Fracture, Fatigue and Failure of Materials

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Lecture 01

Modes of Fracture

Hello everyone, I am offering a course on Fracture, Fatigue and Failure of Materials. And today, we are going to start the first module of this which will cover fracture. And in today's lecture, we are going to discuss more about the modes of fracture.

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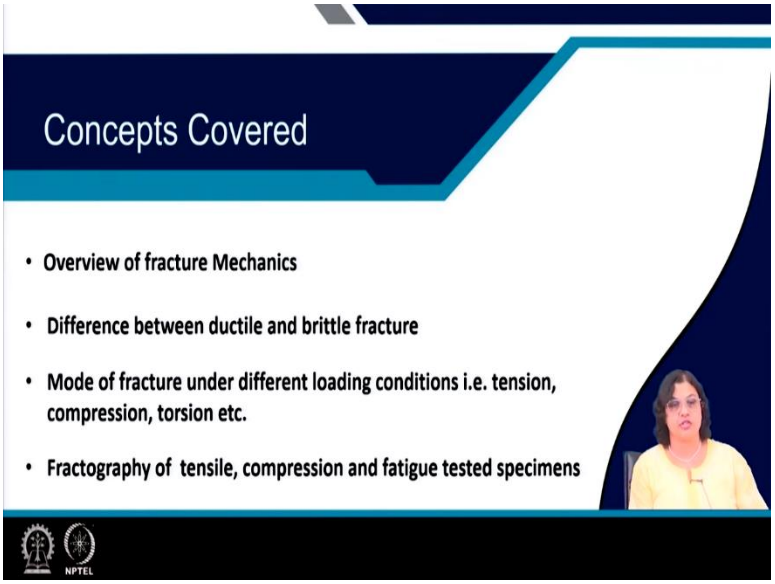

So, these are what we have in store for the first lecture, I would like to give an overview of fracture in general, which will be followed by the different modes of fracture. Particularly, we will be restricting ourselves into ductile and brittle fracture for today's lecture. And the mode of fracture under different loading conditions will also be discussed. And finally, we will look into the fracture surfaces as fractographs under different loading conditions.

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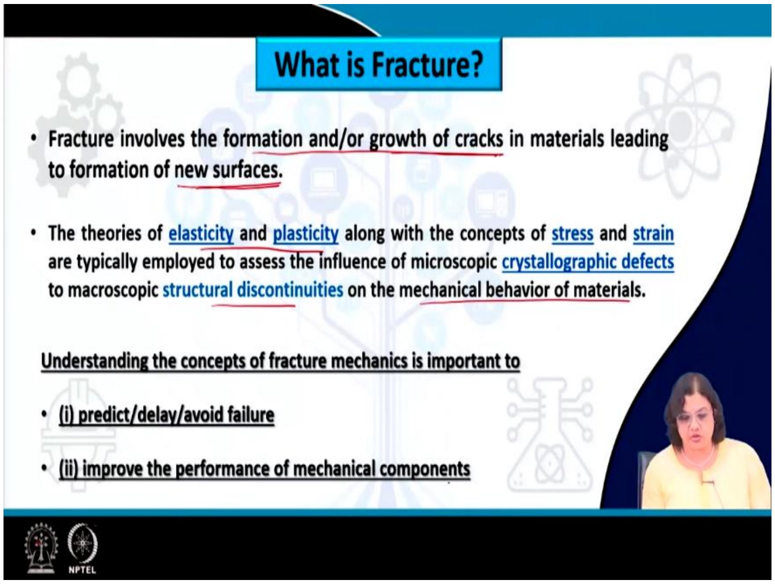

So, to begin with, we all are familiar with fracture, fracture is kind of seen in all different kinds of all different failure modes, we have seen how the bones fracture, how the different components or structure fracture, so in terms of material science and engineering, what do we mean by fracture. So, when it comes to material science, we are mostly dealing with fracture as the formation and growth of cracks in a material and that leads to formation of new surfaces.

To understand fracture mechanics, what we need to understand is the theories of elasticity and plasticity along with the concepts of stress and strain, which are typically employed to understand the influence of microscopic crystallographic defects. And that leads to often macroscopic structural discontinuities on the mechanical behavior of materials.

So, if we want to elaborate this in a more simple words, what fracture for material scientists means is, it leads to formation of two new surfaces, and that is obtained by the presence or the growth of cracks in it. So, cracks are nothing but the discontinuities or defects and that leads to change the stress-strain behavior of the material finally that will employ on the mechanical behavior of materials.

So, what is the importance, why should we study fracture mechanics in the very first place, these are because of the following reasons, that we want to predict delay or avoid failure that is our main motto, we do not want our structure or component or anything which is on service to fail. Overall, we need to improve the performance or the mechanical performance of the components.

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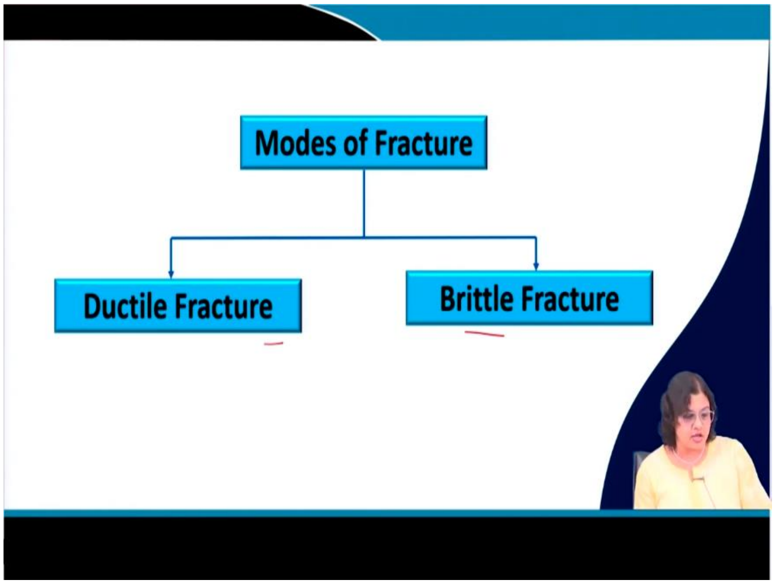

So, let us talk about the different modes of fracture, there are different ways by which we can categorize fracture, let us look into the first one through which we can very well differentiate between the different modes that is through ductile fracture or brittle fracture. Now, ductile or brittle are the two different modes of fracture, sometimes, we often refer materials as ductile materials or brittle materials. And at the very first lecture itself, I would like to mention that ductile fracture versus ductile materials, these are not exactly the same thing, we would look into more details of what a ductile and a brittle fracture mode means.

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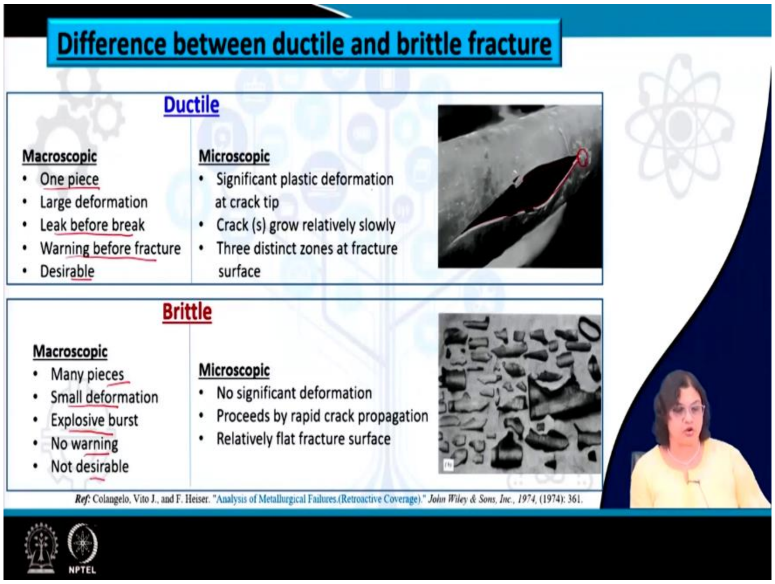

So, let us look into the very basic differences between ductile and brittle fracture. So, in the macroscopic way means, what we can see with our eyes without the help of any microscope or any other accessories, we can simply see a failure and we can differentiate whether it is a ductile one or a brittle one for example, as you can see in this picture here, we can see that this is a pipeline which has a crack in it.

So, this typically signifies ductile fracture, why because this signifies that the fracture has occurred from one location. So, this is just one mode of fracture. In comparison, if we are looking into the pictures on the table below, we can see that there it has been fractured into many number of pieces. So, this is once again a signature of brittle fracture where the fracture usually starts, initiates and continues to form many surfaces.

Ductile fracture typically is associated with significant amount of deformation. By deformation, I mean plastic deformation something by which the shape has been changed permanently. However, in case of brittle fracture deformation is very much restricted and fracture often occurs in form of an explosive burst. Whereas, in case of ductile fracture, we see a leak before break condition this means that there might be a leakage somewhere forming a very tiny hole, but not the entire structure will fracture in a catastrophic manner.

So, of course, if there is a leak before break condition or there is a tiny hole or tiny cracks that develops in a component that acts as a warning before fracture. And hence, ductile fracture is always desirable in comparison to brittle one. Brittle fracture occurs without any warning and hence is not desirable, we have no clue that something is going to fracture in case of a brittle one and then suddenly there is a catastrophic event which is difficult to control.

Now, these are all the macroscopic signatures, but if we want to look into more details, what we see in case of ductile fracture is that here there is a significant amount of plastic deformation at the crack tip. So, if there is a tip of the crack there is significant amount of plastic deformation or permanent deformation or shape change that acts that occurs right at the crack tip. However, in case of brittle one, no such significant deformation is observed.

In case of ductile fracture actually the crack whatever has generated that grows very slowly, because, the crack is typically been hindered by this plastic deformation at the crack tip, which makes the growth of the crack slow. On the other hand, crack proceeds very rapidly in case of a brittle fracture. In case of ductile fracture, we also see three distinctly different zones at the fracture surface.

So, again by looking at the fracture surface, if we can identify that there are different zones, we can also understand that that is because of the ductile nature of the fracture. On the other hand, in case of brittle fracture, we see a relatively flat fracture surface and that means, that there is no signature or prior intimation about the fracture to occur, there is no shape change or permanent or plastic deformation in the component.

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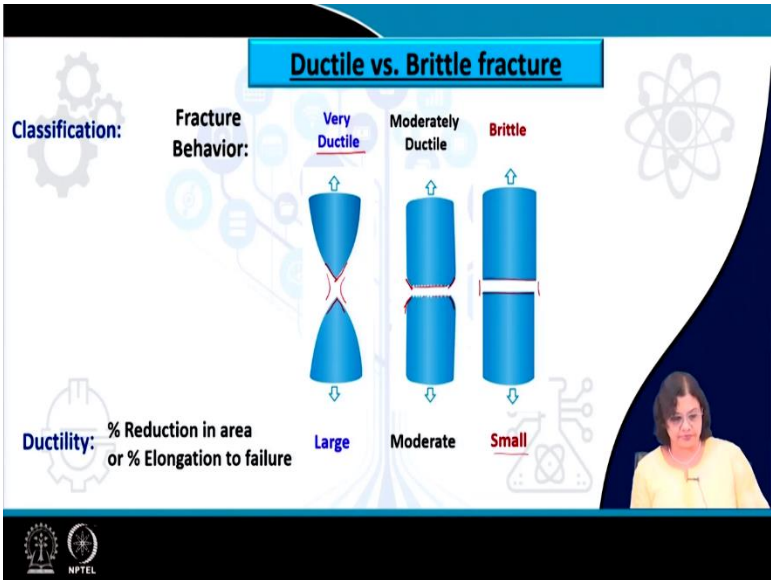

So, those are all what we can see in real life and when we want to test this in lab, so we want to test different kinds of specimens to understand whether the material or the specimen fails in a ductile or a brittle manner. So, here are the three ways by which typically, material system fails, the first one shows a typical cup and cone kind of appearance. So, you can see the top one here signifies like a cup, whereas, the bottom one is like a cone.

So, there is a significant amount of deformation that has happened in the central part that led to this kind of fracture and this signifies a very ductile behavior, the reduction in area in comparison to the initial area as well as the elongation to failure are pretty large in this case. On the other hand, if we are looking for brittle fracture, we typically see a flat fracture surface. So, there is no signature of any permanent deformation here.

And what we see is it is failing or it is fracturing just as a flat fracture surface. So, here the reduction in area or the elongation to failure is very, very small and sometimes often negligible. Now, in between this ductile and the brittle what we see in most of the cases at least for metallic system is where it is moderately ductile, it is always having some mode of ductile failure particularly near the edges where it you can see that there are some slant surfaces here signifies that this is the ductile mode of failure that has happened here.

On the other hand, in the interior part, we see that there is a comparatively flatter fracture surface and that is because of the brittle one. So, we see essentially a mixed mode kind of fracture in this case.

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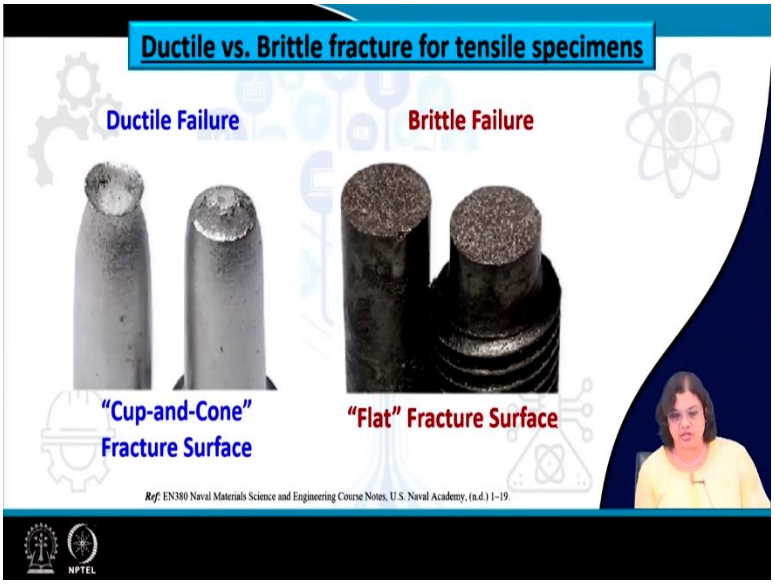

If we look into the fracture surface on the specimen, this is how it looks. So, this is a tensile specimen means the specimen has been tensile tested and what we can see is a typical cup and cone kind of fracture you can see that this takes the shape of a cup and this takes the shape of a cone. So, this is how the fracture surface of a typical tensile specimen looks like.

On the other hand, if it is a brittle failure then you see the same kind of specimen has a completely flat fracture surface and there is no signature of any cup or cone or any kind of permanent deformation happening over this. So, we see essentially a flat fracture surface in this case.

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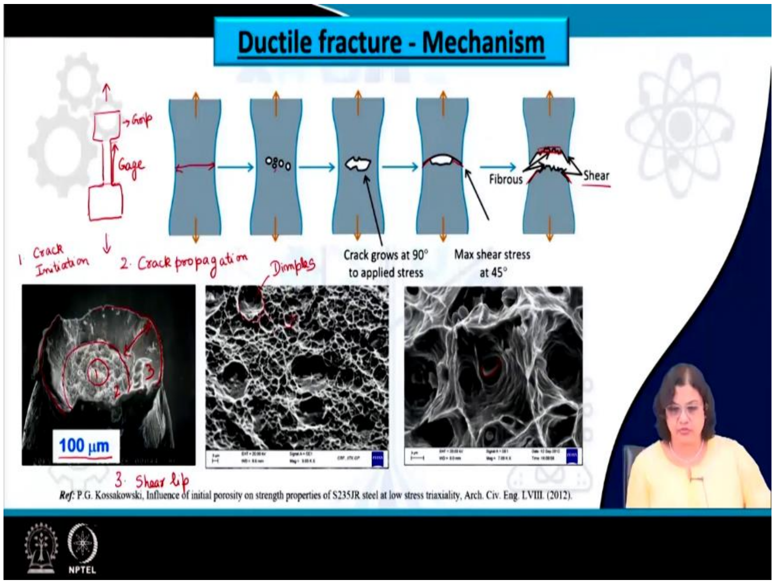

Now, coming to the mechanism of fracture, how actually ductile fracture is occurring. So, to understand that, let us look into it in a schematic fashion, and let us see how the fracture surface actually occurs. So, this is a typical tensile specimen, let me just draw a typical tensile specimen how it looks like.

So, this is how a flat tensile specimen will look like this is known as dog bone shaped specimen, this part here the straight portion here is known as the gauge section and this one here is known as the grip section. So, in UTM universal testing machine the grip part is being fixed with the machine and then some tensile stresses are being applied from both the sides and whatever elongation or whatever deformation is happening that is restricted within the good section itself.

So, you can see that there are some signatures of deformation in this gauge section from the very first schematic itself you can see that this section has a reduced cross section compared to the initial one. And after we deform it to certain extent, what happens is that there are some weak points some defects already existing in a system.

However, perfect we try to make our material there still exists some kind of defects and these defects could be anything even in case of a polycrystalline system, a polycrystalline metallic system, even the grain boundaries can act as a defect. Similarly, any kind of inclusions, second phases, anything can act as a defect that can trigger fracture.

So, in this case, whatever defects are present at the interior of the specimen particularly in the central location of the specimen, they form voids and then these voids coalesce with each other forming a crack. Simultaneously, as we are increasing the stresses continuously at the edges near towards the edges, this cracks deflects along 45-degree direction to maintain the critical result shear stress criterion and finally, fracture happens. So, that is the reason that we see a cup and cone kind of fracture in case of ductile failure.

So, you see that the edges are due to the formation of shear. So, often this edge is known as the shear lip at the interior at the central part we have this cup structure and that is a fibrous one. So, if we look into the fracture surface in a 3D mode, this is how it looks like at a very low magnification, this is how it looks like. When we are looking at the fracture surface of a system that is known as fractography.

So, whatever we are seeing here, all these images are actually fractographs. So, this is a very low magnification one, which shows a cup kind of appearance, the other half will show a cone kind of appearance. So, in this case, you see that there are typically three distinct regimes, first of all is the central one from which the crack initiation has started representing this one here, and then we have the crack propagation one, up to this regime.

Let me just and then we have the third regime here you can see it very distinctly. So, let me write it down as 1, 2 and 3, 1 signifies crack initiation, 2 mostly signifies crack propagation and this 1 and 2 are sometimes difficult to differentiate very distinctly, but we can always see that 3 is very distinctly differentiated and this 3 is known as the shear lip and this is because of the deflection of the crack to 45 degree.

Now, the shear lip width is the most important signature for ductile failure. This signifies whether the failure is ductile and if we are comparing between two materials, two specimens, we can also say that which one is more ductile compared to the others based on this shear lip width. This section here this 1 and 2 basically consists of a fibrous nature and if we look into this in more detail, this is what we see, these are again the signature of ductile fracture in high magnification microscope.

So, we can see here again another typical signature of ductile failure in the microscopic level that are known as dimples. So, you see some round spherical kind of features here as you can see there are big ones there are small ones and these features are known as dimples. Within the dimples in most of the cases, we can see this dimples have size ranges in the order of a few micrometers only.

So, in this case, we can see that the fracture surface the entire factor surfaces in millimeter range maybe and in the dimples are seeing only in the regime 1 and particularly in 2 and what we see here that the dimples are in the range of a few micrometers. If we are magnifying this part again we are seeing that within the dimples there are some inclusions, which are sitting here.

So, these are the typical inclusions that we can see within the dimples and this signifies that these are the one which led the crack to initiate. So, these are the particular crack initiations sites and crack initiations locations from which the ductile mode of failure has happened.

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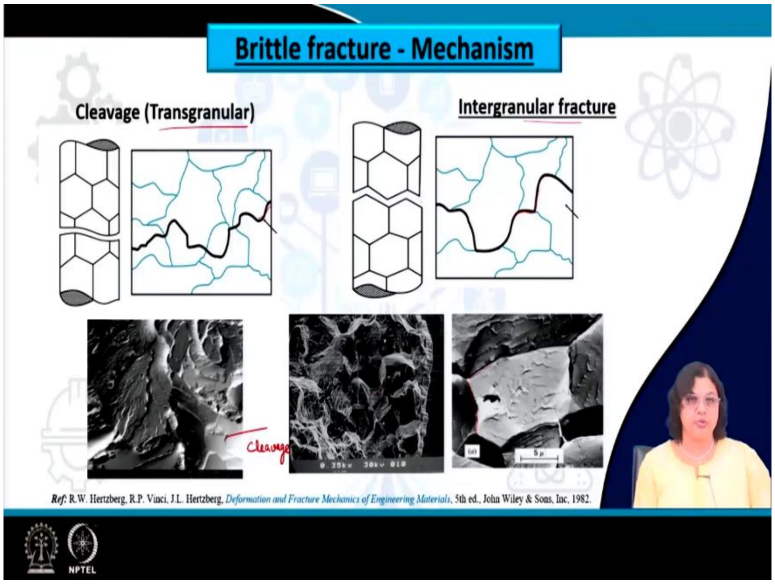

Now, moving towards the brittle fracture mechanism what we see here is instead of the one starting from the center and then the void coalescence. In case of brittle fracture, what we see is that the crack is propagating through the grains, there can be two different ways either the crack is propagating through the grains, this is a 3D image where you can see the grains shown here as a hexagonal one.

And the cracks can anyway pass through these grains known as that transgranular means, through the grains. On the other hand, cracks can also pass through the grain boundaries itself, as you can see, that cracks can pass from one grain boundary to the others and so on. And these are known as intergranular fracture. Again from the fracture surface itself we can differentiate between the not only the ductile and the brittle but also between the transgranular or the intergranular fractures.

In case of transgranular one, we can see some flat facets on the fracture surface on the fractograph and these are known as cleavage. On the other hand, if it is a case of intergranular fracture, we can make out the size of the grains very clearly you can see the grains size are quite apparent from the structures here particularly, you can see that the grain sizes like this and we can understand from the fractograph itself that it has been a brittle fracture and that too it has been an intergranular fracture.

So, just by looking on the fracture surface itself both with our eyes as well as with the microscope at higher magnification we can clarify whether a fracture mode is ductile or brittle.

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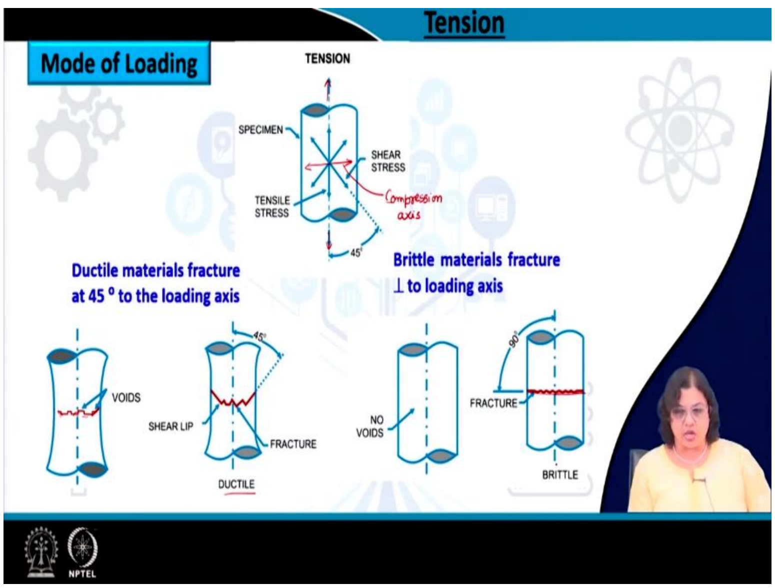

Now, that is not the end mode of loading is also another factor, which makes a difference on the fracture surface between a ductile and a brittle fracture, the most common mode of loading that we apply in case of laboratory testing is tension, we apply tensile stresses and we see how the fracture surface becomes different under ductile fracture mode or a brittle fracture mode. So, here is an example again schematically shown.

So, you can see that we are applying tensile stresses along this direction. So, this forms the tensile axis and perpendicular to that would be compression axis. So, this would be our compression axis and then 45 degree angle we have the shear stress axis. Now, what happens if we are having a ductile failure what happens is that as we explained that the cracks initiate right from the center and then it propagates and finally, towards the end it fractures along 45 degree plane leading to a fracture like this a typical cup and cone kind of fracture that will occur.

On the other hand, if we are having a brittle mode of fracture, then fracture typically occurs perpendicular, so along this compression axis itself. So, that is how we can just by looking on the fracture surface, we can say that whether it has a 45 degree shear lip which signifies a ductile modal fracture, if we if there is a perfectly flat kind of fracture, we can say that this is a brittle modal fracture.

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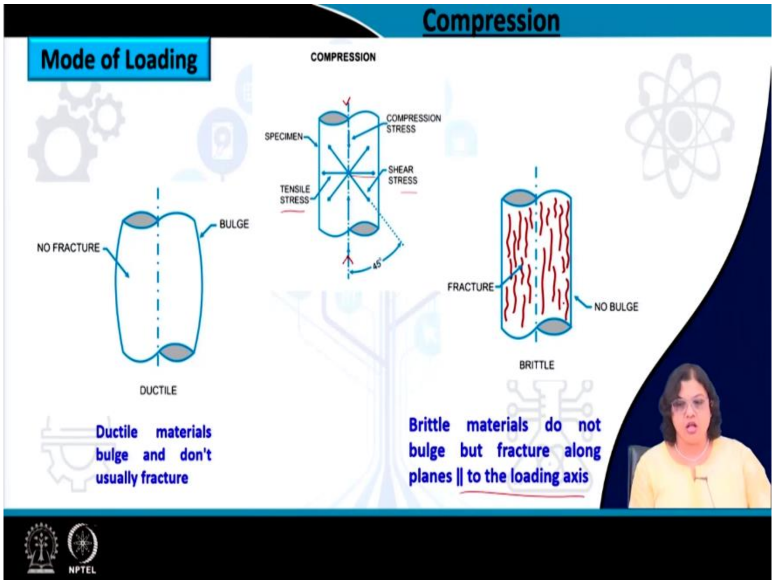

Now, coming to the compression mode of loading, compression is just the reverse of tension. So, in this case, we are applying compressive stresses along this direction. So, this is our compression axis and perpendicular to that, we have the tensile stress axis. And once again 45-degree angle there is the shear stress axis. So, in this case however, the mode of failure and the fracture surface will be different from what we have observed from the tensile stress axis.

In case of ductile material or ductile failure, what we see is there is no failure at all in most of the cases for example, for metallic system, there is no failure rather what we are seeing is a bulging out particularly from the central location perpendicular to the axis, because in this axis here along this direction, there is a tensile stress acting on. So, there is an enhancement in the cross section area in this case rather than the reduction in cross section area that we have seen for the case of tensile loading.

So, we have seen that ductile materials bulge and they do not usually fracture. So, if we see of features like this, where there is a bulging in the structure, we can immediately understand that that could be because of the compression loading and the material or the failure mode is ductile. On the other hand, in case of brittle failure, there are failure that is starting from multiple locations and you can see that all these locations are running parallel to the loading axis.

So, once again this is also distinctly different from what we have seen for the case of ductile failure under tension loading. For tension loading, we see that the fracture happened mostly towards the central part on a direction which is perpendicular to the loading direction. Whereas, in this case under compression loading for ductile failure, we see that failure is offering along the direction which are parallel to the loading direction.

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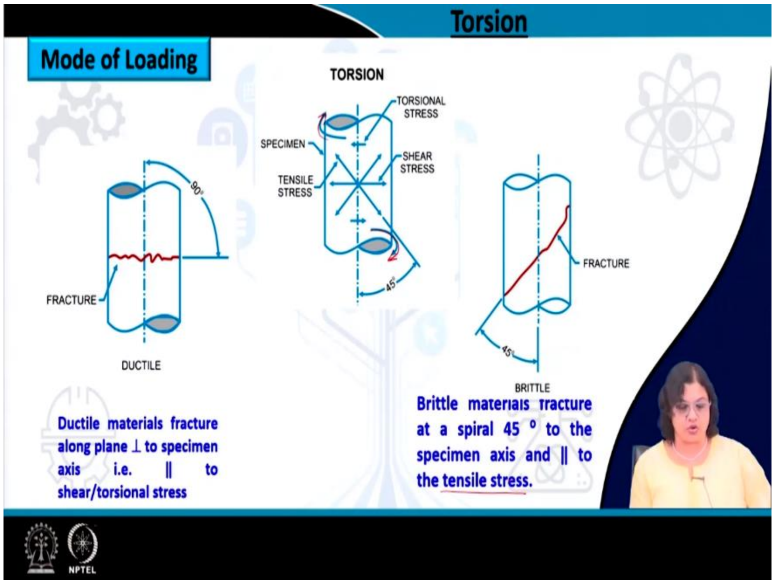

Now, moving on to the more complex form of loading, which is torsion. So, in torsion what we have is a stress or a force acting along for the opposite direction kind of twisting. So, in this case what we have the tensile and the compressive stresses are acting at 45 degrees to the specimen axis not the stress axis, but now we are talking about the specimen axis.

So, if this is a cylindrical specimen and this the central line here dashed line here signifies a specimen axis if we are applying a torsional loading, then the 45-degree angle signifies the tensile and the compressive stresses. If this one is tensile the one which is perpendicular to the tensile one is the compressive stresses and in this case the shear stress is perpendicular to the specimen axis. So, let us see how the ductile failure and the brittle failure results in case of torsional loading. So, this is quite interesting.

In this case, what we see is fracture is occurring right from the central part in a more or less perpendicular to the specimen axis. So, that signifies a ductile failure unlike this is a brittle one that we have seen for tensile loading, we see almost similar kind of features like flat fracture surface perpendicular to the specimen axis, but in this case, because we were applying a torsional loading, what we see here is a ductile failure.

And in the subsequent slides, I will elaborate more on how to differentiate between torsion as well as the brittle under tensile loading condition. If it is a brittle one, then on the other hand fracture occurs at 45 degrees to the specimen axis. So, along the tension of the compression axis particularly along the tensile stress axis fracture occurs in case there is a brittle motor fracture under torsional loading.

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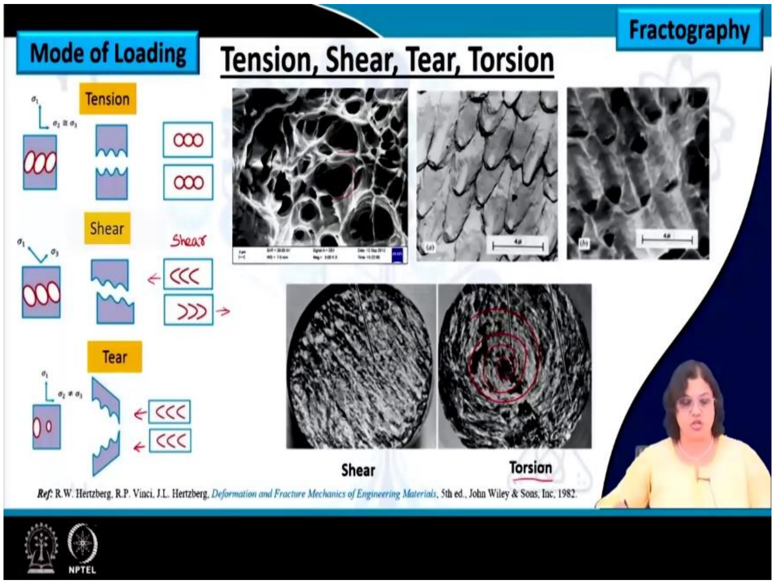

In the last slide, we were discussing this on the basis of the schematic representation, but what we need to verify it with is the fractograph. So, let us see here how it looks like. In case of tension loading particularly tension or compression what we see is, so here we see typically spherical dimples which are being elongated and what we see on the fracture surface are similar spherical dimples on it.

On the other hand, if there is a shear there we see again dimples, but these are elongated dimples and not only that, this elongated dimples are on the opposite direction, if we are looking on the two fracture surfaces, so in one case this is oriented along this direction, whereas, on the other case this is oriented along this direction. Let me write it in a clearer way this is a shear dimple.

On the other hand, if there is a tear loading like tearing what we see once again that you can see that how the fracture surface is being teared here and in this case also we are looking into an elongated dimples, but the only difference between tear loading and shear loading is that in this case, we see both the dimples are along the same direction. So, in this case, we see that both the dimples are in the same direction whereas, in case of shear loading, we see that dimples are in the opposite direction.

So, we often need to look into the fracture surface and not only that, we need to look into both the fracture surfaces to clarify or validate which mode of loading has occurred. So, you can see here distinctly that these are the dimples more or less are spherical size and this is what is seen for the case of tensile loading.

On the other hand, if we have dimples, elongated dimple this means that this is a shear or tear and based on the counterpart of the fracture surface, we can say that whether this has been sheared or teared. In case of shear also we see such kind of elongated features on the macroscopic fracture surface itself.

Whereas, in case of torsion as we have seen that sometimes the torsion or the brittle mode of fracture versus the ductile mode of fracture under torsion are sometimes very confusing. So, for that we need to look into the fractograph and if we are looking to fractography even with our eyes with in the macroscale we can see that there is a spiral kind of loading. This is what we can see this kind of typical feature. So, this signifies that there is a twisting stress that has been applied which signifies that there has been torsion loading.

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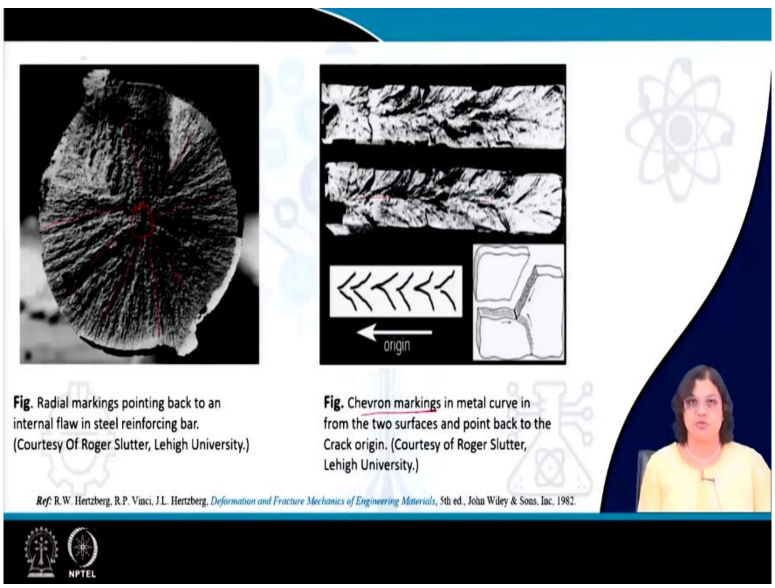

Now, other than tension, compression, shear, tear, torsion, etcetera, there could be other modes of fracture, which will be covered in this course itself, since this covers not only fracture, but also fatigue and different types of failure. So, in the first lecture itself I thought of giving a hint of what are the different kind of failure and how does the fracture surface looks like.

So, in this case, if you look into this fractograph very very carefully other than looking into whether this has been failed in a ductile manner or brittle manner, what we can we obviously, see from here is that all the cracks or whatever defects has formed this are merging to a central location. So, if we kind of track down the movement, we can see that something has happened over there and from which it has been spread radially.

So, similarly, in this figure here, there is a chevron marking which we can see that it has been leading to a particular location. So, this signifies that the crack initiation has started from some locations and we can track it back from the fracture surface itself. This often such kind of fractograph and the information generated from there often helps in different kinds of failure analysis, which we will illustrate in details in the subsequent lectures.

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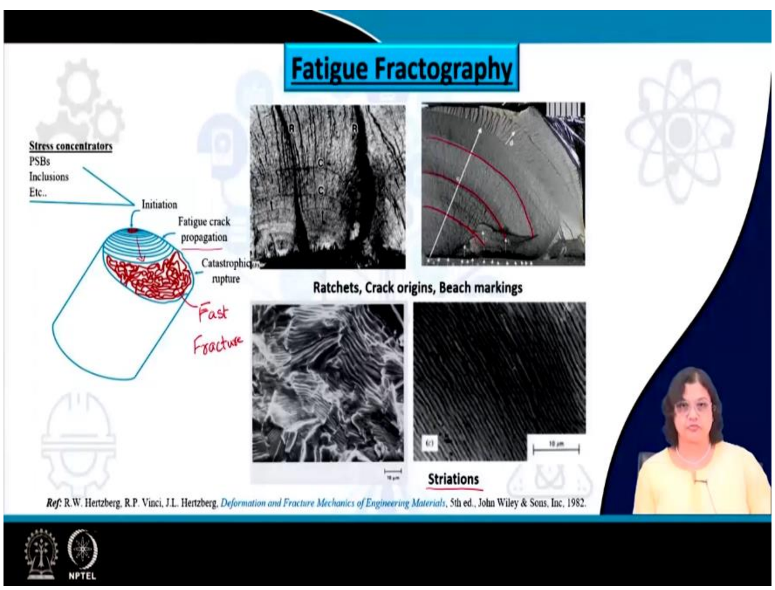

And other thing which I thought of bringing to you in the very first class itself is the fatigue fracture, how does the fracture surface looks like. So, here also if we are looking into the very macroscopic scale, there are typically three different sections, but unlike that for the typical ductile sections, what we see here is a crack initiation mostly towards the surface or the edge of the specimen followed by a crack propagation regime and then a catastrophic rupture or a fast fracture regime.

So, if we look into the fractograph at low magnification or just with our eyes, we will look into features like this, these are called ratchets, ratchets are nothing but looks like a steps. We can see that there is some periodic loading that has happened. And here you can see the beach markings if we look into this, it looks like the beach markings that we can see from here the circular or semi circular loops.

So, this signifies that fatigue failure or periodic loading has happened. And if we look into this at a much higher magnification particularly in the crack propagation zone in this regime here, we will see the formation of striations. So, these are again the signature features for fatigue fracture.

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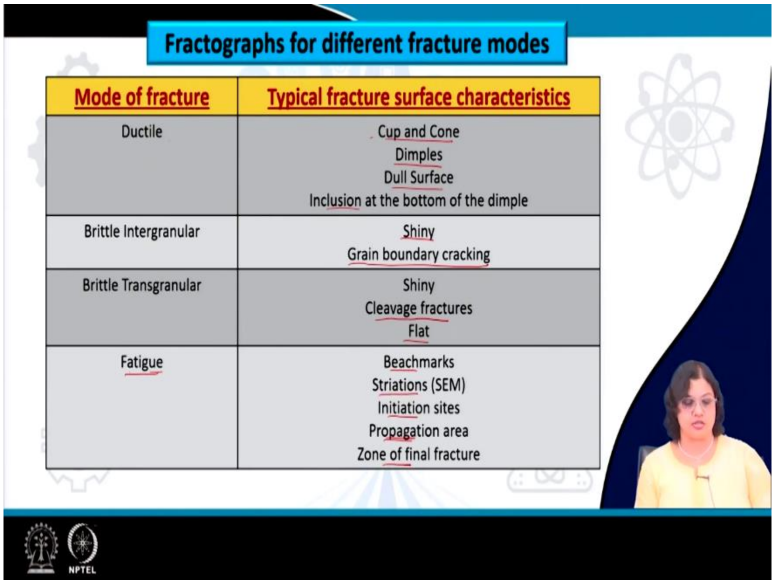

In short, if we try to differentiate between the different fracture surfaces based on the different modes, this is how we can do that, that if there is a cup and cone kind of fracture that signifies a ductile mode of fracture of course, if we look into this at low magnification, what we see is other than cup and cone it looks like a very dull appearance not a shiny one.

And if we look at this at high magnification, we can see the presence of dimples and inclusions at the bottom of those dimples. In case of brittle fracture on the other hand, we see shiny fracture surface shiny and flat in most of the cases and this at higher magnification will show us presence of cleavage or if there is an intergranular one, we can see the grain structures very clearly from there.

If it is a fatigue fracture on the other hand, we have seen that there are some signature features of fatigue such as the beach marks at low magnification and initiation site, propagation area and the final fracture zone can be seen also at very low magnification or sometimes with our eyes or just with a magnifying glass. And if we look into the central part, particularly the crack propagation part at a high magnification, we can see the presence of striations there.

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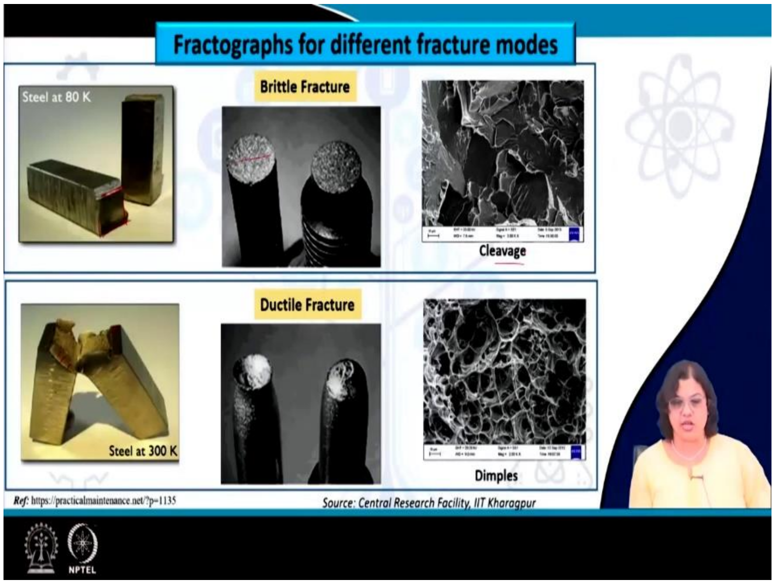

So, these are for you some of the fracture surfaces and how it looks like. So, the presence of the shear lip and the uneven fracture surface signifies that it is a ductile fracture we can see here as a cup and cone kind of fracture appearance and at high magnification we can see the presence of dimples within inclusions. On the other hand, if we are looking into a flat fracture surface, comparatively flat fracture surface, you can see it here and at high magnification that shows the presence of cleavage that signifies brittle fracture.

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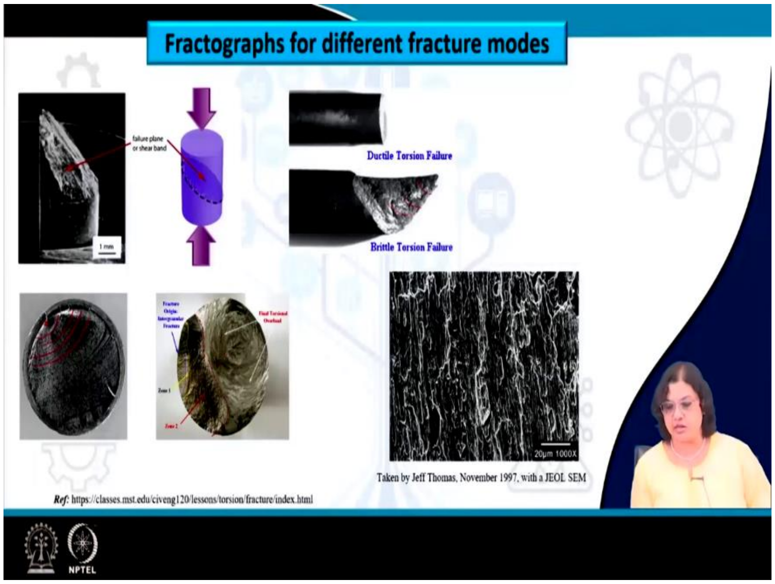

Now, we can see the shear band in case this is happening at this 45 degree clearly from such kind of fracture surfaces, if there is a torsional failure, we can see that how this has been the cross section has been reduced continuously and we can understand that there has been some torsional loading. If there is a fatigue fracture, we can once again see the crack initiation very clearly from here and then there are some locations where there the signatures of periodic or repeated loading are apparent.

In this case, we can once again see a torsional overload in or torsional loading simply and if you look into this carefully, it looks like a whirlpool. So, that signifies that torsional loading might have been active.

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So, in conclusion for this lectures, what we have discussed is that the ductile fracture shows typically cup and cone kind of mode of fracture and that at higher magnification shows dimples, whereas, a brittle fracture shows shiny and flat surfaces and at higher magnification that shows presence of a cleavage.

During tensile loading ductile material typically fractures 45 degree to the loading axis forming shear lip, whereas, a brittle materials fracture perpendicular to the loading axis. On the other hand, during compressive loading ductile materials bulge and they sometimes do not even fail. On the other hand, brittle materials fracture along planes parallel to the loading axis.

During torsional loading, ductile materials fracture along a plane which is perpendicular to the specimen axis, whereas, brittle materials fracture at a spiral 45 degree to the specimen axis. So, just by looking into the fracture surface, we can understand the difference in the different loading condition along with the different fracture mode, if it is a fatigue one fatigue fracture, then we can understand this on the basis of the fractograph, which shows a clear crack initiation site, which is followed by crack propagation site and the final fracture zone.

And some of the typical signatures at low magnification at macro scale is ratchets or beach markings. And if we are looking at higher magnification, we should be able to see the striations as a signature of fatigue fracture.

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So, these are some of the references that we have used for this lecture. And we will be using for the subsequent lectures as well.

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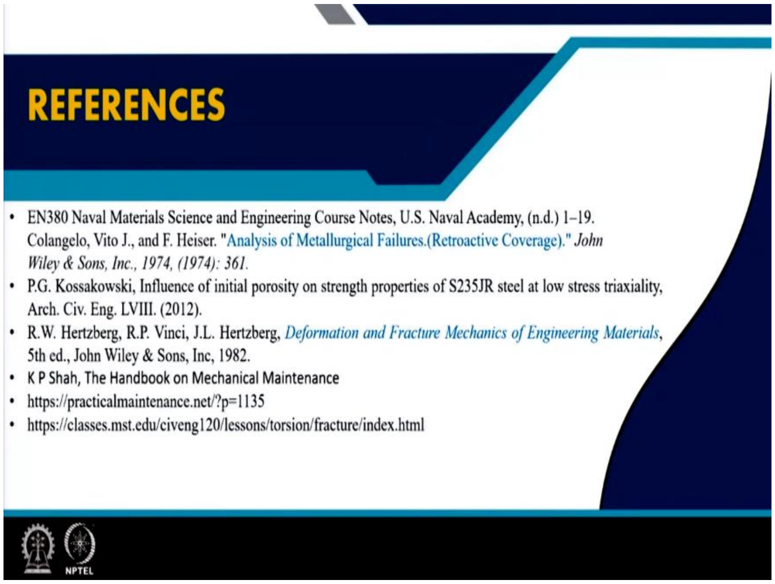

Typically, some of the textbooks as well as some internet sources, which has been used for to take the different fractograph or different other source of images. Thank you very much.