Fracture, Fatigue and Failure of Materials
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Lecture 21
Impact Toughness (Contd.)

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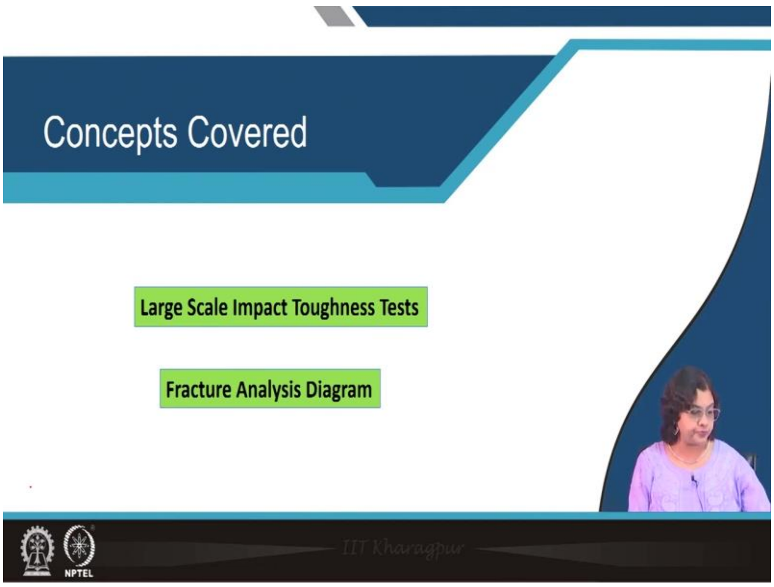

Hello everyone, welcome to the twenty first lecture of this course Fracture, Fatigue and Failure of Materials. And in this lecture today we will conclude the Impact Toughness topic and we will particularly look into the large scale impact toughness test, which are more relevant from the practical point of view. So, the kind of impact toughness test that we will be talking about and the results that we will be obtaining from those tests will be correlated with the fracture analysis diagram in this lecture.

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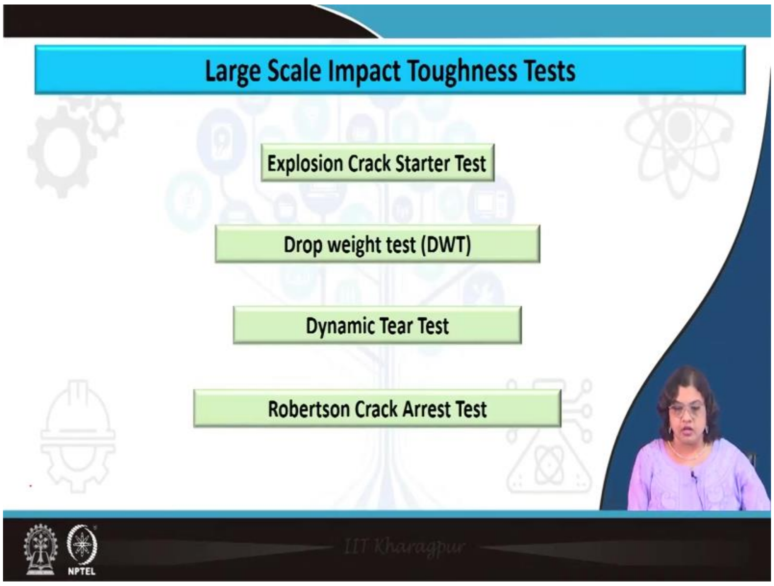

So, when we talk about the large scale impact toughness test, practically we look for bigger specimen the specimen the kind of specimen which could be of equivalent size to the component that are used for any service.

So, there are several ways by which we can do such kind of impact toughness test as we have seen that for the lab scale tests, particularly Charpy impact test is mostly used or sometimes maybe Izod which is also very much equivalent to that of Charpy, but when we are talking about the large scale impact toughness test, often we need a bigger block of material, so, that we can find out the properties of the actual test component.

And we have also seen in the previous lectures that particularly for the case of brittle failure size or the volume of the component is a real issue, if we are determining the properties on the basis of a smallest specimen in the lab scale and then we try to correlate that with the larger dimension, which is used in the service often they do not match with each other.

So, the first one that we will be discussing today is the explosion crack starter test, which typically is done on a rectangular block of component and then there is a drop weight test, dynamic tear test, which is very much similar to the Charpy impact test only thing is that here the specimen size is much larger and the machine capacity is much higher than that use for the Charpy impact test. And finally, we will be talking about the Robertson crack arrest test.

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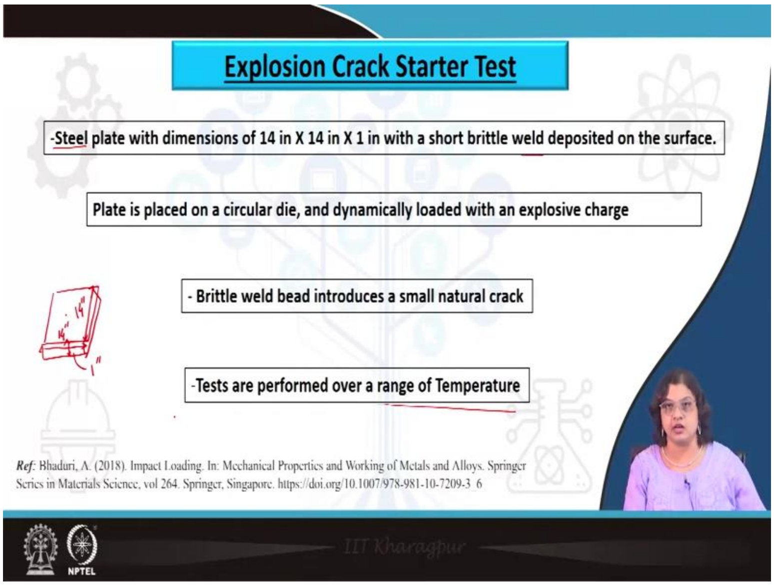

So, let us move on to the explosion crack starter test. So, this uses a steel plate typically most of these tests are done on steel or the different iron component which undergoes ductile to brittle transition where ductile to brittle transition is an issue and that is why we try to find out this property.

So, in most of the cases, we will see that the tests are particularly done on the steel. So, we need a rectangular component here which has this dimension as 14 inch as well as this dimension also as 14 inch and it has a certain thickness of just 1 inch. So, and the plate is placed on a circular dye and most importantly, it is loaded with an explosive charge.

It has a brittle weld on the other side on the backside of the surface and because of this explosive charge the crack initiates from that brittle weld portion and then it propagates either to the edge or maybe not depending upon the temperature. So, typically these tests are being repeated at a series of temperature over a range of temperature.

And from there we particularly can figure out the nil ductility temperature, the temperature at which the crack is able to propagate without like in an unstable fashion, elastic way or the amount of the kind of temperature at which the crack propagation will be stopped by the plastic deformation all this can be found out from this kind of explosion crack started test.

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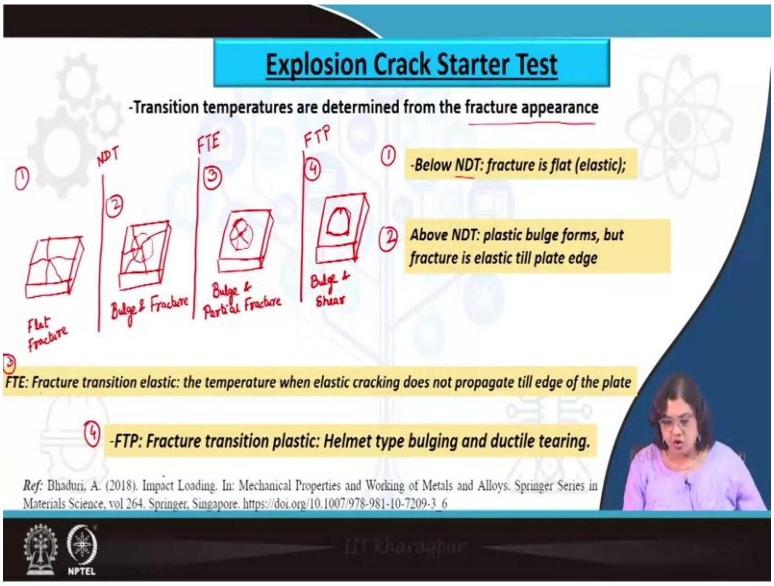

So, let us look on this a little bit more. Transition temperatures are particularly determined based on the fracture surface appearance. So, let me draw this once again. So, if this is the specimen that we are having and there is a brittle weld here and as the explosive charges are there the crack initiates from the brittle weld and it typically grows till the end and have a catastrophic fracture. So, it looks like a flat fracture.

So, if that is the case, we can safely say that that is the nil ductility temperature or NDT. If we are increasing the temperature on a second specimen and we are using the same explosive charge again it may happen that there is some amount of plastic deformation in front of this well beam and the crack will be kind of stopped up to certain extent, it may still grow till the ages depending on the temperature that we are talking about.

And if such is the case, then we know that there is some amount of plastic deformation which slows down the crack growth, but it is not able to stop it completely. So, here we have a bulge. So, this portion is the bulge because of the plastic deformation and after that we have a fracture. On the other hand, if we are increasing the temperature of test further this is what we are seeing again.

So, now, since we are doing this at a higher temperature, this plastic deformation will be even more pronounced and the crack which has initiated from the well might have grown till the plastic region here, but it will be completely restricted the growth will be completely restricted at this ages and it is not able to grow any further.

So, here we are seeing a bulge and partial fracture. So, this is not reaching till the edge and we are not seeing a catastrophic fracture. So, in such case this temperature can be called as fracture transition elastic. On the other hand, if we are still doing this at a higher temperature, what we can see is a complete plastic deformation with no sign of crack growing to the edge.

So, here we actually see a kind of helmet kind of appearance, complete bulge and no crack and all that can lead to fracture. So, here we can see bulge and shear and if such is the case, this temperature can be termed as fracture transition plastic. So, this is what eventually we are seeing that below this NDT temperature.

So, here at step one, we are seeing a flat fracture. So, this represents the elastic fracture basically complete brittleness and that is why this is known as nil ductility temperature. So, there is absolutely no ductility at all. So, this is what is one and then above the NDT, the plastic bulge forms, but the fracture is elastic and it still reaches the edge of the plate.

However, if we keep on increasing the temperature even further to that what we are seeing is the fracture transition elastic. So, this temperature here so, this one will be two as this one and then it will be three the fracture transition elastic which says the temperature when the elastic cracking is there it has initiated, but it has not propagated till the edge of the plate and finally, we if we are doing this at even higher temperature, we are going to see the step four which is the fracture transition plastic.

So, basically it says that there will be a bulging a complete bulging it says here helmet kind of bulging and there will be ductile tearing, so, there will be no elastic fracture at all. So, based on this based on the series of tests we can figure out the nil ductility temperature, the fracture transition elastic fracture transition plastic etc. And based on this information we can figure out the service requirement and if that is matching the service expectation and or not. So, that is one mode of testing.

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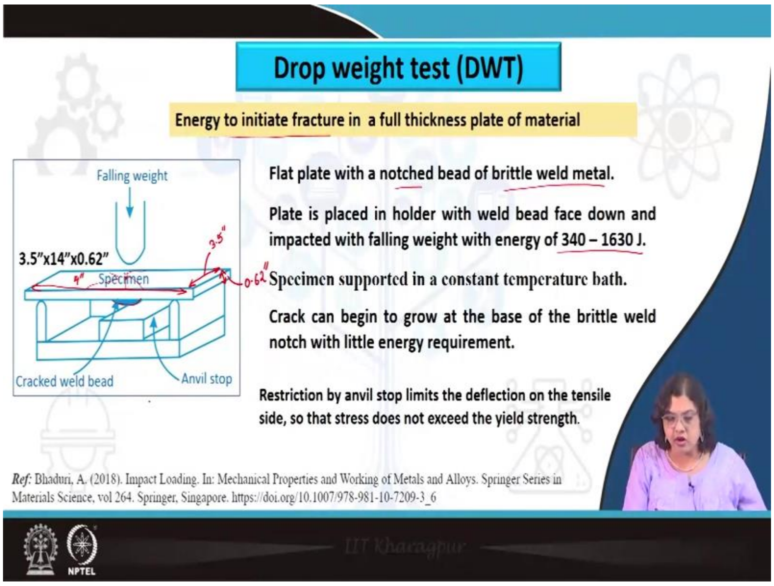

The second one is a drop weight test as the name suggests itself, so, there is a weight that is being dropped. So, this is the falling weight here on the specimen, which has a dimension something like this 3.5 inch into 0.62 inch is the thickness. So, the thickness here is 0.62 inch and the width is actually 3.5 inch as well as the length is same as that used for the explosion crack started test the length is 14 inch.

So, obviously, this is much bigger a specimen than that we have used for the Charpy test and in this case also there is a brittle weld which is notched and this is placed right beneath the specimen surface, what we can figure out from such kind of drop weight test is the energy to initiate fracture in a full thickness plate of a material.

So, as the weight falls the notch bead which is there that initiates the crack and then it either grows or till the edges and have a catastrophe fracture or depending on the temperature it may not be able to grow till the end.

So, the plate is placed in holder with the weld bead face down. So, this is typically on the beneath the specimen surface here over which the weight is falling. In most of the cases when we have even a machine notch as for example in the Charpy test it is being hit or the impacted from the opposite side just exactly at the same point, but on the opposite face.

And the energy used here is around 340 to 1630 joules. So, that is a quite large range of energy depending on the material, we may require different kinds of energy also depending upon the temperature, we may require different kinds of energies.

Of course, if we are doing this at a higher temperature, we will require a higher energy for fracture because the toughness in that case will be higher or more or if you are doing this at a lower temperature much more much less energy will be consumed in that case, so, specimen is supported on a constant temperature bath, so that it is maintained at a particular temperature and we keep on doing this test at different series of temperatures so that we can finally end up having the different kind of temperature that we have discussed in the previous slide.

So, crack can begin to grow at the base of the brittle weld notch with little energy requirement and that can change as we are changing the temperature. And this anvil here that the main purpose of this is to limit the deflection on the tensile side so that there the fracture can be detected there and the stress does not exceed the ill strength of the material.

So, based on this once again the crack initiates from this point here because of this notch weld the brittle weld here and then either it may reach to the edges as we have seen for the crack the previous slide itself or depending on the temperature it may have a plastic deformation that is restricting the growth of the crack.

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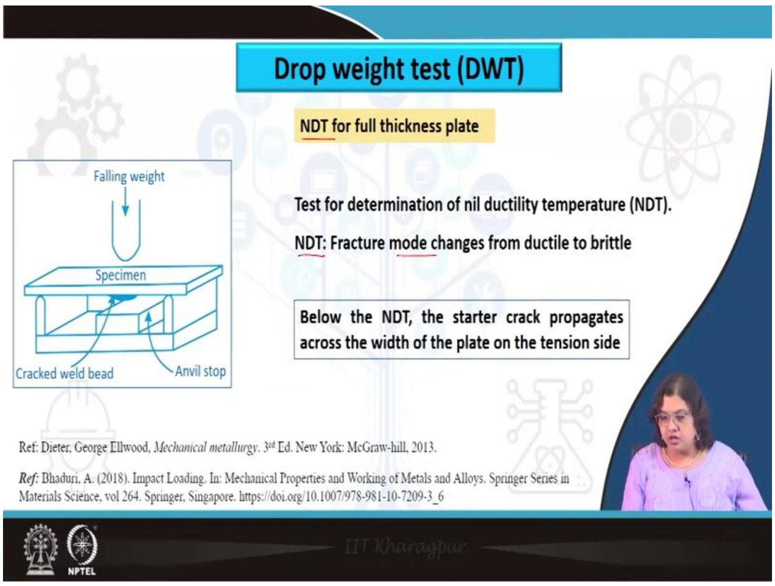

So, typically what we can find out from there and what is of interest here is particularly the nil ductility temperature, which is the one where the fracture mode changes from ductile to brittle and from there we can determine whether there is a flat fracture or there is some kind of bulging happening and based on that we can determine the practical application of that material in service.

So, that there that is once again the lower limit of the toughness at which it will fail completely in a brutal fashion and at a higher temperature than this NDT, we know that we are in a safe zone compared to the NDT so that means that there is some provision of plastic deformation there. So, below the NDT the startup crack propagates across the width of the plate and this particularly happens on the tension side because there is the notch weld that is present.

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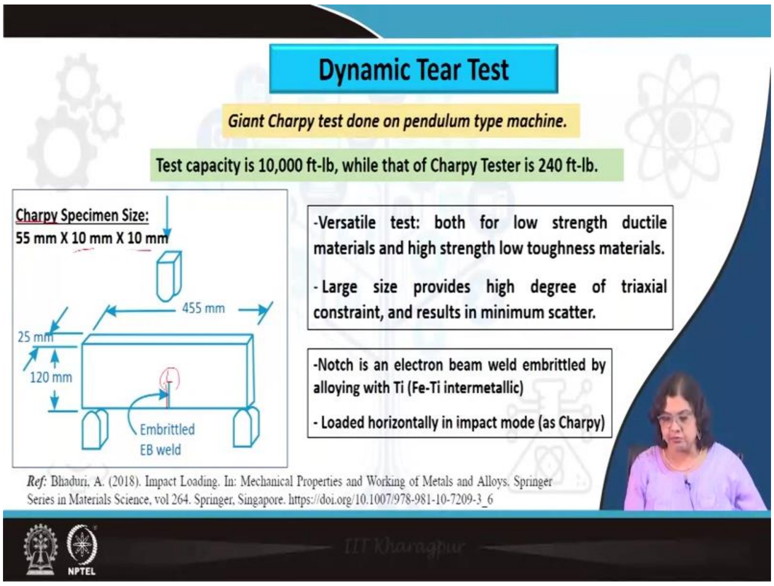

Now the next one here is the dynamic tear test, which is nothing but a giant Charpy test done on a pendulum type of machine. So, the test capacity here is 10,000 foot pound. And in comparison to that, we can see that the Charpy test has only 240 foot pounds. So, of course, we can understand that this is done on a much bigger machine with a much higher capacity so that we can evaluate the properties in the actual service condition. The specimen dimensions as shown here, which says that it has a length of 455 millimeter and a width of 120 whereas the thickness is around 25 millimeter.

And in comparison, if we look into the Charpy specimen size, it has a square cross section of 10 millimeter into 10 millimeter. So, this side was supposed to be 10 into 10 and then the total length is 55 whereas in this case, the total length is 455. So, this is almost an order of magnitude higher compared to the Charpy one.

But the test procedure is almost very similar, it is a very versatile test we can use both low strength material or high strength material the one which is having low strength means it is having higher toughness, it is basically ductile and the one which is having high strength means it has lower toughness.

So, all such kinds of material can be tested in this and because of the large size actually we have the triaxial constraint very much active here. So, we know that the plane strain condition is acting and we are getting the real or the valid plane strain conditions so that we can have a result with minimum scatter and can use this safely in practice and the notch that is used here in unlike the Charpy test where we have used a machine notch or V type notch which has been machined because of this huge specimen and machining a notch is extremely difficult, we use an electron beam weld embrittled section here as the notch.

So, this is basically we are creating a defect here such that on the effect of this impact, crack will initiate to grow from this location here. So, we just are making this location specific and then loaded horizontally in impact mode same as that of Charpy.

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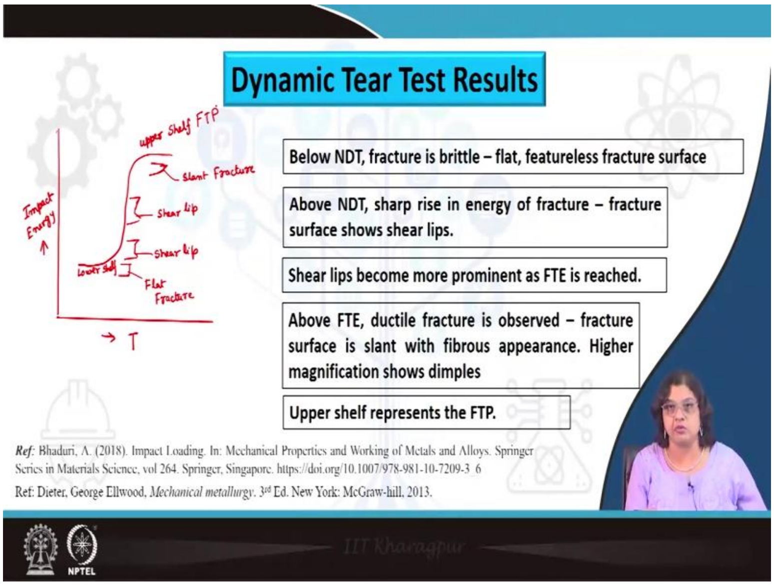

So, if that is the case, what we can obtain from here are the typical Charpy in the energy impact energy versus temperature curve that we have seen previously also for the case of Charpy.

So, here also we are supposed to get a similar kind of curve where we have the impact energy on the y axis typically in Jule and the x axis we have the temperature we do the test of the series of temperature and eventually we end up having a complete S kind of curve, where we have the upper shelf and lower shelf. So, the two previous tests that we have discussed those were the explosion crack starter test or the dynamic tear test those were giving us the NDT or the FTE such kind of temperatures are here.

On the other hand, in case of dynamic tear tests, we are getting the complete S shaped curve having the upper and the lower shelf and we can also from here from the fracture specimens, we can figure out that what kind of fracture has actually happened for example, if we are doing this at a temperature lower than the lower shelf or close to that, we will see a complete flat fracture. So, if the fracture surface is flat, then we know for sure that that is a signature of brittle fracture. So, that must be at a temperature lower than the lower shelf or close to the NDT.

If we are at this transition zone, we will see that the some amount of shear lip is there. So, this here is the shear lip, we can see some amount of shear lip is there. If we are more into the transition zone depending on the plasticity, we can see that this shear lip size is increasing further.

And finally when we are in the upper shelf, we can see that will have a slant kind of fracture. So, obviously that signifies that there is significant amount of ductility that has happened at this temperature. So, we can eventually figure out the entire transition regime for a much bigger specimen size, which can be practically relevant. So, this is what has been discussed here.

So, above the NDT there is a sharp rise in energy of fracture and fracture surface shows some amount of shear lip and the shear lip becomes more prominent as FTE is reached. And finally, above the FTE ductile fracture is observed, fracture surface is slant and with fibrous appearance and if we are looking this at a higher magnification, we should be able to see the dimples as a signature of the ductile fracture. So, upper shelf here represents the FTP we have seen that earlier also that this is the FTP, or the fracture transition plastic temperature or the T_1 temperature also.

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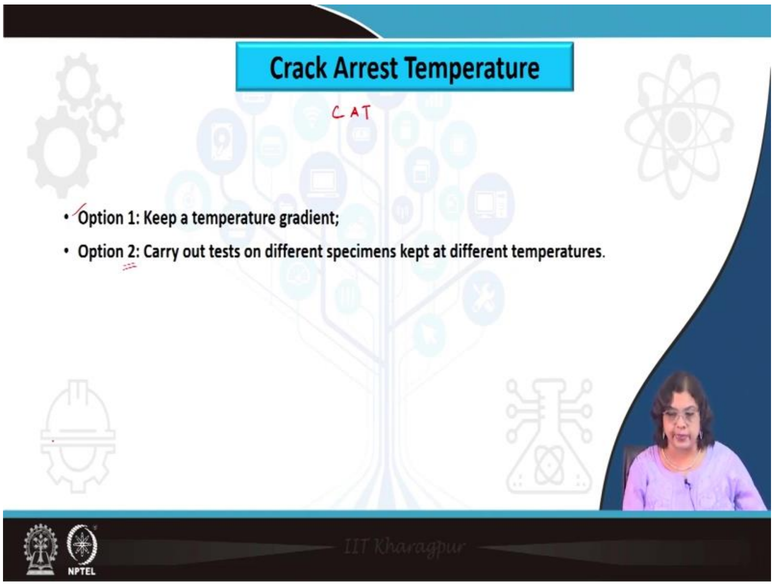

Apart from that, we also have another very interesting way by which we can determine the crack arrest temperature also known as CAT. So, in this case, we either we have two options either we can do the test perform the test, when the specimen is kept by maintaining a temperature gradient from one edge to the other, there is a variation of temperature that is being maintained. So, that is one of the options and the second one is when we are doing the test on similar specimen but at different temperatures.

So, this is the option two is what we have seen for other kinds of tests also we typically, impact toughness tests are done on a series of specimens at different temperatures and finally, from there we can find out the relevant temperatures.

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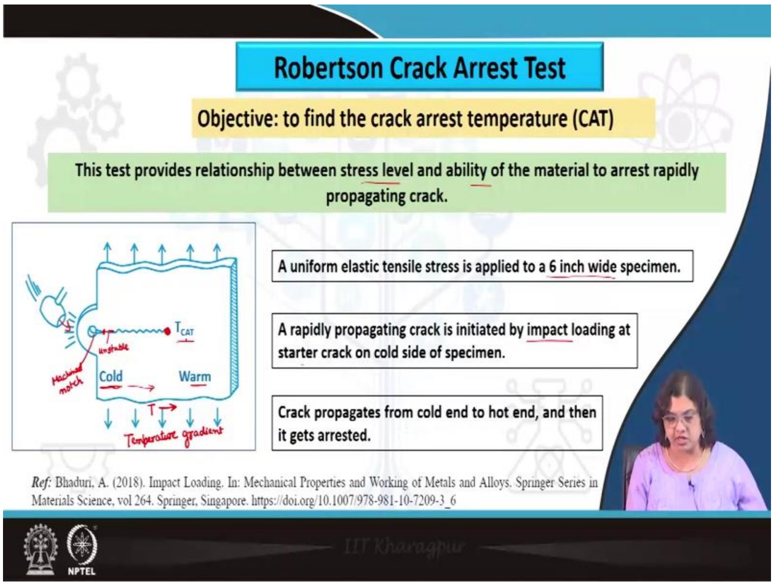

And what is interesting for Robertson crack arrest test is the kind of specimen that we use here. The objective here as I said is to find a crack arrest temperature. So, this particular temperature when the growth of the crack will be stopped or will be arrested that is the crack arrest temperature.

So, a relationship between the stress level and the ability of the material to arrest a rapidly propagating crack a crack which is propagating in an unstable fashion or in a rapid manner is an elastic crack, it fails in a ductile manner. And if we keep on increasing the temperature means the ability for ductile deformation increases and the ductile more is the ductile deformation more is a resistance to the growth of the crack, the r value increases and as a result the growth of the crack will be stopped.

So, this can be obtained from the test which uses such kind of specimen as I said a temperature gradient is being maintained. So, we can see that one end has a cold zone whereas the other edge has a warm zone. So, there is a continuously increasing temperature along the specimen with itself and here is a machine notch.

So, we can see that there is a hole and then there is a machine notch here and this is being impacted with this hammer and due to this impact actually, the crack will start growing from the tip of this machine notch and since this is at a lower temperature. So, that means that the fracture mode is supposed to be brittle here and brittle means unstable growth of crack.

So, here what we are seeing is an unstable growth of crack and the crack will propagate very fast, but as the temperature is increasing along the width of the specimen, the growth rate of the crack will be decreasing and finally, a particular point will be reached when the crack growth will be completely arrested. So, we see that there is a plastic zone formation that is the growth of the crack completely and that is the temperature considered as a crack arrest temperature of our interest.

And the specimen dimension is given here as a 6 inch wide specimen and it has a rapidly propagating crack as we are loading it with an impact within the hammer that started mostly from the cold surface of the specimen the cold side of the specimen and then the crack propagates from the cold end to the hot end until it reaches the temperature at which the growth of the crack gets completely arrested and that is the crack arrest temperature as we have seen.

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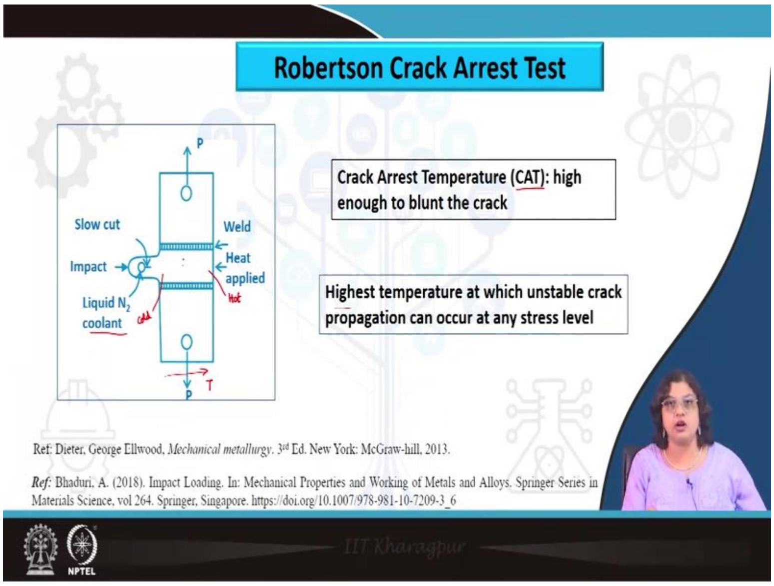

So, actually this crack is temporary is the one which is high enough to blunt the crack to the maximum and at this point the unstable crack propagation can occur at any stress level like up to this temperature level that is the highest temperature that we can see that up to this level the crack growth would be unstable, but after that because of this plastic deformation the growth of the crack will be completely arrested.

Apart from this the first option that we have seen the temperature gradient we can use this at a particular temperature also, this one here is also the option one which shows a temperature gradient and we can see that at one end there is this liquid nitrogen which acts as the coolant. So, that makes it the cold zone and then on the other hand on the other side there is the heat applied. So, that makes it the hot or the warm zone and at some point the crack will get arrested which is our temperature of interest.

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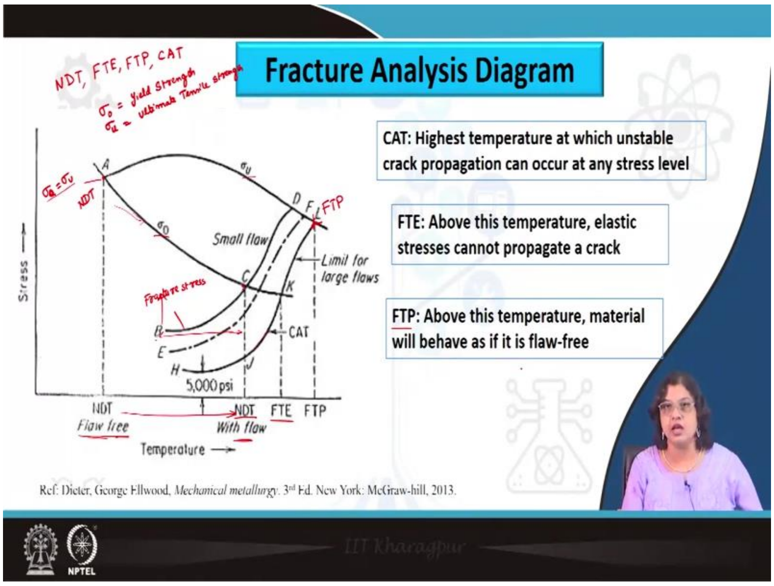

Now, so, far we have heard about the different kind of terminologies and we have used that for example, NDT and fracture transition elastic, fracture transition plastic, crack arrest temperature, etc, etc. So, let us see what this actually signified let us see this on the basis of the typical stress versus temperature diagram.

So, this one here is known as the fracture analysis diagram which is very much helpful to find out the behavior of the material at certain condition, what we know that at in case there is a component which is apparently flow free or defect free, we know that that kind of specimen could survive up to very low temperature without even undergoing any ductile to brittle transformation.

So, any kind of mechanical property degradation is particularly dependent on the presence of the crack or defect or flow etc. So, this diagram here shows the point A, which is where we have the yield strength equivalent to the ultimate tensile strength of the material. So, yield strength is represented as σ_0 and the ultimate. So, σ_0 is nothing but the yield strength of a material and σ_u is the ultimate tensile strength. So, at this point at such a low temperature of A when σ_0 equals to σ_u that is the temperature which can be considered as nil ductility temperature because there is no plastic deformation at this point.

The yield point whatever is the yield strength that is just the one that is required for fracture to occur according to the ultimate tensile strength. So, that is enough for fracture to occur. So, that means that this the fracture occurs here without any plastic deformation at all which is nothing but the definition of nil ductility temperature. Now, this is for a flow free material the one which is not having any defect in it at all there we can find this as the nil ductility temperature at the point A.

Now, this the both the yield strength as well as the ultimate tensile strength do vary with the change in the temperature as we are increasing the temperature we know that the yield strength of the material decreases the material or the specimen or component is supposed to yield much more easily if we are increasing the temperature at a much lower stress because the temperature the thermal energy is the one which is in association with the applied stress is helping for the dislocation to move further and that leads to a reduction in the yield strength with temperature. There is variation in the ultimate tensile strength also with temperature and this is what is being shown here with this curve.

Now, we have seen the point A for a flow free material. On the other hand, if we are having a specimen with some amount of flow in it with some dimension of flow, then the fracture energy will change completely. And this B, C, D, this curve here shows the one the fracture energy curve or the fracture stress curve for a component which is having a flow of certain dimension.

Here also we see that as we are increasing the temperature the fracture strength will increase, why, because there will be some amount of plastic deformation always. So, from B to C, we can see that there is an enhancement in the temperature like this much and that leads to some enhancement in the stress requirement for fracture also and this point C here is the one where it is cutting the yield strength line or yield strength curve.

So, that means that this is the point when the fracture is occurring without any plastic deformation because this is the same as the yielding, so, that means that there is no yielding has happened so far. So, this is nothing but the nil ductility temperature for the material when there is a flaw and we can see interestingly that just without the flaw the material has much lower NDT and just when we are adding some flaw, there is a significant enhancement in the nil ductility temperature.

So, we can see that the temperature at which the fracture is occurring is much higher or the NDT when it is happening without any plastic deformation is much higher just with the presence of a flaw. So, we are kind of mapping the behavior of any materials through this fracture analysis diagram.

Now, again, if the flow size is increasing, then we are achieving the same behavior and the temperature for NDT is increasing even further. So, this dashed line here EF shows the one with increasing dimension of flaw compared to the BCD line. And this one here the solid line HJKL, this curve here signifies the maximum limit of the flaw and what we can see here is apart from the NDT but we can also appreciate here very distinctly is the crack arrest temperature zone where we can see that there is a rapid rise in the fracture strength curve because of some amount of plastic deformation to occur and whenever that hits the yield strength curve that is the fracture transition elastic that we can see.

So, this crack arrest zone here signifies the highest temperature at which the unstable crack propagation can occur at any stress level that we have seen. And just when it touches this yield strength curve, this is the one at which the fracture transition elastic is happening. So, such that above this temperature elastic stresses are not sufficient to propagate a crack.

And then we are reaching the fracture transition plastic which is when this fracture curve hits the ultimate tensile strength curve. So, this point of intersection is when we are getting the point L or the fracture transition plastic such that above this temperature material will behave at is as if this is a flow free material. So, this is what we can find out for all different kinds of materials based on the fracture analysis diagram and we can implement that in the actual practice.

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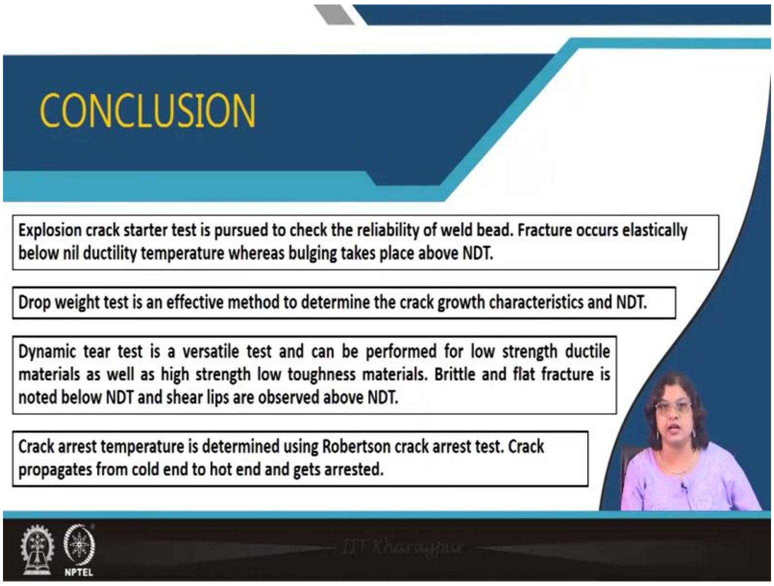

So, let us conclude this lecture and the impact toughness in general we have seen that the explosion crack starter test is a kind of test is pursued on much bigger specimen to check the reliability of the weld bead.

Often we have seen that impact of testing is done in presence of a weld bead because welding is one of the issue that has been faced long before in the case of the Liberty ship failure that because of this weld joints at those sections at those points serve as a point from which the failure has occurred. So, to design that often specimens include a weld bead which serves as a brittle notch that can lead to the insertion of the fracture and we have seen that fracture occurs elastically below the NDT and whereas, if we are increasing the temperature above NDT then there is an bulging.

If we keep on increasing the temperature it may happen that there is a bulging and there can be shear but there is no fracture at all. Drop weight test is an effective method to determine the crack growth characteristics and NDT. It is also is when we are using very large specimen.

And then there is a dynamic tear test which is a versatile one can be performed on different kind of material for low strength material which has higher toughness or high strength materials which has lower toughness all can be tested with this and because of this large size, it has a complete track shell condition valid active and we can from the fracture surface also we can figure out what kind of fracture has happened, if it is below NDT there should be only brittle fracture which means that the fracture surface should be flat.

On the other hand, if there are shear lip which can be seen on the fracture surface we mean that it has it is above the NDT and more it is approaching the fracture transition plastic temperature on the upper shelf more and more should be the shear of the shear lip. And from the Robertson crack arrest test, we have determined the CAT, or the crack arrest temperature, crack typically propagates from the cold end to the hot end until it reaches the CAT. So, that the crack is not capable to propagate any further because of that ductility that is there at higher temperature.

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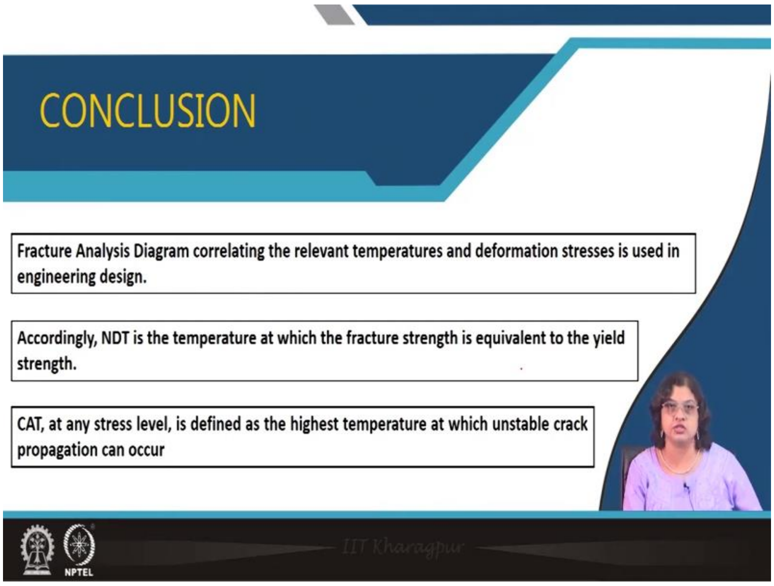

We have also seen how to get the fracture analysis diagram. So, that the relevant temperature and deformation stress can be correlated in engineering design and NDT from there also we have seen is the temperature at which the fracture strength and the yield strength the ultimate tensile strength or yield strength both of them matches or both of them are equivalent. And then CAT is the stress level which is defined as the highest temperature at which unstable crack propagation can occur up to which those unstable crack propagation can occur.

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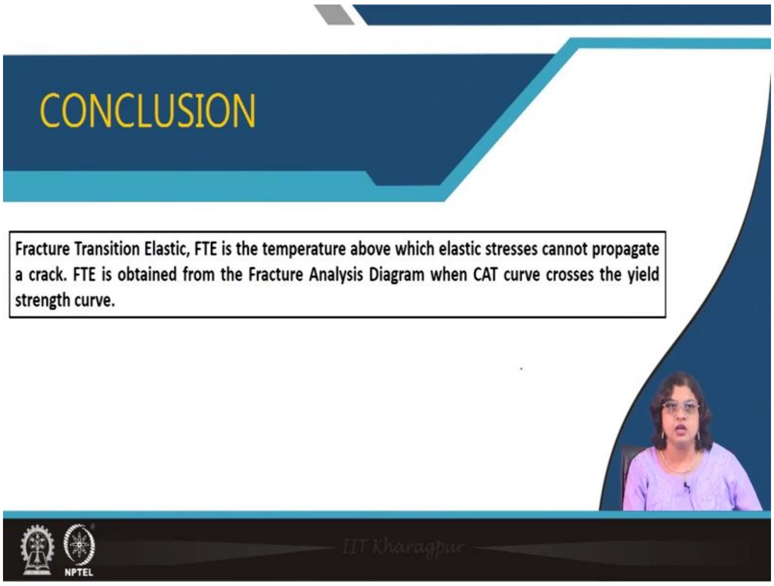

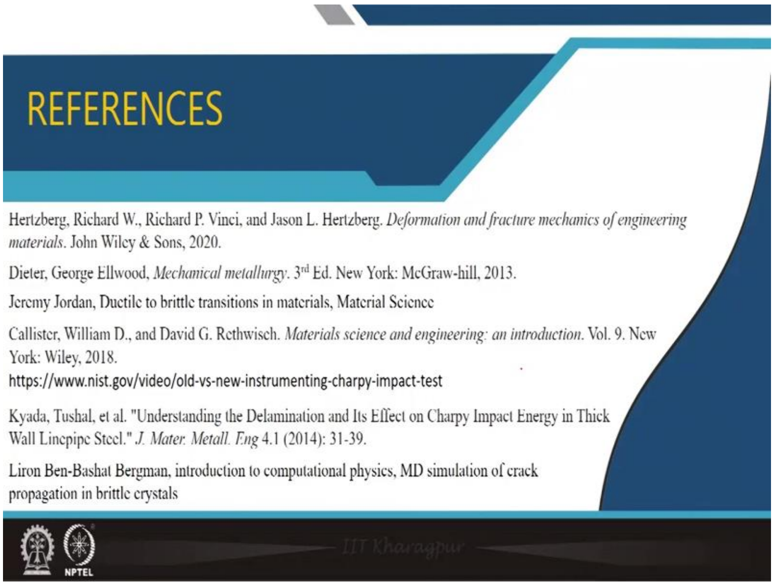

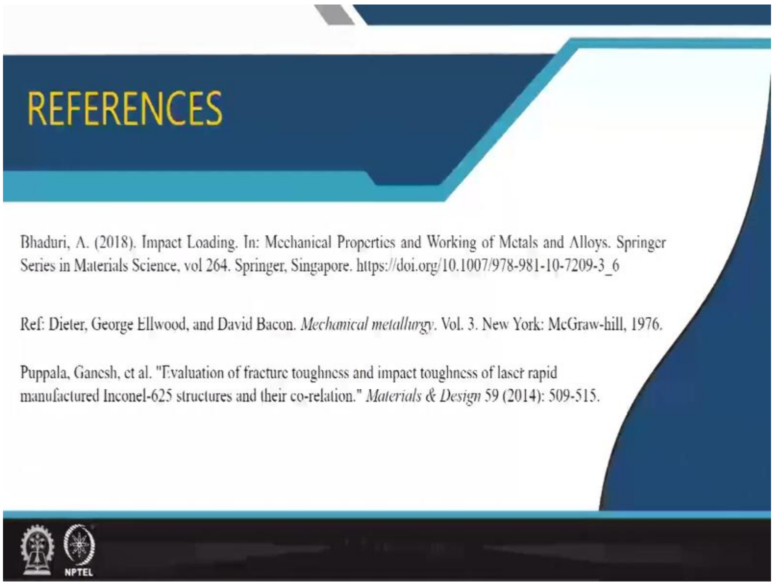

On the other hand, fracture transition elastic is the temperature above which elastic stresses cannot propagate a crack. FTE is obtained from the structure analysis diagram when the CAT curve that crosses the yield point or the yield strength curve, which means the point of intersection of the fracture curve with the yield strength curve that leads to the FTE and the fracture transition plastic is the temperature that we have seen above which the flow of any size cannot propagate to an unstable fracture.

So, this is obtained from the fracture analysis diagram when the CAT curve of the fracture curve crosses the ultimate tensile strength curve. So, this point of intersection with the ultimate tensile strength curve gives us the value of FTP. So, these are the references used for this lecture. Thank you very much.