Fracture, Fatigue and Failure of Materials
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Lecture 17
Impact Toughness

Hello everyone, and here we are with the seventeenth lecture of the course fracture, fatigue and failure of materials. And in this lecture, we are going to start another new concept new topic which is on impact toughness.

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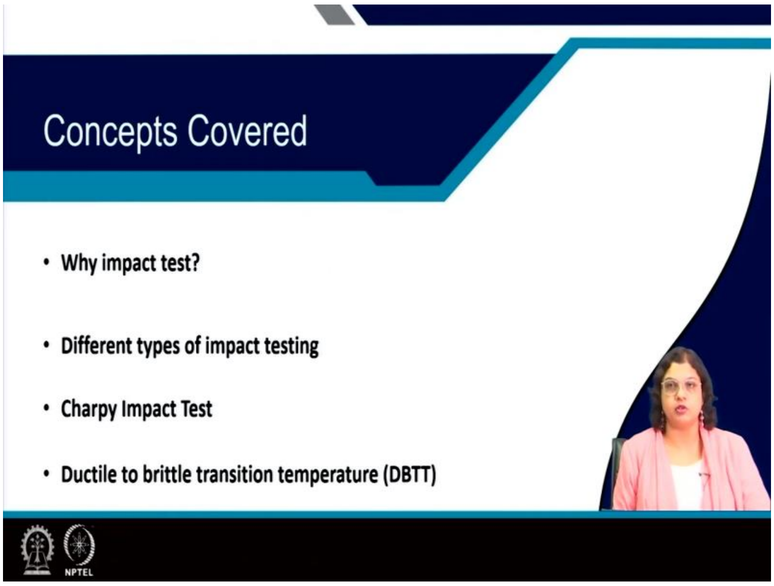

So, let us see what will be covered in this lecture today. So, we will be talking about impact test and what is the necessity for that, why do we need to know the impact toughness of a material, the practical significance and of course, that will be also associated with the different types of testing that are done to find out the impact toughness of a material. And most likely, we will be talking about the Charpy impact test, which is the most common and most widely used impact toughness testing. And from there, we will lead to the concept of ductile to brittle transition and the temperature associated with that.

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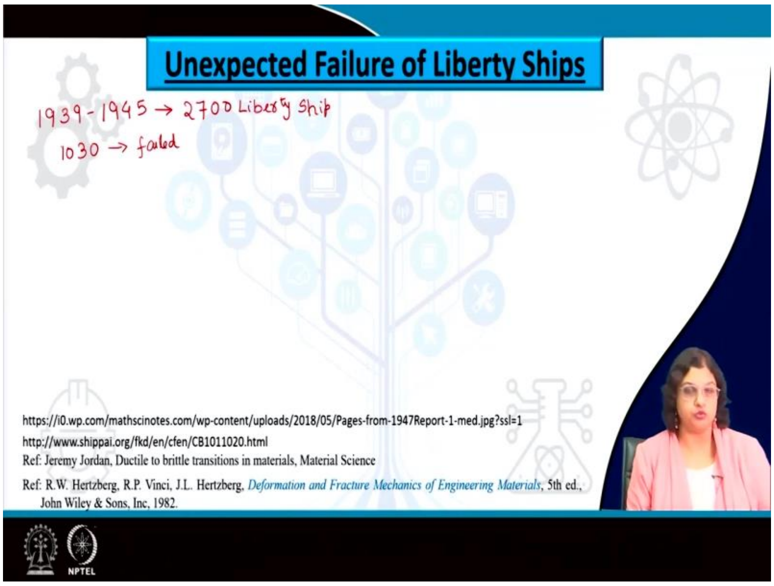

So, let's start with why the impact toughness characterization has become very important, it dated long back more than a century back during the time of the Second World War, when there was a lot of failure events that people have noticed. So, there were this liberty ships which were built during this period of early 1940s and so, and the main purpose of this kind of ships are for the transportation.

So, during this period of around say 1939 to 45, over this period of time, more than 2700 of liberty ships are being built. So, let me just state this fact a little bit, over this period of six years almost more than 2700 liberty ships were built and they were of course, different sources specify this number a little bit in a different way, but more or less, there was a huge number of ships that has been built over this period.

So, it is obvious that much of the manufacturing has been done in a hurried way, in a way that they can complete their assignment their job that ships will be functioning soon. So, that was one of the fact that later on people came to know that could be related to their failure incident. So, out of these 2700 or more than that ships, there was a failure incident of more than 1000 ships. So, to be specific, more than 1000 ships got failed or damaged or showed significant amount of defect that they had been retired from their service. And most importantly, there were few incidents that showed that the ships actually cracked into two.

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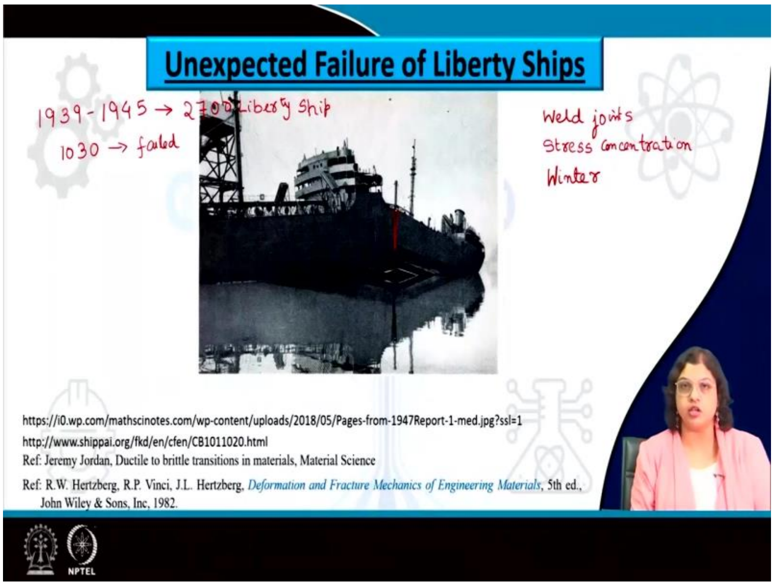

So, here is an example of one if you can see that the ship has been actually fractured right from the middle and teared into two completely different parts. So, this has actually shook the nation all these incidents and particularly if ship or such a giant structure can tear up into two just like a toy, that is something of concern and people did a lot of investigation, lot of failure analysis has been done to find out the real reason for this and understanding has been developed about the metallurgical concepts that leads to fracture.

Particularly it has been considered that much of this failure originated from the weld joint that has been used in the ships particularly to save time. So, instead of the riveted joint in the ships much of the weld joints has been used, and that leads to some of the defects, the welding defects that could lead to stress concentration, I am bringing up this term because you are already familiar with this terms and now, how this has practically led do failure and how that has impacted the overall fracture mechanics that is something very interesting.

So, all this stress concentration and the associated fracture has been noted particularly during the time of winter. So, majority of this failure actually happened even when the ship is not on the working status or it is just in the dock there also it just suddenly fractured and particularly in the winter season when the water is chilled. So, that also give the idea that something is happening might be that is related to the temperature and that led do this concept of impact testing.

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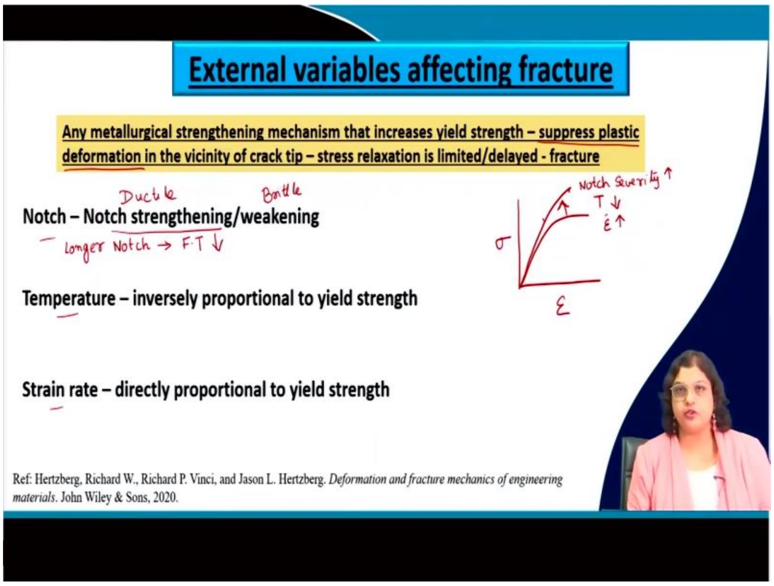

Most importantly, what people have understood from there is that the shipbuilding steel that has been used of course, had not very poor toughness, but quite okay that is supposed to work in that, but due to some external factors, fracture has actually happened. So, scientist and the people working on the area of fracture mechanics understood the concept or the importance of the external factors or the service conditions, experimental factors parameters that could led do failure apart from the materials property itself.

So, actually, for that matter, if we think that we always try to enhance the strength of a material we look for stronger and stronger material, but by whatever way any of the metallurgical strengthening mechanism that we use for increasing the yield strength for example, by having some kind of inclusions or precipitates with a second phase that has a higher hardness, higher strength, so, that we can get an overall enhancement in the yield strength of the material, all such kind of strengthening mechanism actually suppress the plastic deformation.

So, any kind of strengthening or strengthening particularly of the yield strength, any kind of enhancement in the yield strength is associated with retardation in the overall ductility or the plastic deformation. And as we have seen from the plane strain and plane stress concept, so, far that more is the plasticity as we have, we noticed this in case of the plane stress condition when the plastic zone is significant, that actually retards the growth of the crack and that uses up some of the energy whatever applied energy is available, that is partly being used for this plastic deformation and as a result, more and more energy is required for the fracture to materialize.

So, that is actually in a sense good way of increasing the toughness of the material. So, strength and toughness, particularly yield strength and toughness are mostly inversely related. So, any enhancement in the yield strength delays or the stress relaxation is being limited in case there is a plastic deformation.

So, with that we came to the concept that any kind of external factors other than the metallurgical way itself if we are using some kind of notch, we have also seen that particularly for ductile material, this presence of the notch can lead to notch strengthening. In case of brittle material, we see the weakening as expected, but for the case of ductile material, because of the stress triaxiality at the notch tip that leads to notch strengthening.

So, now, if we think about the importance of the notch, we see that longer is the notch for example, if we are increasing the notch size, the A So, longer is the notch that will lead to a reduction in the ductility in the material. So, that essentially reduces the fracture toughness of the material. So, fracture toughness reduces.

On the other hand, if we are talking about the temperature, now, temperature is inversely proportional to the yield strength, more is the temperature, more ductile the material is means the yield strength is reducing so, that in a sense, we can say that if we are reducing the temperature or in most cases if the service temperature is much low than the strength of the material increases, because there is not enough plastic deformation and that means that more and more energy needs to be supplied to have the material yield.

So, if we can simply draw the stress versus strain curve. Let’s say this is for a regular material. And in case we are seeing any of these conditions there will be enhancement in the yield strength but there is at the same time reduction in the total elongation to failure or the ductility or overall, there will be a reduction in the toughness.

So, what we have seen so far is, as the notch severity like the length of the notch or the sharpness of the notch tip reduces under such circumstances, there will be an enhancement in the yield strength part, also we have seen that if we are decreasing the temperature let’s use the symbol T for temperature. So, if the temperature is being decreased, that also leads to an enhancement in the yield strength.

The other important factor is the strain rate, the deformation rate. So, if we are applying a very high strain rate, then the yield strength is also increasing. So, yield strength is directly proportional to the strain rate. Higher is the strain rate, more will be the yield strength of the material. So, there also we are seeing an effect in the stress strain curve. So, these are the three factors which eventually alters the fracture behavior of the material and that is particularly relevant when we are talking about the service condition.

So, we can determine the fracture toughness of a material from the lab scale by using even the plane strain plane stress concept, but when we are using this material, this component in actual service, then we see that because of this conditions like the presence of the notch or the change in the temperature or any alteration in the strain rate can actually lead to enhancement in the yield strength, but the overall toughness reduces.

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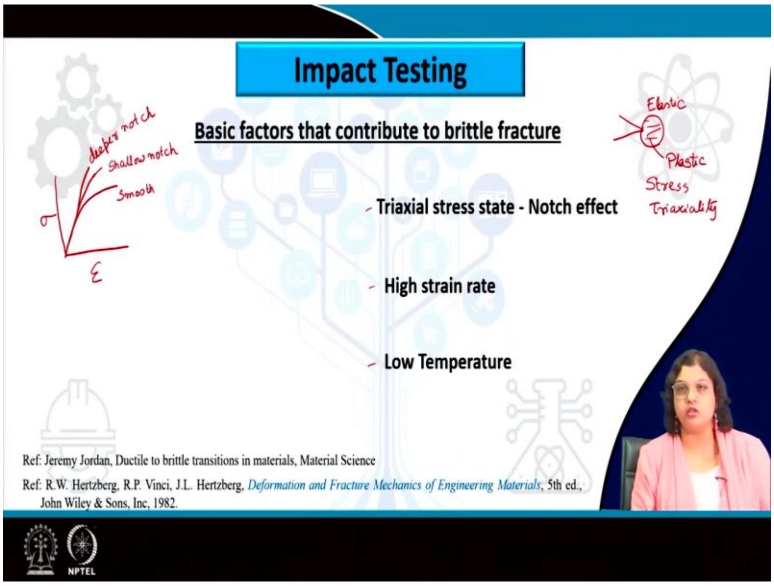

So, if that is the case, we need to figure that out through some testing and there comes the major factors that are of concern for the case of impact testing. So, impact testing was first thought about by Charpy, long back in around 1912, and all when all those failure things are happening, people came to know about the importance of the different factors that could have led to the failure and designed and experimental way to find out the toughness of a material.

So, the basic factors which contribute to the brittle fracture as we have seen is the first of all the presence of this notch and because of the presence of the notch, the stress Triaxiality that offers at the tip, because at in front of a notch there will be always some kind of plastic deformation and how much will be this plastic zone size that depends on several factors also depending on the material of choice apart from the design factors, but surrounding this plastic zone, there will be an elastic part, this elastic part is supposed to constraint any kind of permanent deformation that the plastic part is supposed to have.

So, that leads to a stress triaxiality and as a result, the fracture behavior is being strongly affected. So, for example, if we once again draw the stress strain curve, and if this is one for a regular material, let us say a smooth specimen, if there is a notch we can see that there is an enhancement in the yield strength and reduction in the ductility of the material. Now, if we are increasing the notch severity, so, if let us say this is a shallow notch and if we are increasing the length of the notch or decreasing the tip radius of the notch, we are seeing even further enhancement in the yield strength and reduction in ductility.

So, this is for a deeper notch. So, that means that not only the presence of notch, but the geometry of the notch as well as the total size of the notch that is also very important to manipulate or to alter the overall fracture toughness of the material.

And apart from that, as we have seen that high strain rate has also some role to play and as well as low temperatures. So, when impact testing has been designed, all these three factors are taken into consideration so that all this can be applied simultaneously so that we can figure out the worst-case scenario and the fracture toughness in that.

And in actual practice maybe all the three conditions may not be applicable at the same time and anyway whatever toughness that we are determining based on the impact testing will give us a conservative value a lower bound value, and in the actual service, we are actually expecting better than better value than that, provided all the three conditions do not act simultaneously, but if it does, for this worst case scenario, we are prepared to find out the toughness of the material based on the impact toughness testing.

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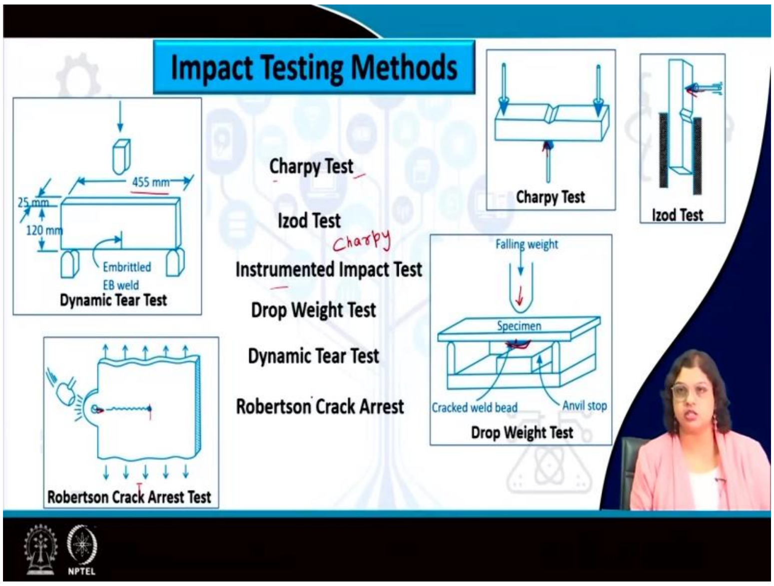

So, there are different methods that has been found out, this one is the most commonly used test the Charpy impact test, we typically use specimen like this, which is a rectangular specimen and which is having a central notch here or the edge notch which is positioned at the center between the two loading points. So, this is again like single edge notch being kind of specimen that we use for Charpy test. Apart from that, Izod taste is also very much used. And this Izod test specimen is very similar to that use for Charpy only in this case, we placed the specimen in a different way.

While in case of Charpy the load is applied from the back of the notch. The Izod test specimen is placed in a vertical way. And this is how the load is impacted on the specimen. On the other hand, there is an instrumented impact test, this is once again more like the Charpy test only so it is an instrumented Charpy impact test. And the difference between a regular Charpy test and an instrumented one is that, in case of the instrumented one, we can actually figure out the variation in the load with respect to time. So, this load versus time plot can also give us much more information about when this deformation is actually started, what is the exact load at fracture, what is the total energy for fracture and so-on.

So, what is the amount of energy that is required for the crack propagation, all this can be determined from the instrumented impact test, we get much detailed information compared to the Charpy test.

And there is a drop weight test in which it looks like this. So, here is the specimen and then there is a weld on beneath the specimen and some weight is impacted from top so that a crack initiate from this part and that determines that is typically done at different temperature to figure out that when at what particular temperature with the same amount of weight and rate and strain rate, what kind of temperature leads to the initiation of the crack.

There is also dynamic tear test. So dynamic to test is also very similar to the Charpy test, this is the kind of specimen that is used. But the only difference between the Charpy test and the dynamic tear test is that this uses a much larger specimen, this is quite a large specimen you can see that the total length is something like 455 millimeters. So, that is pretty high.

And that leads to the toughness behavior can be determined from such tests for the actual service conditions. So, often we, when we are talking about using kind of steel for shipbuilding, we often need to determine the toughness behavior under such dimensional parameters also keeping those dimensions in mind, we have already seen in the very initial lectures that how the different size are different volume of the actual component leads to a much lesser value of the fracture strength; right and that is related to several factors one being the probability related to the number of defects etc.

So, it is always very, very important particularly when we when we are talking about the brittle mode of failure, the size or the volume of the component should be taken into account and that is particularly taken care of when we use the dynamic tear test.

And then there is Robertson crack arrest test also here, there is a specimen and there is a machine notch here and then it is impacted with a pendulum at a very high strain rate. There is a variation in the temperature throughout the specimen so, that we can figure out that what is the temperature at which the crack propagation is being arrested. So, here also we can determine the particular temperature of interest or if we know that the service temperature we can determine that what kind of strain rate is suitable for the crack to stop at that particular temperature.

So, depending on the requirement service requirement, we can design this experiment or we can utilize these results. Now, since the Charpy impact test is the mostly used one, we will start with this one and slowly we will get into the details of the other impact toughness testing methods as well.

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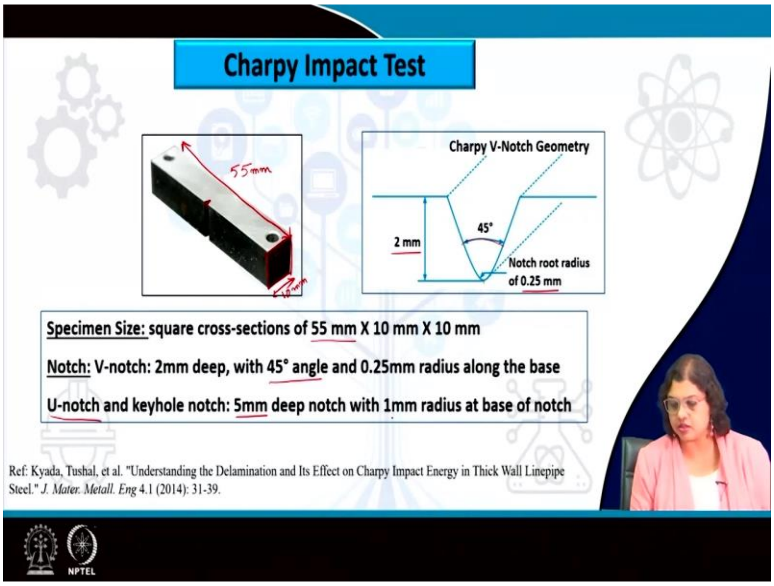

So, coming to the Charpy impact test, this is the kind of specimen that is particularly used here and the specimen size and all the different geometrical parameters has been standardized already and this is the kind of specimen where we use the total length. So, let's say this thing is of something like 55 millimeters so it is a rectangular specimen, but with the square cross section, so, it has the size of each of the size is 10 millimeters and not only the specimen size, but also the notch which is machined here that is also being fully standardized and we typically use a V kind of notch with the notch root radius or 45-degree angle and the root radius is around 0.25 millimeter.

The notch depth is also very important as we have seen that there could be some importance of the notch depth also and this is particularly considered this depth is fixed based on the plane strain condition to be achieved. So, this the standard depth that is used is around 2 millimeters this other than the V Notch, U notch are also sometimes used or used or keyhole kind of notch depending on the service requirement if such is the case of the notch then often U notch or a keyhole are used where the depth is around 5 millimeters and then notch root radius is a little bit higher of one millimeter.

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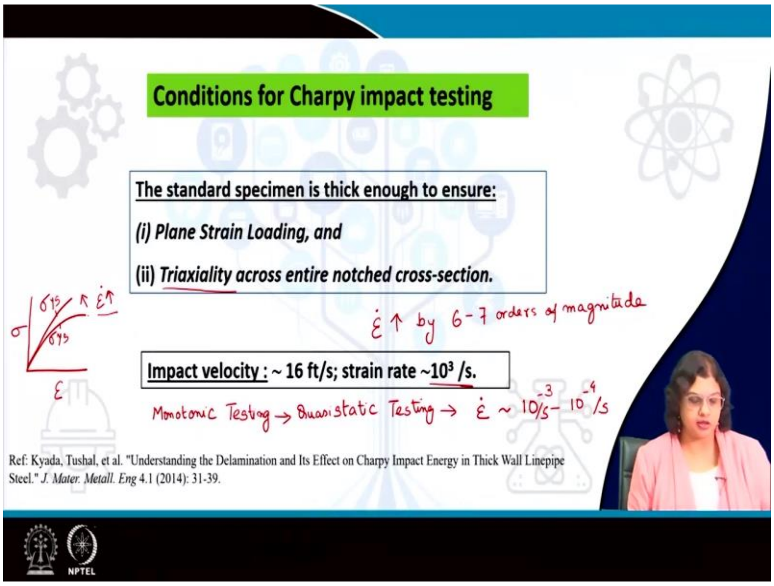

So, the typical conditions as we mentioned that are used for the Charpy impact test are the following when we design the specimen these following points are taken care of. So, first of all, there should be a plane strain loading condition once again we want to determine the materials property. So, we want to have the plane strain condition maintained there and that is how the notch depth or the thickness of the specimen or the other dimensions or the width of the specimen all are being considered to achieve the plane strain loading condition and also because of this notch and notch length and all that the Triaxiality at the notch tip as we just discussed, that is also been mentioned.

So, so that all kinds of restriction is there and that leads to the lowest value of fracture toughness. So, that are being considered while designing the Charpy impact testing. Of course, these are standardized and all this can be found from the standard handbooks.

Most importantly, so far we were talking about the specimen design and we have mentioned about the strain rate, higher strain rate leads to higher yield strength as we have seen from this stress strain diagram itself. So, if this is for a regular specimen, if we are increasing the strain rate then the yield strength is increasing, of course, but that ductility is also reducing.

So, this is let’s say sigma yield strength, we can see that there is an enhancement in the yield strength with the enhancement in the strain rate but so, far we have not specified that what is the strain rate of concern. In this case for the case of Charpy impact test, we typically use a strain rate of around 10 to power 3 per second. So, 1000 per second strain rate is a dimensionless parameter, no dimension of length is there just the time dimension is there and time unit is there.

And what is important here to also appreciate the fact that what is the regular strain rate that is used for any other tests for example, if we are talking about a three-point bend test, which is very similar to the we use very similar kind of specimen for fracture toughness testing through AC and B specimen that we have seen in the last lecture.

But the strain rate that are typically used for the tensile testing, the mode one fracture condition is something let me just write it down here. So normal monotonic testing. Now, this could be also applicable for tensile testing or fracture toughness testing, when we are increasing the load monotonically also known as static or quasi static testing let me that is more appropriate term will be quasi static testing. So, for that typical strain rate is something like 10 to the power minus 3 to 10 to the power minus 4 per second.

So, in comparison to that for the case of impact toughness testing we are increasing the strain rate by almost 10 to the power of by 6 or 7 orders of magnitude. So, strain rate increases by 6 to 7 orders of magnitude. So, that is of course, a huge enhancement and any such effect of strain rate will be completely pronounced in this case and we can figure out the influence of the strain rate in there.

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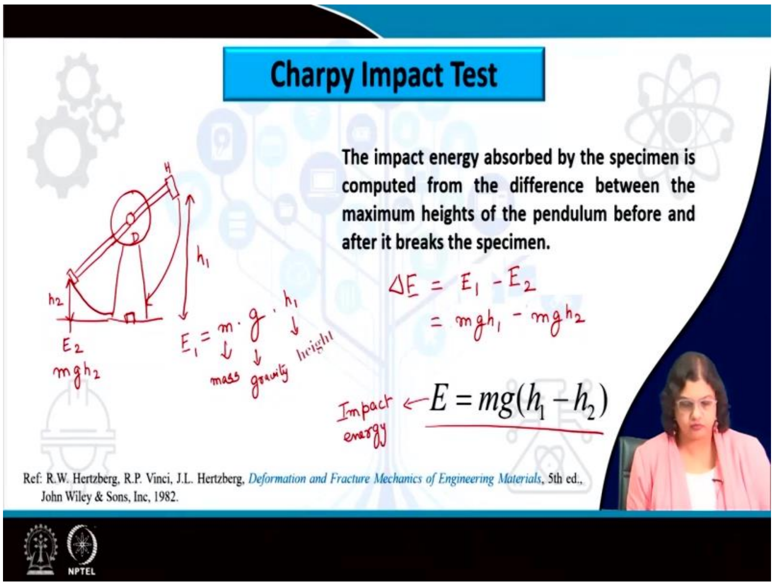

So, let us see how the Charpy impact test is typically done. So, what we have here is a dial and with this is a pendulum or a hammer. So, this is the base of the instrument in which the specimen is being kept. Now, this hammer hits the specimen like this to the specimen and then it stops after certain distance, the specimen flies up it breaks or it gets deformed.

And in turn, we are able to figure out the change in the position of the pendulum from the, so, this was the starting position let’s say this as h1, let’s name this dial as D, the hammer or the pendulum as H or sometimes like this carries a particular amount of weight and this is being impacted with certain velocity as I mentioned the velocity is something like 10 to the power 3 per second and then after it hits the sample, the energy of this pendulum the potential energy of this pendulum is being absorbed by the sample by the specimen and then with this absorbed energy there is some amount of deformation in the specimen.

And since the pendulum or the hammer has lost this energy because the specimen has absorbed it, it did not reach the same height as the starting one. So, it stopped at a lower height than that. So that let’s say from the base, that height is done as h2. So, in this case the total energy that the pendulum was carrying the potential energy, let’s name this as E1. So, E1 is the m, m is the mass right the typical relation for energy is m g, g is the acceleration due to gravity and h1 so, that is the height of the pendulum, on the other hand for the condition E2 we have similarly m g h2.

So, this is essentially what is being used the concept of the Charpy impact test which means that the energy that is being absorbed by the specimen is computed from the difference in this energy. So, overall what we see delta E here is or eventually we end up finding out this energy or the difference in energy which is given by mg h1 minus h2 and this is termed as the impact energy, this delta E is actually what is known as the impact energy.

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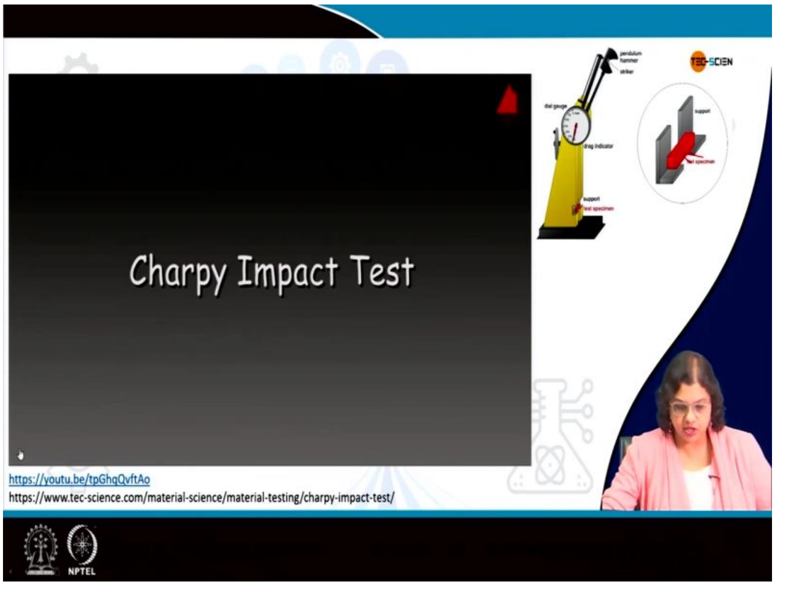

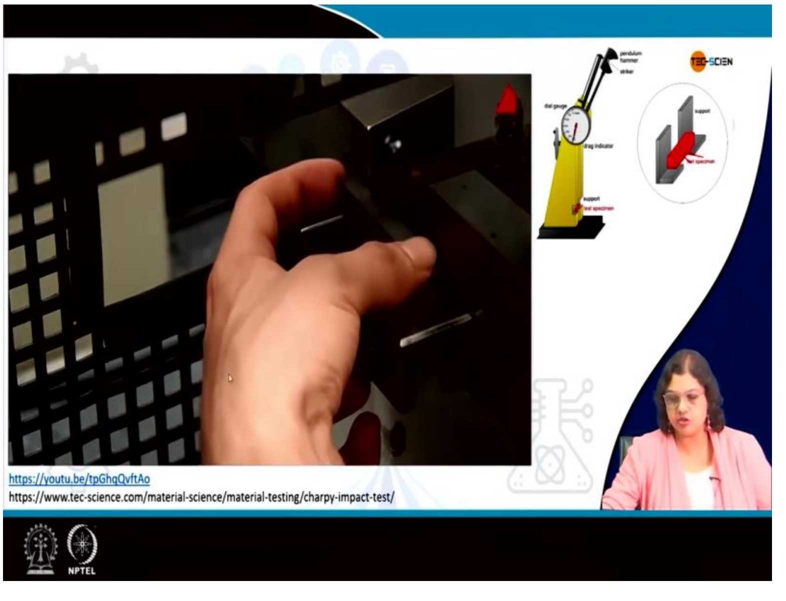


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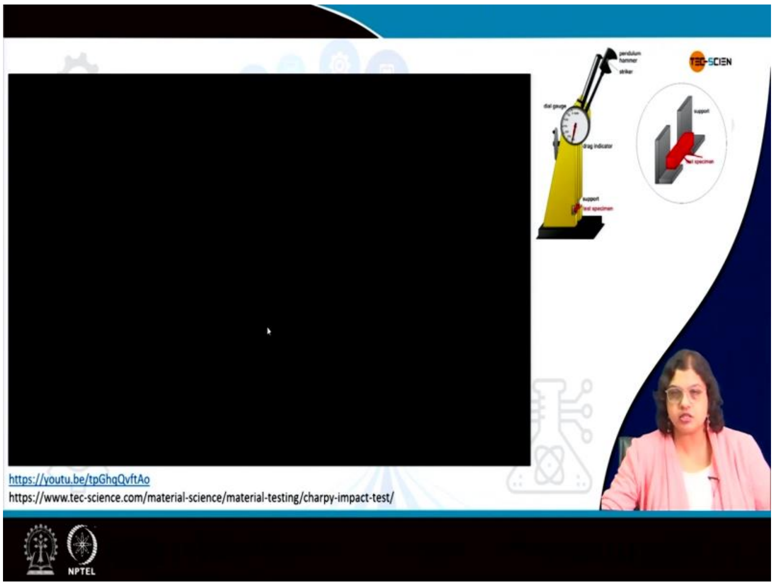

So, here is the machine and how it looks like so, this is the dial in which records the position of the edge, the initial case as well as once it hits the specimen the specimen is kept like this, so, that the hammer typically hits from this direction just directly opposite to the notch tip here. And as a result, the specimen absorbs the energy and gets default. So, here is a small video just to show how the impact tests are being done. So, this is how the specimen is placed and then the hammer is released it hits the specimen and the dial comes to certain position and the specimen gets deformed.

So, this is how from the deformation of the specimen, we can determine that what kind of fracture has happened whether the fracture has happened or not at the first place and if has it been, then what is the typical mode, if there is no fracture, then what kind of deformation has happened, we can all figure this out from the specimen itself and from the record of the dial, we can determine the exact energy we can quantify this and we can correlate this deformation with the energy required and we can get the information about the toughness of the material from them.

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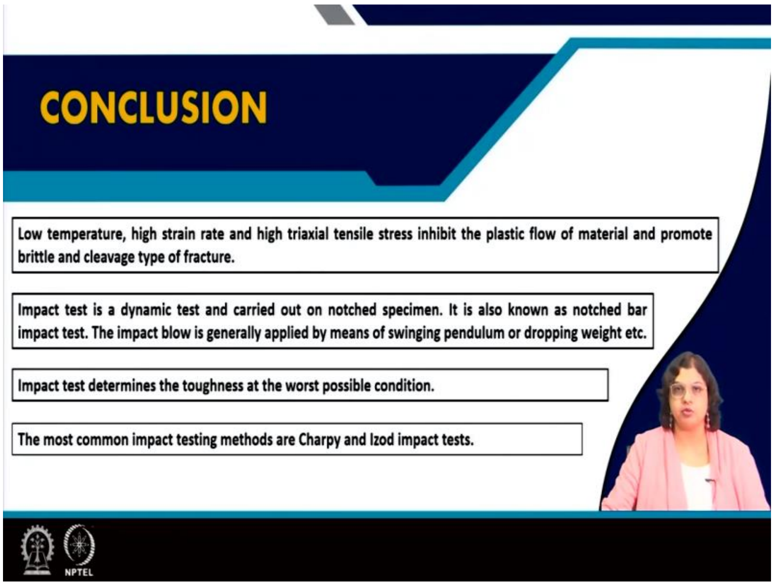

So, let's come to the conclusion of this lecture. This is what we have discussed over this lecture is that low temperature, high strain rate as well as the high triaxial stress because of the presence of a notch; all this external conditions lead to inhibition in the plastic flow of the material and that particularly promotes brittle and cleavage kind of fracture. So, to find out the property of a material under such condition impact toughness test is determined and that is a dynamic test which is carried out on notched specimen.

It is also known as the notched bar impact test, the impact blow is generally applied at a very high strain rate by means of either swinging pendulum that we have seen for the case of Charpy test or it could be a dropping weight as well. Basically, impact test is determined at the worst possible conditions such that all the inhibiting conditions such as high strain rate, high triaxial tensile stress, because of the presence of the notch as well as low temperature; all these three factors are acted simultaneously and the toughness is determined on that basis. The most common impact testing methods are however, Charpy and the Izod impact test.

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So, these are the references used for this lecture. Thank you very much.