processing experimental data, I need to take an appropriate analytical equation with as many terms as possible.

So, that analytical modeling of the region from where I take the experimental data is valid, then we looked some of the books and references and then we moved on to understanding a shear lip; what is seen in a simple tension test as cup and cone fracture, we utilize that understanding for appreciating the growth of a crack by fatigue, then we moved on to another crack growth mechanism named as stress corrosion cracking thank you.