Fracture, Fatigue and Failure of Materials
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Lecture 18
Impact Toughness (Contd.)

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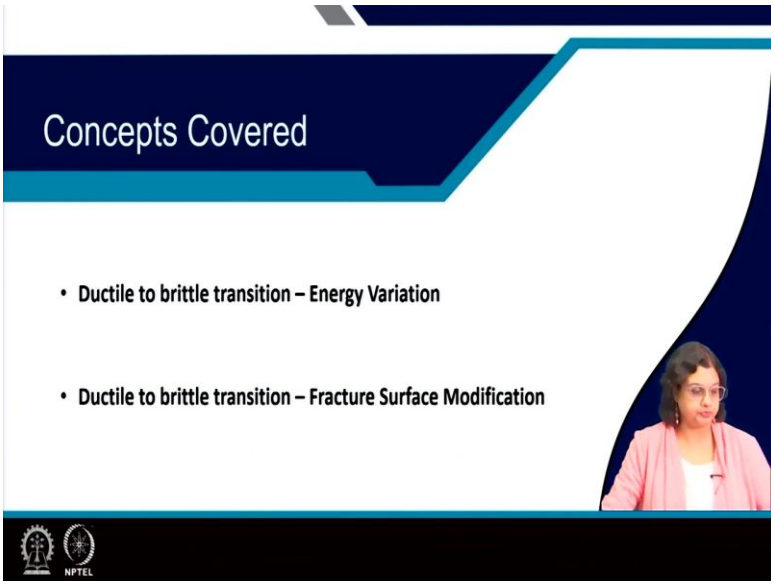

Welcome back everyone, here we are with the eighteenth lecture of this course fracture, fatigue and failure of materials. And in this lecture, we will be discussing some more on the impact toughness, particularly the concepts that will be covered in this lecture are the following, we will be talking about the ductile to brittle transition in depth particularly, if there is any change on the energy variation as well as the variation on the fracture surface that leads to make us understand that how this ductile to brittle transition is happening.

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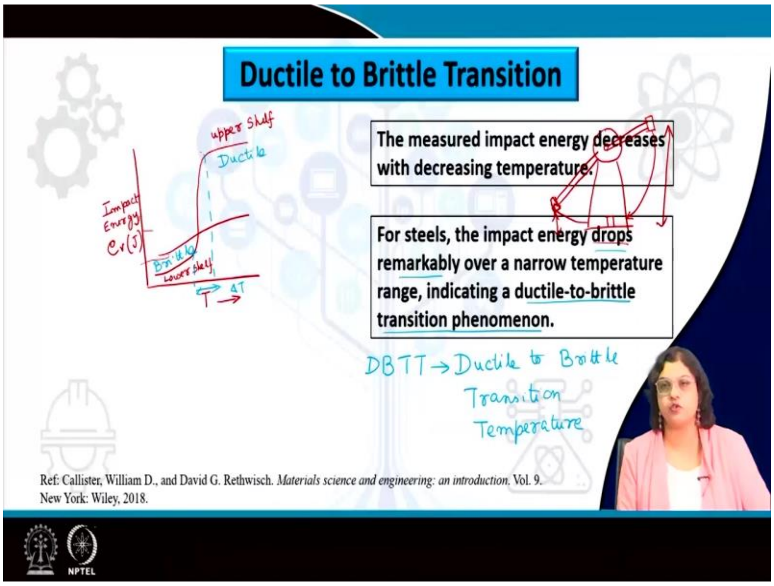

So, in case of any material which undergoes a change in the mode of failure from ductile to brittle with temperature or with the strain rate that we have seen in the last lecture, we can determine their toughness and their variation in the toughness values as well as mode of fracture through the impact toughness testing, for example, the Charpy test and in any such test, what we can determine is the variation in the energy with temperature, we have seen that how Charpy test is being done, we use a pendulum to hit a specimen and so, let me draw this one more time when we have a specimen like this.

And we hit it with a pendulum so that the specimen deforms absorbing some part of the energy and the pendulum stops at a lower height and from the difference in the height, we can figure out the energy that is being absorbed by the specimen. Now, we can correlate that we can perform this test at different temperatures and eventually, we should be able to plot the variation of this energy also known as the impact energy. Impact energy typically, the unit that is used is Joule and the symbol that is particularly used for Charpy impact test is C_V the unit is Joule and on the X axis we have the variation in temperature. So, temperature increases along this direction.

And eventually if we carry on such kind of test at different temperatures, we can see that how the energy is varying with temperature. Typically, the measured impact energy always decreases with as the temperature decreases. So, if we are getting for some cases we get something like this, when at high temperature it absorbs higher amount of energy as well as at low temperature, it absorbs lower value of energy. But in some cases, we actually see a very distinct differences such as it shows a typical S shaped curve something like this, where we have a distinct upper shelf, which typically uses much higher amount of energy as well as a lower shelf, which means that fracture has occurred at much lesser value of energy and in between there is a narrow temperature range.

So, within this temperature range actually, we can see that there is a very drastic change in the fracture behavior and the fracture energy consumption. So, this temperature range like ΔT is where we are seeing a difference. Now, when it is absorbing higher amount of energy, it means that there is some kind of ductile deformation that is happening here. So, the failure in this case will be ductile mode of failure.

On the other hand, if we are performing the experiments at lower temperature, there will be a brittle mode of failure and that is reflected in consuming lesser amount of energy, the Charpy impact energy will be much less for the case of brittle failure. So, overall the same material just by changing the temperature even if when we are applying same kind of strain rate very high strain rate, but it is being the same at a higher temperature as well as lower temperature, we see a completely different mode of failure for both the cases.

And this is essentially figured out from the Charpy impact test in general or impact toughness test what we are concerned of is this temperature range over which this ductile to brittle transition is happening. Now, this is seen such kind of change in the failure mode is seen not for all the materials, but for certain materials particularly depending on their crystal structure, we see these for steels where the impact energy drops remarkably over a narrow temperature range and that is known as a ductile to brittle transition phenomena as well as this temperature is known as the ductile to brittle transition temperature or DBTT.

So, we try to figure this temperature from this kind of impact toughness testing. Of course, this temperature range varies from materials to materials and for the particular one that we are planning to use for any service needs to be tested for such kind of properties.

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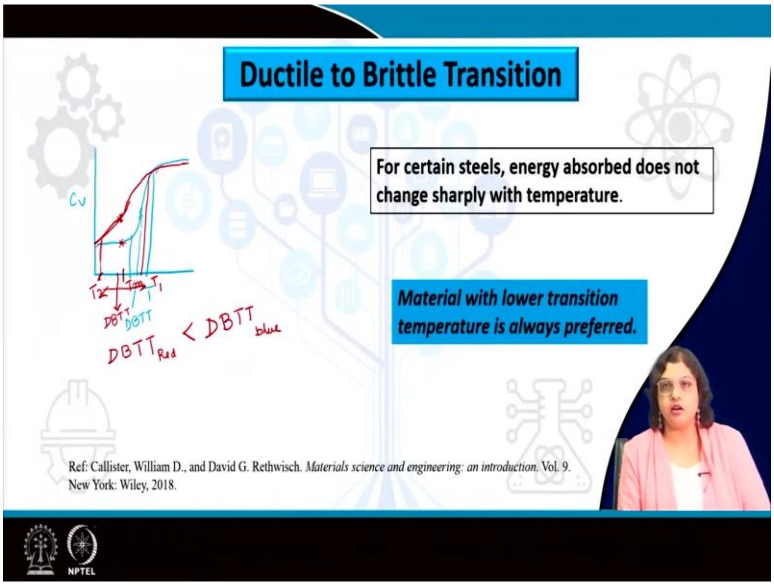

Apart from that, let me also indicate that as I mentioned this ductile to brittle transition behavior changes from materials to materials. So, for certain steel this energy absorbed does not change very sharply as well as for some cases there is a very drastic change in the failure mode. For example, if we are plotting this once again as the C_V versus T we can see that for some kind of steel it is following a very drastic change.

And for some cases, although it is let me again change the color to make it more apparent. So, for some cases we can see that although it is starting from more or less the same values which varies over a certain range. So, it behaves like this and in this case for the former one if we see the transition is happening within this range only. And if we want to just take the average to specify this ductile to brittle transition, we can say that this is the point or this particular is the temperature at which DBTT can be called.

If we are for now, considering this as the exact midpoint of this transition zone. On the other hand, when we are talking about the one with the red curve, we see that this is happening although the lower shelf and the upper shelf energy are almost the same in this case, we are seeing that the transition is happening over a very wide range of temperature.

So, that is the major differences first of all the range is very high. And also if we are looking for the one near to the middle, which we can consider as DBTT, so, that one for the red one will be much lesser than the blue one. So, we can see that this DBTT for the red curve is of much lesser value in terms of temperature for the DBTT of the blue curve.

Now, this also gives us a dilemma that when we want to use this for service, although both of them showed similar kind of fracture behavior or similar kind of energy requirements. So, similar toughness at a certain temperature let us say room temperature, but at service temperature, it may have different kinds of behavior and that depends on what exact temperature we are talking about.

If we are using this again at such a low temperature, both this material or both this component will behave in a similar fashion. So this will show a brittle failure mode at such a low temperature. Let us name this temperature at as T_1 and T_2. So, at T_1 both the blue and the red curve coincides, which means that both of them absorbs equal values of energy at a higher temperature.

At a comparatively lower temperature again both of them absorbs almost similar values of energy. So, both of them shows brittle failure, but, if we are talking about any temperature in between this T_1 and T_2 for example, somewhere in the middle, let us name this as Tm at such temperature, we will see that the red one is absorbing higher amounts of energy compared to the blue one.

So, this also leads us to while we are designing are we selecting a particular material for certain application, we have to make sure that the DBTT is lower or the lowest value possible. So, it is always preferred to have the lower transition temperature. So, that in service condition even if the temperature is decreased, that should not lead to rapid change or very drastic change in the failure behavior.

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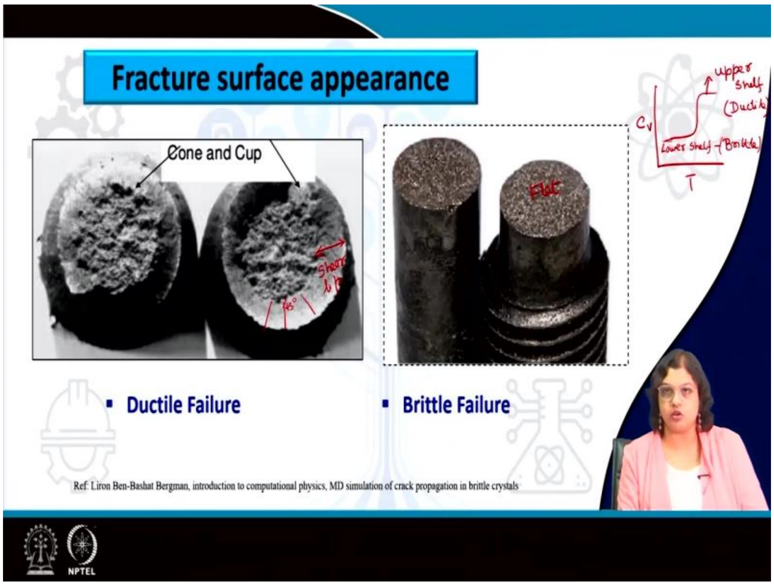

Now, when we are talking about the energy versus temperature diagram, we basically can see that it leads to two completely different failure mode, right this S shaped curve is a very typical one that we can see. So, this one here also known as the upper shelf shows ductile behavior and that is the reason that it is absorbing more amount of energy, as I mentioned in the last lecture, any kind of ductile deformation leads to absorption of part of the energy and that means that the toughness of that material increases.

On the other hand, at lower temperature the same material behaves in a completely different way. So, this is known as the lower shelf when it has a brittle kind of failure. And this is apparent from the fracture surface itself from the specimen itself. So, this is just for reference, the difference between the ductile and the brittle failure in case of the ductile one we see a significant amount of shear lip present here.

So, this is a round tensile specimen and for the case of Charpy test or impact toughness test typically use a rectangular SENB kind of specimen, but, in any case, there will be significant amount of deformation or that is reflected as the shear lip near the edges. So, this is what we can see that there is a 45-degree deviation with respect to the loading direction.

On the other hand, if we are talking about a brittle failure, which is particularly seen here at the lower shelf, we will see a perfectly flat fracture surface. So, that signifies that it is a brittle fracture. So, just by looking on the fracture surface itself, we can figure out that whether the mode of failure is ductile or brittle as we have seen earlier also.

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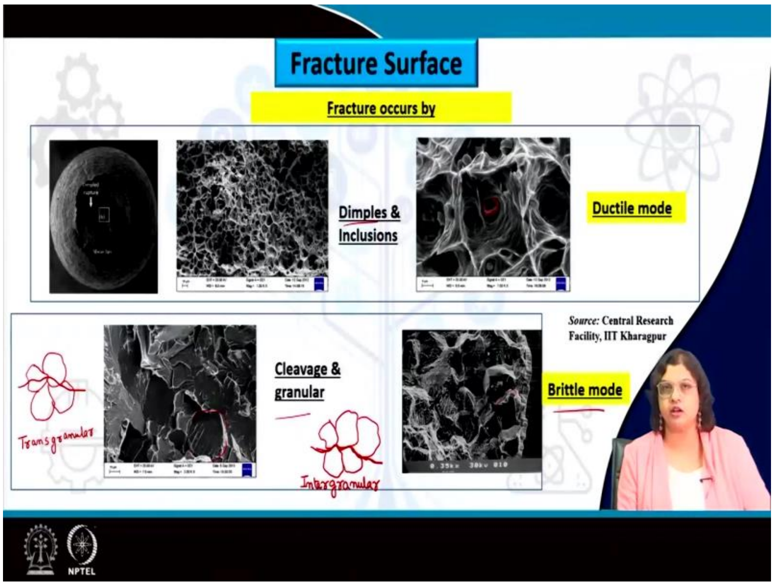

So, in for most of the materials fracture offers by either of these two method. In case of the ductile one, we have seen already that apart from the shear lip the other signature of the ductile failure if you are looking at in a microscope in a scanning electronic microscope, we can see the presence of dimples. So, all these spherical or semi spherical voids kind of things are the dimples that are seen here and within the dimples, we can also see the presence of the inclusions which are actually the reason for the failure it mostly occurs by micro void coalescence.

On the other hand, if it is a brittle one, there can be again different modes of failure. In some cases, if there are grains like this adjacent grains and crack can pass through the grains that is known as the trans granular fracture. And in such cases, we can see the presence of this cleavage this flat facets here with which we can see very nicely flat facets and no sign of dimple.

So, that is the signature of brittle failure on the other hand in some cases, where we have this grains like this and the crack prefers to grow through the grain boundaries itself. So, this is the crack where you can see that the crack propagates through the grain boundaries and this is known as intergranular fracture and this is represented or this is reflected in the fracture surface as this kind of granular structure here we can very well figure out the grain structure from the fracture surface itself.

So, these are all typical signatures of brittle mode of failure. So, we can if we are looking onto the Charpy impact test fracture specimens at low magnification we should be able to figure out if there are any presence of shear lip or there is a complete flat fracture and at higher magnification if you are looking this under a scanning electron microscope, we should be able to figure out whether there are dimples presence of dimples or presence of cleavage there.

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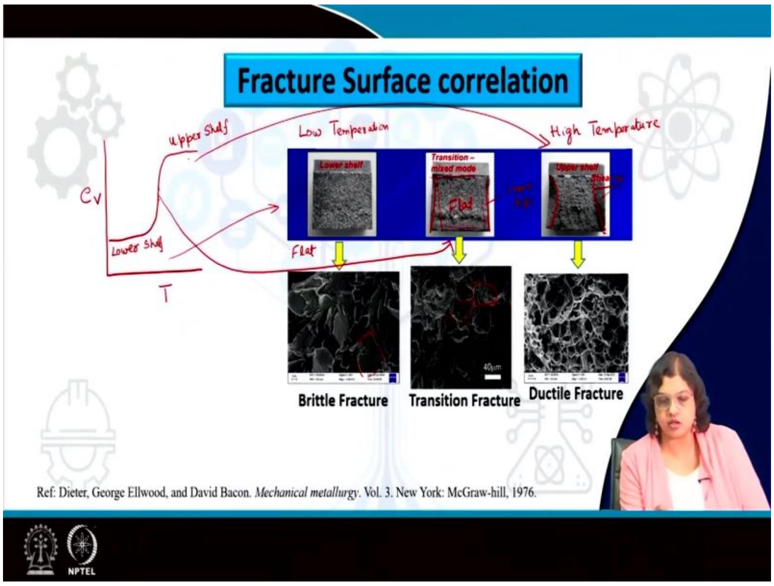

So, if now, we try to correlate this with the energy diagram, once again let me draw this in parallel. So, this is the energy and this is the temperature and we are very well seeing the upper shelf and the lower shelf, this is for a case when it shows a very distinct ductile to brittle transition mechanism.

And if we look into the broken specimen, the fractured specimens, we can see different kinds of characteristics firstly, if we are looking into the lower shelf that means, when the test has been done at a low temperature, the specimen dimension as well as everything else remaining same only the temperature has been changed and we can see a perfectly flat fracture surface. So, there is just by looking on the fracture surface with our eyes, we can figure out that this is a brittle mode of failure.

On the other hand, if we are doing this at a higher temperature, doing the test a comparatively higher temperature we can see in some cases there has been no failure at all or even if there is a failure, there is a typical signature of sheer leap here we can very well see that how a particular section nearer to the edges, there is a change in the direction that is typically the shear leap.

So, this signifies that this is a ductile fracture and this is typically seen on the upper shelf here. So, this is for the lower shelf and this here is for the upper shelf and in between at any position here we are actually seeing a mixed mode kind of fracture where there are some signatures of both the ductile and the brittle fracture we can see some amount of shear lip here also, but this is much narrower compared to the this one here at the upper shelf.

So, this is a mixed mode kind of fracture, where we see some part which is flat the internal particularly near the central part this is completely flat whereas near the edges we, you see some amount of shear lip. So, that is a mixed mode kind of fracture, if now we are so, this is typically for this part here.

If we are now correlating that with the higher magnification micrograph This is how it looks, the brittle one shows a completely flat facets and the cleavage is very well apparent. From here you can see the flat structures very well. On the other hand, in case of the transition mode, that is in between we can see some locations where there are some dimples present here and on the other part, there are some amount of cleavages also present there.

So, we can figure out that how much is the percentage of each of these based on some microstructure analysis. And we can definitely understand this based on the macro graph or the fractograph at the higher magnification that whether there is a complete ductile failure complete brittle failure or a mixed mode kind of fracture this one like here typically shows a ductile fracture and all nicely formed dimples shows the mechanism being a micro void coalescence as has been discussed previously. So, if such is the case, once again this are still giving us a qualitative value, this is ductile fracture, this is brittle fracture.

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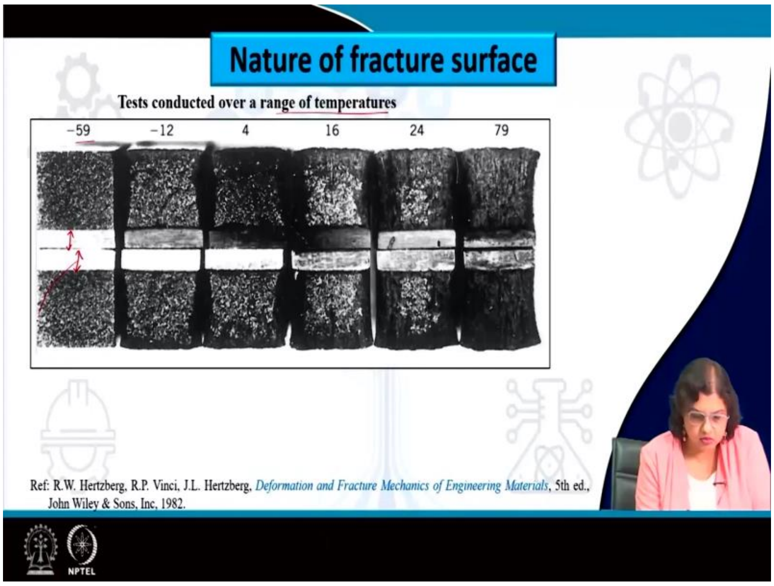

But we always try to find out the quantitative value for that so that we can specify the amount of ductility or the amount of brittle mode there. So for that we actually need to perform a series of test and to figure out this kind of the S shaped curve that we have seen so far. So, here are some examples of the fracture surfaces for both the pieces after fracture and this has been done at over a range of temperatures typically these are mentioned at Fahrenheit and we can see that, how if we are decreasing the temperature, how the fracture surface are being changed. So, let me also point this out that this is or for that matter this is actually the machine notch part.

And here what we are seeing is the fracture surface so any features that we are seeing over this regime that is the fracture surface behavior and what we can see that at a lower temperature when the temperature is negative we can see that this is a complete flat fracture there is no signature of any ductility even near the edges whereas if it is done at a very high temperature compared to this one here we can see that there are significant amount of shear lip forming near the edges, so this is very well seen here.

And in between we can see that the extent of the shear lip is decreasing if the temperature is decreased and right at even this kind of negative numbers of -12° we can see that the shear lip has been there is some indication for shear lip compared to the -59° one, of course so a series of tests are being done so that we can quantify this and for the quantification this is the schematic representation of this you can see that for some cases we can see a flat fracture when there is no signature of shear lip on the other hand if we are doing this repeating the test at higher and higher temperature we can see the formation of shear lip is increasing.

And till we see that most of the fracture surface is completely covered with shear lip so that can also happen in case we have a very ductile material which is ductile even at a high temperature sometimes even at room temperature also, so to find out the percentage of shear lip we need to understand this and measure this to quantify, so let us say this is the fracture surface here considering that this dimensions as A this length and this length is B and in case there is some shear lip forming here so that is the shear lip that is forming and if we are simply considering that this is forming in the all edges we can see that there is another square or rectangle that is being formed.

Now if we are just to show that this is the shear lip let us just shade this part here so now we if we are considering this dimension as x and this dimension as y we can figure out the percentage of shear lip as the following so the total area A cross B and then x cross y which signifies the area of this inner portion and if we divide that with the total area to find out the percentage we can figure out that how much is the percentage of shear lip simple maths will tell us this.

So at least we more than the qualitative one now we have some way to quantify this amount of shear lip and based on this once again correlating this percent of shear lip with the energy absorbed we can once again figure out the exact impact toughness energy and the material behavior for that matter.

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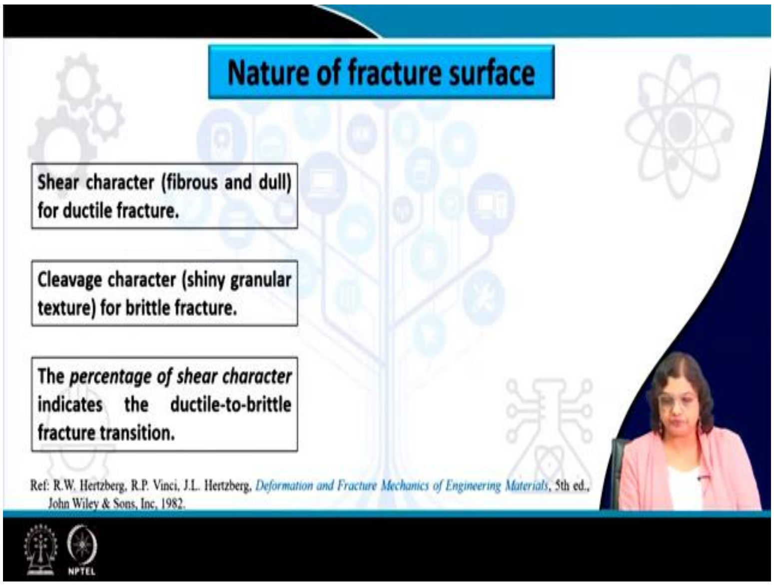

So the nature of the fracture surface typically gives us either of this three so it could be a shear character as we have seen there that near the edges there could be shear lip so essentially that if we are looking with our eyes it looks like a fibrous and dull appearance rough appearance overall and in case there is a shiny or granular texture at the middle or most part of this that is the signature of the brittle fracture and this percentage of shear character indicates if the way that we have determined the percentage it indicates the ductile to brittle transition and we can say on the basis that whether there is 50 % transition or 90 % or maybe just 10 % based on the quantification of that.

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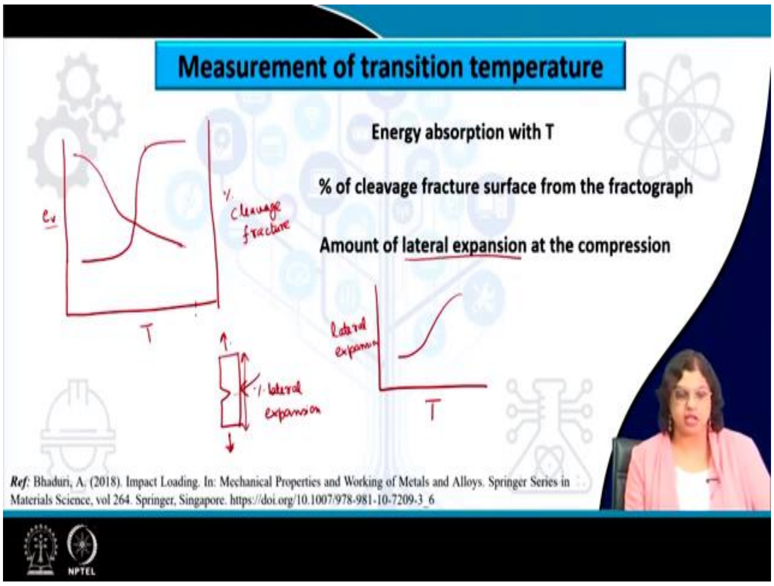

So for that case the transition temperature is determined based on the following ways so first of all let me once again draw this, so this is the energy versus temperature and as we mentioned that this shows a typical S kind of curve that there is an upper shelf and there is a lower shelf, now this is the energy variation if we are not talking about the percent cleavage fracture.

Let us again draw this on the y2 axis here so this is the percent cleavage fracture which signifies basically brittle mode of failure right so that means that brittle mode of failure is seen in the low temperature range so that means that the percent cleavage fracture will be 100 % at this temperature here whereas the percent cleavage fracture will be 0 % at the high temperature one here so that means that the curve will look something like this and based on this we can figure out the transition temperature.

As we have seen the transition temperature transition is happening over a range of temperatures so we need to figure out that if we want to quantify, if we want to specify this ductile to brittle transition temperature or DBTT we often code this as a range of temperature but in case that it is happening over a narrow range or even a wider range that is more appropriate to mention a particular temperature instead of a range so that we know that that kind of temperature needs to be avoided and for that quantification we need to correlate this temperature versus energy diagram as well as this person cleavage fracture versus temperature graph.

So let us say there are five different ways by which we can specify this temperature so the energy absorption with T is one of the way by which as we have seen already this kind of S-shaped curve are being obtained and then also the percentage of cleavage fracture surface as we have shown for this y2 curve here that will show that how the cleavage fracture is changing and there is another way by which we can figure out the transition and that is through the lateral expansion of the specimen.

So what happens is if we have a specimen like this which is getting hit from here so that means that there is a tensile stress that is being applied on the direction perpendicular to this right so if the pendulum is hitting this so there is a kind of compression mode that is happening in this direction and that leads to a tensile mode on the perpendicular direction as we are all well aware of and that leads to some kind of expansion in the lateral dimension so that is termed as the lateral expansion and if we are plotting this once again with the varying T we can determine from the broken specimen itself we can determine that what is the total length and compare it from the initial length and we can find out the percent lateral expansion.

And if we are plotting that with respect to temperature this also looks something like this and we often needs to correlate all this ways to figure out the exact or specify the exact temperature for ductile to brittle transition mechanism.

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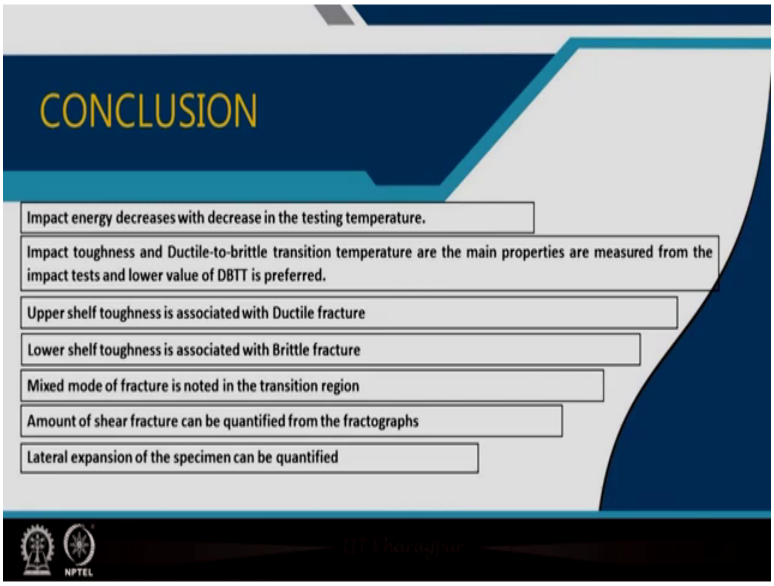

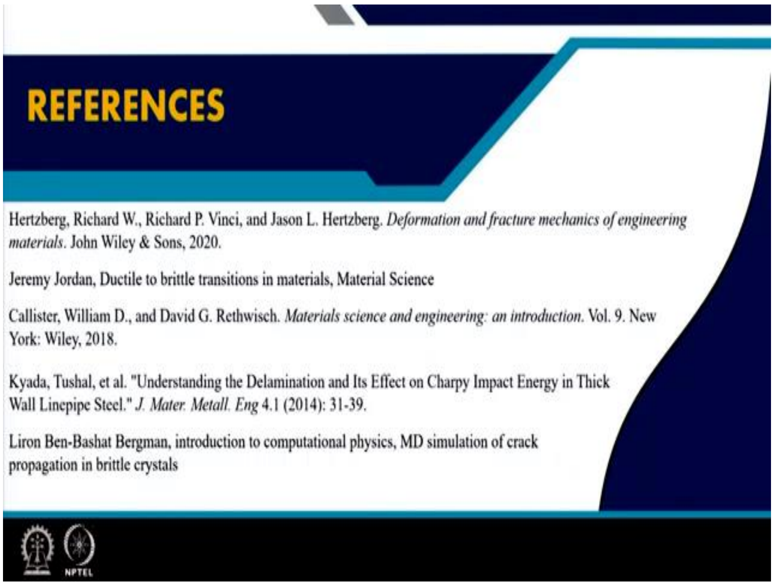

With this let us conclude this lecture that impact energy we have seen that it decreases with the decrease in the testing temperature or the service temperature and in some cases this reduction in the energy or this change in energy is very very drastic that leads to a completely different mode of failure. Impact toughness and this ductile to brittle transition temperature are the main properties which are determined from the impact test for service actually we have seen that any material which is having lower ductile to brittle transition temperature that is preferred if we are thinking of designing component and the upper shelf toughness is associated with ductile fracture so all the signatures of ductile fracture like the presence of shear lip or the presence of dimples at higher magnification will be apparent from this upper shelf if specimen has fractured within this energy of the upper shelf.

And in case it has fractured in the lower shelf one then there should be lower value of the energy and that is indicated with a brittle fracture, so all the signatures of brittle fracture for example a flat fracture surface or the presence of cleavage that will be seen for the fracture in such case and in between within the transition regime we actually see mixed mode kind of fracture which is carrying the signatures of both the ductile and the brittle, the amount of shear fracture can be quantified from the fractograph, we have seen that how we can determine the shear lip area and we can determine the percentage of the shear fracture, lateral expansion of the specimen can also be quantified. These are some of the references that are used for this lecture, thank you very much.