

Failure Analysis & Prevention
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Lecture – 26

General Procedure of Failure Analysis: Macroscopy of Fracture Surfaces – III

Hello. I welcome you all in this presentation related with the subject failure analysis and prevention, we are talking about the general procedure of the failure analysis under this subject. And under the failure analysis under the general procedure for the failure analysis, we have talked about the collection of the background information, preliminary examination of the field component, non destructive testing, destructive testing of the field component and selection, preservation and cleaning, sectioning of the samples from the field component.

And now we are talking about the macroscopy of the fracture surfaces. So, the macroscopy of the fracture surface which is the carried out using the naked eye or the low magnification lenses or a stereo scopic microscope or maybe scanning electron microscope also below the 100 magnification

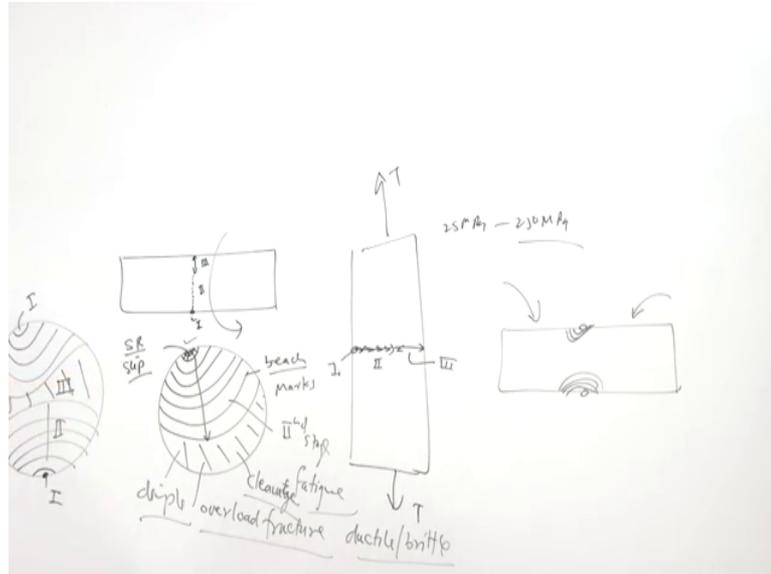
And whenever microscope is carried out it helps together lot of information about the failure which may be about like the location where from failure was triggered or failure was initiated, the direction in which the fracture growth took place means the crack growth direction can also be identified and the kind of the loading conditions means it is the tensile load, the bending load or the shear load. And then we can also identify the kind of the stress state of the a stress state in which failure has taken place, whether the failure has occurred under the plane stress condition or the plane strain conditions.

So, likewise we have talked about some of the features like how to identify whether the failure is a ductile or the brittle based on the macroscopic deformation in the material or the field component. Now we will be seeing in this presentation few additional features related to the microscopy of the fracture surfaces and under this like one is the beach marks if they are present in the field component.

So, to understand these me beach marks we need what we need to see is a let us take this is the shaft which is under the continuous tension and compression during the operation

due to the continuous rotation and some where the crack is initiated due to the prolong the application of the loading and then crack grows

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. So, the growth of the crack will be occurring. So, the crack will be initiating somewhere this is the first stage of the crack initiation thereafter its growth. The crack will continue to grow until it reaches to certain a stage where the load resisting cross sectional area or the left out cross sectional area is a such that it is not able to take the service load anymore.

So, that forms the third stage and in between when this continuous growth of the crack takes place forms the second stage of the fatigue fracture because the load is a nature of the load is continuously changing here from tension to compression. And similarly, similar kind of things can happen when the load is fluctuating like say from tension to tension between certain values of like say 25 MPA to 250 MPA, then similar kind of things will happen where somewhere crack will nucleate and then it will grow and during the growth the crack the load resisting cross sectional area will keep on reducing and then sudden fracture in third stage. So, third stage, second stage and the first stage of the crack nucleation.

So, if we see both these cross section means that the cross section or the field fracture surface of both these components then what we will observe like one location where the crack has initiated that will offer us the typical morphology which will be completely

different from the remaining portion. So, this site which whether I whether we have some stress raiser at this location or even if the component was a smooth, then due to the localized slip where some kind of the crack was created after the prolonged application of the load and once the crack has been nucleated it will be growing.

So, the growth of the crack results in the formation of the concentric circle and the centre of the circles will be the location where from it has initiated. So, if we see all these concentric circles we will have their centre at the location where from it has initiated. So, these concentric circles are similar to the beach marks and these indicate that how far or up to what extent there has been the second stage of the fatigue fracture. So, basically these concentric circles or the beach marks indicate; beach marks indicate the second stage of the fatigue fracture.

And thereafter you see the load resisting load resisting cross sectional area is reduced to such an extent that it does not it is not able to take the load. So, the overload fracture will be occurring in the remaining portion. So, the third stage will be corresponding to the overload fracture now this overload fracture can be ductile type or can be brittle type as per the nature of the material.

So, ductile means this portion will have lot of dimples that is the microscopic mechanism of the fracture or it can have the cleavage facets that is the another microscopic mechanism of the brittle fracture. So, so, there are three stages and it will be indicating how far particular a stage was present.

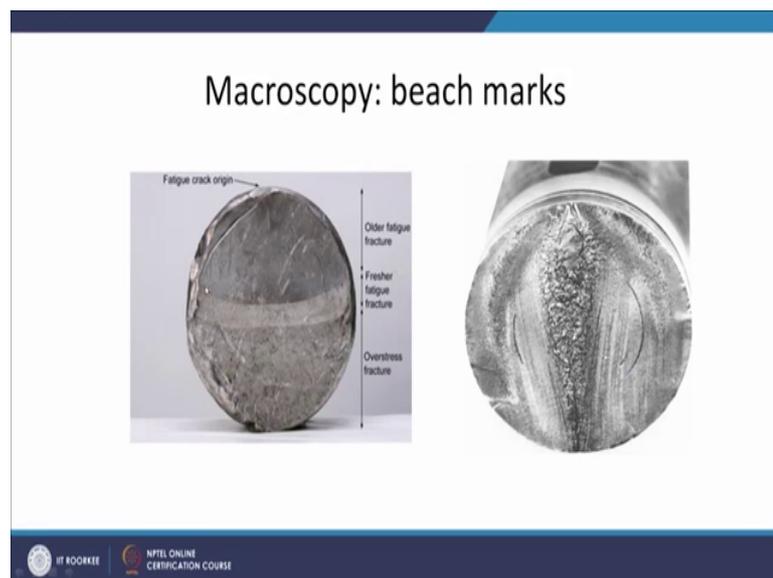
So, this is the first stage, this corresponds to the second stage and this corresponds to the third stage. This is the case when the load is unidirectional in this case the crack is growing from one direction only, but there can be other situation situations also where like say one simple rod is subjected to the bending in both the directions, in that case, the crack may nucleate from one side as well as from other side and then in that case, crack will be growing from the both the sides. And if we if we that is the case if the crack is growing from both the sides then it will offer us that different kind of the surface morphology on the fracture surface.

So, the case where the crack is initiating both the sides of the cross section; so, in that case say, this is one stage for one side of the crack and this is also first stage for another side of the crack and then it will be growing in concentric circle manners like this and it

will be growing like this and from another side and both and these concentric circles will be representing, the second stage growth and the centre of both and the centre of the concentric circles in both the cases will be the location of the location where from the crack was initiated.

So, this is the first stage, this is the second stage and the third stage is covered for both type of fracture. So, this will be corresponding to the third stage. So, when the crack from both the sides grows to such an extent that load resisting cross sectional area at the centre is reduced to such an extent that you know, it cannot take the load anymore and then the sudden fracture will be occurring which is the which is called overload fracture and overload fracture can be ductile or brittle as means it can be through the dimple mechanism or through the cleavage facets formation. So, I can be ductile and brittle in terms of the mechanisms.

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So, this is what has been shown in both these diagrams this so, is the initiation site and the remaining one is showing the beach marks, these are not very clear in this case ah, but it is these are very clear in this case where the crack is really starting from both the sides and then. So, this is the second case where the and the crack is growing from both the sides and finally, the third stage fracture is occurring at the centre. And in this case the crack is starting from one side and then it is going and there of the third stage fracture is taking place.

So, this is the over load or over a stress fracture and this is the; this is this is what we can say the zone which has a been formed due to the growth of the crack if it takes over a long period of time. Then; obviously, the surface which was a formed a due to the crack growth can get oxidized and it can be come dull also.

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So, for example, if there is a the this crack was formed long back and it has taken very long time to cause the certain fracture then all the surface may get a oxidized. So, we need to understand this aspect from another perspective like 10 to 15 percent of the fatigue life goes in creation of the or creation or nucleation of the crack.

And a remaining like say the like say 70 to 80 percent of the fatigue life goes in the steady growth of crack and the third stage is the overload fracture like very limited time, it takes like 5 percent or so, of the fatigue life or sometimes it is very quick. So, a third stage does not take much time, but most of the portion goes a portion of the fatigue life goes in the second stage of the fatigue fracture. And since it is a very long time is fatigue life which may be like in years and where crack is growing gradually.

So, the surface which has been formed due to the growth of crack, we will get oxidized and it will become dull. So, that is why to what will what will be seeing that the location where crack was initiated and the fracture surface which has grown during the steady growth of the crack in second stage that may become dull over a period of time. And then certain then the that the zone which has failed in catastrophic manner are due to the

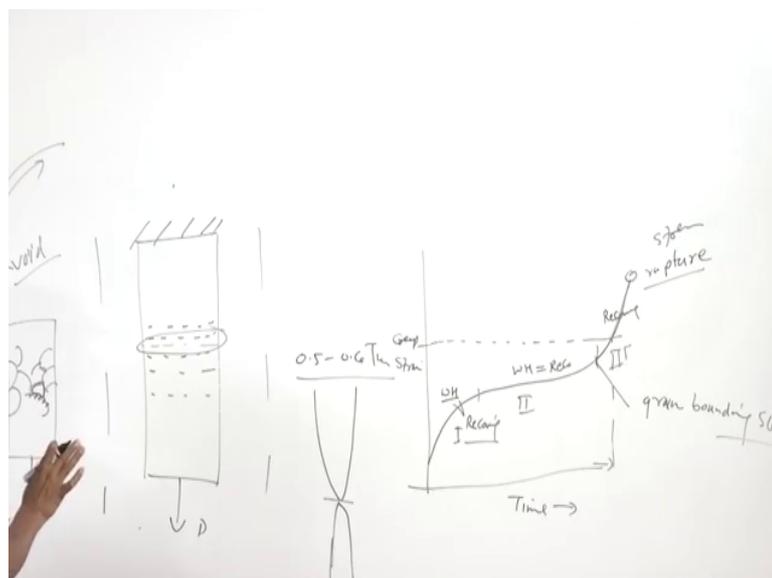
over stressing or overloading that of course, will be the bright and the shining as compared to the first stage and the second stage of the fatigue fracture.

So, these are the beach marks which indicate that the fracture has occurred under the cyclic load conditions one and the how far the contribution of the second stage of the fatigue fracture was and what was the portion which has failed under the third stage of the fracture where from crack has nucleated and in which direction, it has grown all that can be seen from these beach marks. Another important thing is the beach marks indicate lot of information like the beach marks can be very close to each other on this beach or they can be widely spaced or they can be of the varying spaced.

Like say so, the spacing between the beach marks indicate that the loading conditions have been fluctuating. And if the spacing is constant then that will indicate that the fluctuation of the load is constant if the spacing between the beach mark is changing, then that will indicate that load magnitude during the cyclic loading is also or changing.

So, the load fluctuation extent of load fluctuation is also indicated by the a spacing between the beach marks usually the spacing is closed in the beginning of the second stage and the spacing will keep on increasing as the time grows in the second stage of the failure., The another one is the fracture of sample occurring due to the high temperature exposure; we know that that when a component is subjected to the constant load P.

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Say, this is the tensile load at high temperature, say the temperature exposure temperature is a high about a like say 0.5 to 0.6 times of the melting point the T_m is the melting point in the Kelvin. So, such a high temperature exposure at a constant load results in the continuous increase in the length of the sample which we quantify in terms of the a strain.

So, a strain if that we can say as a creep strain creep strain increases as a function of time at a high temperature; so, there is a continuous increase in length in this situation or there is a continuous change in dimension of the component during the exposure at a high temperature. So, depending upon the load and temperature conditions that the strain variation as a function of time is observed normally in this way where we have stage I is stage II and stage III. So, the stage I corresponds to the decreasing rate of the creep strain, stage II involves the constant rate of the increase in creep strain and increasing creep strain as a function of the increasing rate of the creep strain as a function of the time.

So, basically slope of the curve indicates the creep rate the strain is the quantity. So, as soon as our the creep strain exceeds the acceptable limit, we say that the component life is over. Now, it needs to be rejected or there may be another option that we may allow the change in dimensions until the complete fracture takes place which is termed as rupture a stress rupture in case of the creep. So, this is the case when the fracture takes place.

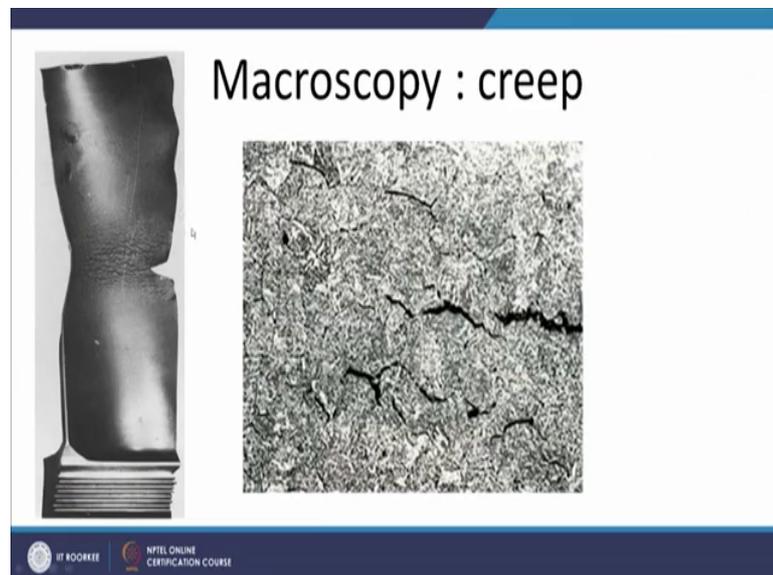
So, the creep experience is the various phenomena in course of the creep life. So, in the initial stage what we see that the work hardening effect is dominating over the recovery which is leading to the softening of the material. So, here work hardening dominates that is why creep rate is decreasing and here work hardening is balanced by almost the recovery. So, that is why the creep rate is almost constant and the second stage recovery is softening and work hardening is increasing is strengthening the material. So, when the recovery dominates; material is softened and the of the creep increased rapidly.

Another mechanism here is the grain boundary sliding. So, the grain boundary sliding leads to the situation of the separation of the grains from each other. Like say, this is the component and it is made of the number of grains like this. So, since at high temperature or above the equate cohesive temperature, the grain boundaries are weakened

significantly and that is why the grains start to move with respect to each other and that results in the void formation between the grains.

So, like say this is one grain and this is another grain; so, when the one grain moves with respect to the other grain some void is created and this void formation leads to the creation of their space between the grains. So, when the number of voids are formed in to the relative movement between the grains a lot of voids are formed and subsequently their coalescence leads to the reduction in loaded string cross sectional area and subsequently fracture takes place.

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So, this diagram typically shows the location near the fracture surface of the component subjected to the creep. So, if the component fracture is occurring at this location then we will see a lot of circumferential cracks where, due to the grain boundary sliding, the grains have separated, leading to the formation of a lot of circumferential cracks. Mostly these cracks are localized near the fracture surface and their numbers will be decreasing on moving away from the fracture surface.

So, such kind of circumferential cracks are attributed to the separation of the grains and this is what can be seen typically in this diagram where a lot of cracks all around the circumference are present. And this is the typical indicative of the stress rupture at which means the fracture of the component at elevated temperature. Another possibility is that if; another possibility is that at high temperature material may show the necking to the

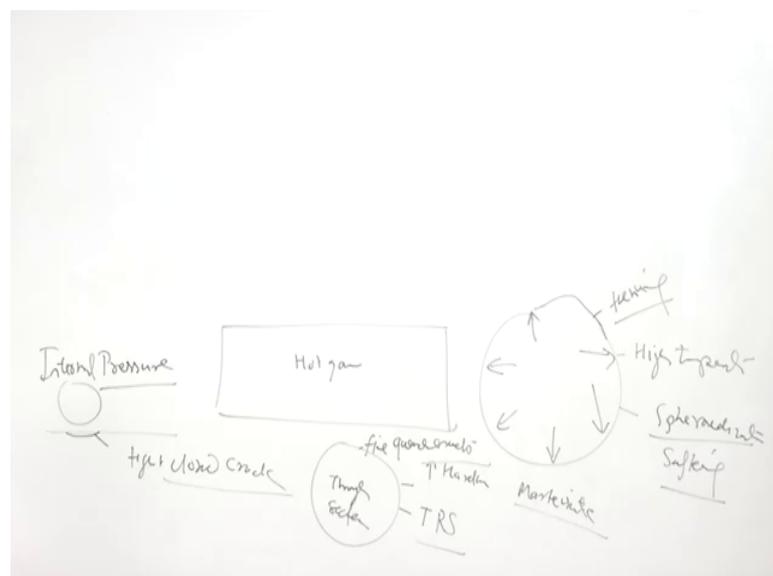
point where reduction in cross sectional area is almost a 100 percent. So, here the significant reduction in cross sectional area and eventually due to the overloading fracture takes place.

So, this is also common in phenomena if the material is a strong and in grain boundary sliding is resisted, then continuous creep can lead to the significant reduction in cross sectional area and if which eventually will be leading to the fracture with the almost 99 to 100 percent reduction in cross sectional area of the component.

So, as per the case there may be lot of circumferential cracks or the reduction in cross sectional area may be above 98 or 99 percent, if the material is resisting the grain boundary sliding. So, this is these are the macro graphs showing the lot of the cracks and as I have said that due to the relative movement due to the grain boundary sliding and lot of voids are formed at the grain boundaries. And that is why this kind of fracture also becomes the inter granular fracture. I will talk about the inter granular and trans granular fracture subsequently when we will be talking about the microscopy of the fracture surfaces.

The another type of the fracture which occurs at a high temperature especially the components or the systems which are subjected to the internal pressure. And they are exposed to the high temperature like the boiler tubes like the boiler tubes are having the hot gases being under pressure being passed through the tubes.

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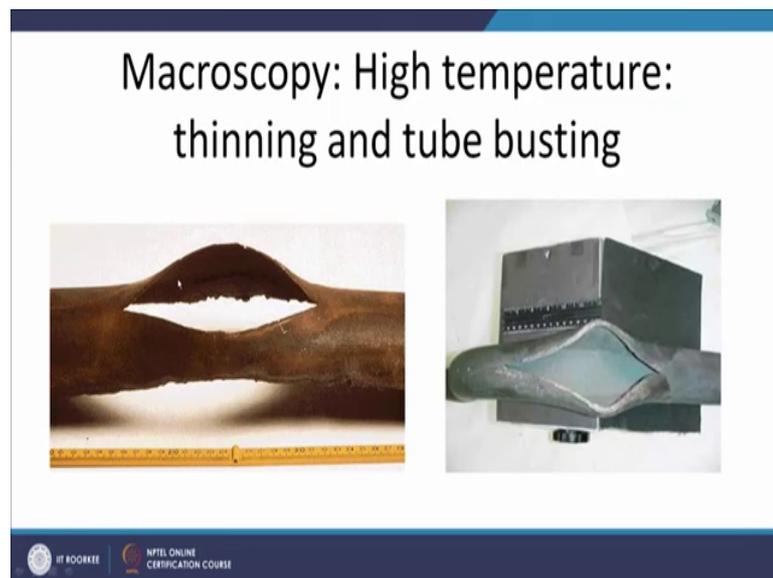


So, at a high temperature continuous internal pressure will be leading to the action or internal pressure will be applying the force on the wall of the tube. And at a high temperature high temperature will be leading to the continuous increase in the wall thickness may be it may be localized also and this high temperature actually degrades the material properties, it may cause the spheroidization of the steel.

And which may lead to the softening of their steel under the softened conditions, under the presser, it may lead to the localized bulging or the change in dimension and then thinning can takes place. So, such kind of thinning will be leading to the thinning under the internal pressure when the thinning crosses the limit under the effect of internal pressure busting of the tube takes place.

So, this busting of the tube happens in a in typical form which is called eye shape fracture the fracture is of the eye shape.

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So, this is one these are the two diagrams which are showing that this fracture. morphology is the similar to the shape of the eye and the this is also similar to the shape of I indicating that high temperature the this kind of the morphology of the fracture indicates that the tube has been subjected to the high temperature and because of the thinning the busting of the tube has taken place. So, this is another high temperature fracture here the fracture is occurring due to the thinning.

And this primarily happens due to the degradation in mechanical properties, due to the instability of the microstructure at a high temperature and that micro structural instability primarily observed in form of the as per digestion of the steel. Then we know that whenever the component is produced by casting. So, for the cleaning purpose we do the sand blasting, shot blasting sometimes for improving the fatigue life of the component also the shot blasting and the shot pinning is carried out. So, these this kind of the crack; so when the component is subjected to the cyclic loading also show certain types of the crack when which happens due to the localized slip phenomena at the surface.

So, some of the cracks which are very tight very close may be difficult to be detected under the entity. So, if such kind of the cracks are present then they indicate the possibility of occurrence or development of such kind of cracks under the cyclic loading or the component has been subjected to the shot pinning or the component has been subjected to the inappropriate heat treatment like quenching. Because in these cases what happens in the case of the shot pinning; the shots will be directed onto the surface continuously and if the material is not able to absorb those shocks is not able to deform enough.

Then it will be forming the cracks and the continuous application of the shocks will be leading to the closing of these cracks also. So, these will be very tight and closed kind of the cracks; similarly the such kind of the cracks are also formed when the component is subjected to the quenching wherein when the component is subjected to the quenching or especially through section hardening; through section hardening this leads to the increase in hardness of the steel especially by the martensitic transformation. And when such kind of the martensite is formed this is accompanied with the development of the tensile residual stresses also.

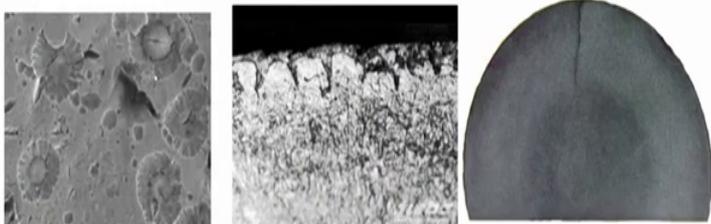
So, the combination of the increased hardness due to the martensite presence of tensile stresses; this leads to the development of the fine quench cracks. So, the closed tight closed cracks indicate the possibility of the fatigue fracture or the cyclic loading on the component development or the quench cracks or the shot pinning. So, if these are present we need to really explore that if the component has been subjected to cyclic loading or not or it has been subjected to the heat treatment like the quenching or if it has been shot pinned.

So, according to the way by which material has been had has been processed during the manufacturing or the material has been used during the service, we can identify the kind of the loading it was there or if there was a problem with the manufacturing procedure when they got to the short pinning or the quench crack formation.

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Tightly closed cracks

- Cyclic loading
- Surface imperfections: quench cracks, shot peening



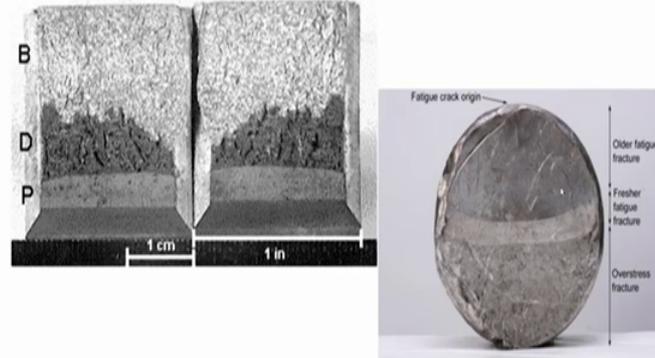
The slide contains three images. The first is a microscopic view showing a crack with a rough, irregular surface. The second is a cross-sectional view of a crack, showing its depth and the surrounding material. The third is a macroscopic view of a crack on a curved surface, showing its orientation and the surrounding material's texture.

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So, the these close cracks are you see difficult to be checked by the naked eye and they need very careful observation for this purpose.

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Changing mechanisms: shade, texture, colour, roughness



The slide contains two images. The first is a cross-sectional view of a crack, showing its depth and the surrounding material. The second is a macroscopic view of a crack on a curved surface, showing its orientation and the surrounding material's texture. The labels B, D, P are on the left side of the cross-section. The labels Fatigue crack origin, Older fatigue fracture, Fresher fatigue fracture, and Overstress fracture are on the right side of the macroscopic view.

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Now we know that whenever the fracture occurs. So, the fracture here also like in case of the fatigue, what we have seen the nucleation then continuous growth in the second stage if the continuous growth of crack in second stage and then sudden fracture in third stage.

Similarly the cast iron fails in different way than the common mild steel. So, depending upon the kind of the metal under the and the kind of load under which the failure is taking place the different kind of the fracture surfaces are created and those fracture surfaces offer the unique features with regard to the shade with regard to the texture colour and the roughness.

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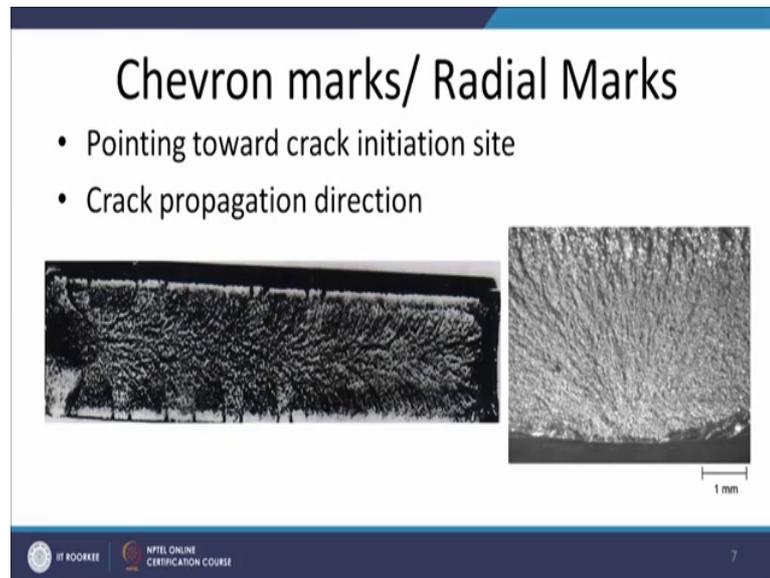


So, we can gather lot of information from the roughness variation present in the fracture surface.

The kind of the texture which is there in or the kind of the shade or the brightness or the dullness which is present on the fracture surface. So, the colour, the roughness, the texture or so, or their variation will indicate that what is going on and to what extent to the which type of mechanism was involved. So, all the idea about those kind of things can be taken from such kind of from this kind features which are present on to the fracture surface like say one this is one typical one where like say this zone shows the one color, this is the another color and this is the third colour and as per the case, it will be indicating the variety of the feature.

So, we will be we will be talking in detail about the colour roughness and the kind of the surface texture which is there with a different type of the fracture surfaces in the subsequent slides.

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So, the chevron marks or the radial marks these are the two features which are used to indicate the direction in which the crack has crack has grown. Chevron marks are basically on the fracture surface they are of the v shape normally the tip of the v indicates a the direction opposite to that of the crack growth.

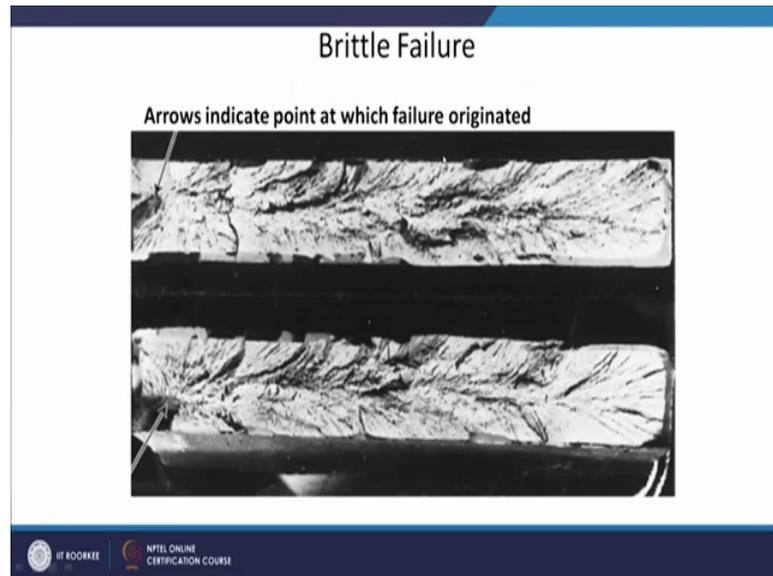
So, here if we see all these the tips are pointing towards the direction of the direction where from the crack is initiated and the growth direction is opposite to this one. So, here the growth the growth direction will be this one and in this will be indicating the direction where from it has initiated. So, this is the other general conventions there may be exceptions also in some of the cases where the chevron marks the tip of the chevron marks indicates just the reverse phenomena. So, basically the chevron marks these points towards the initiation site.

So, if the chevron marks are oriented like this then they will be pointing towards the initiation site the this is this normal general understanding, but in exceptional cases in some of the cases also the chevron marks will be pointing towards the end fracture zone, but that happens the very rarely. And similarly here what we can see the these are the

chevron marks here or there are the different morphology here chevron marks are going like this.

So, they are pointing towards the initiation side this is the initiation site and the crack has grown in direction opposite to that of.

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So, crack propagation direction and the initiation side these are the two indications which are given by the chevron marks. So, here we can see this is the initiation site and the chevron marks are being shown like this inverted v shape.

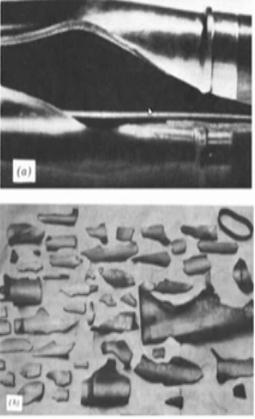
So, these inverted v shapes in case of the thin and thick sections it can be of the different morphologies, but this will be pointing the v inverted v will be pointing or the tip of, then chevron marks will be pointing towards the crack initiation and they will be indicating the direction opposite to the means the tip will be indicating direction opposite to that of the crack growth. So, arrows indicate the point here this is the arrow which is indicating the direction where from the failure has been triggered or initiated and this is the direction in which it has growled.

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Example: Failure of a Pipe

- **Ductile failure:**
 - one piece
 - large deformation
- **Brittle failure:**
 - many pieces
 - small deformation

Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66. John Wiley and Sons, Inc., 1987. Used with permission.



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So, the about this I have already talked that when the fracture is a ductile in nature we will see lot of deformation and the suppression. And when the fracture is brittle we will be able to observe with many small pieces of the failed component just like a cast iron when we cast when you drop the cast iron from a height which is of thin sections it will break into the fine pieces. So, the like glass fracture is also a brittle fracture.

So, the cast iron also fails in the similar manner. So, we will see the lot of the deformation in the case of the ductile fractures as compared to that of the brittle fracture.

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Radial marks



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Now these are the radial marks the radial marks feature are poor here we can see the chevron marks are here we can see a lot of chevron marks.

And all these are pointing towards the initiation site; this is the fracture initiation site ah, but here if we see the radial marks these are the weak radial marks which are present and there will be indicating towards them. So, these are the indicating the direction in which the crack is the growing on their centre will be towards the initiation site.

Now, I will summarize this presentation here I have talked about the few macroscopic features and what inferences can be obtained about the loading conditions and the technical information about the conditions under which fracture has taken place. And these features were primarily like the beach marks or the circumferential crack in the component which failed under the stress rupture conditions which failed in stress rupture manner and also the chevron marks and the radial marks present on the fracture surface. So, what kind of inferences can be obtained from these features present on the fracture surface.

Thank you for your attention.