Fracture, Fatigue and Failure of Materials
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Lecture 20
Impact Toughness (Contd.)

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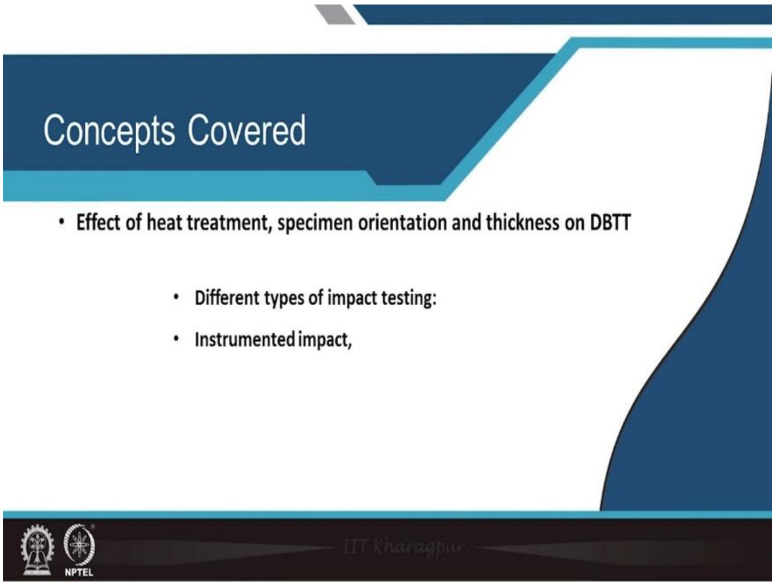

Hello everyone, we are here with the 20th lecture of the course fracture fatigue and failure of materials. And in this lecture also we will be elaborating some more on the impact toughness. So, particularly in the last class, we have, we were discussing about the importance of different metallurgical factors that are controlling the ductile to brittle transition behavior and the DBTT.

So, in this lecture also, we will be talking about the heat treatment as well as specimen orientation and thickness on the effect of DBTT. And after that, we will be talking about some other types of impact toughness testing rather than the Charpy impact test and we will be talking about the instrumented way by which impact toughness can be determined.

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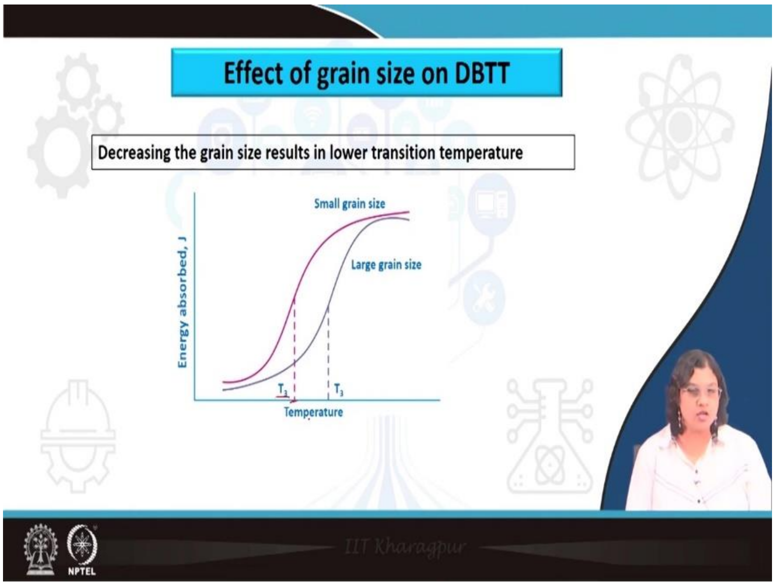

So, where we stopped in the last lecture, we were discussing about the influence of grain size and particularly, we have seen that finer grain size so, the refined grains are giving us lower ductile to brittle transition. So, as you can see that this is based on the T_3 DBTT, T_3 mode that we can see that for the finer grain size, the value of this DBTT is lesser than that for the larger grain size. And that leads us to the next way by which we can control the grain size and in turn control the DBTT.

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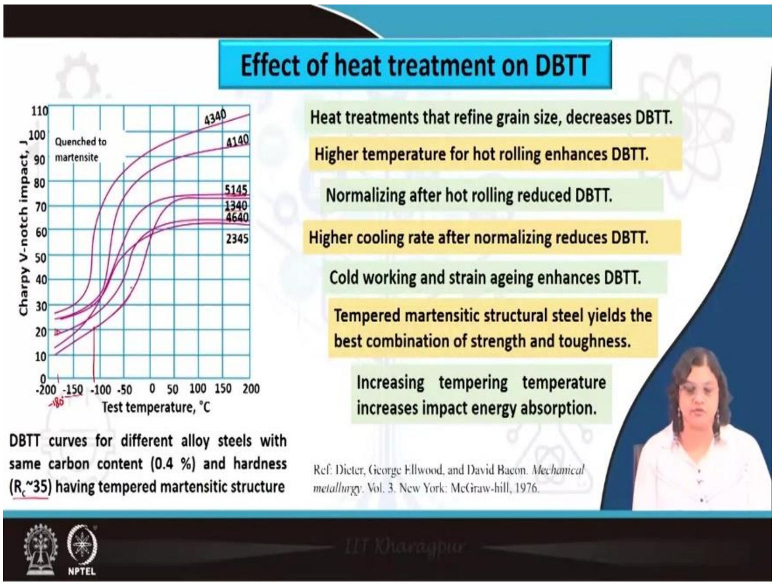

So, as I mentioned that we often need to do heat treatment on the material on the component to give it a particular shape or to machine it for different kinds of practical reasons, we often need to do heat treatment and one of the very prime reason for pursuing heat treatment is to modify the microstructure and more precisely modify the grain size or the microstructural size.

So, basically what we can see from here that any kind of heat treatment that refines the grain size will be having a positive role on the DBTT and that will lead to a reduction in the ductile to brittle transition temperature. So, we often need to do rolling and that is being done at a higher temperature hot rolling. So, in case we are reducing the temperature can lead to having a beneficial effect in reducing the DBTT.

Compared to that, if we are using higher temperature for hot rolling that can also act as coarsening because hot rolling is typically done for a certain time and with that, there can be some amount of coarsening due to the aging simultaneously happening, just because we are doing it over a sequence of time.

So, that may lead to some grain growth at higher temperature and that may enhance the DBTT. And on the other hand after hot rolling if we are normalizing this, then also there is a possibility that the grain size could be reduced and with that, we will end up having lower ductile to brittle transition temperature if we are normalizing this.

Again while we are doing the normalizing treatment, we can employ a higher cooling rate. So, if we are cooling at a faster rate, then the grain size will be lower, grain size will be finer because there is not enough time for the grain to grow to a certain size level and so, that means that higher cooling rate will act like a quenching and that can refine the grain size and if we are refining the grain size that can reduce the ductile to brittle transition temperature as well.

On the other hand, if we are cold working this, so working that means we are applying some amount of deformation and that to at lower temperature that can also act to have a negative influence and can lead to enhancement in the DBTT. Similarly, if we are doing strange ageing or for that matter any kind of ageing, which typically leads to an enhancement in the grain size and once again if the grain size has been increased, that can increase the ductile to brittle transmission temperature also. So we have to be careful while pursuing these different heat treatments.

Typically for the martensitic steels, we prefer to perform some kind of tempering operations and that yields the best combination of strength and toughness. Often we cannot obtain the maximum value of strength or maximum value of toughness because most of the cases these two are inversely related strength and toughness. So, we have to deal with an optimum combination of the best possible combination of properties if we perform the tempering.

And increasing the tempering temperature also increases the impact energy absorption. So, these are some of the example shown for different categories of steel all having the same carbon content of 0.4 percent and hardness of each of these steels, different grades, but still having the same value of the hardness, the Rockwell hardness of 35 and they had been tempered and what we can see here, like if we are comparing the 20 Joule impact energy which is the T_4 DBTT.

So, there we can see that a variation of around 200 degrees Centigrade can be obtained if we are using different kinds of tempering operations. So, what we can see is, let's say this one here, which belongs to the category 5145 I guess, having this 20 Joule energy of lesser than minus 150 degrees Centigrade actually close to 170 or 180 degree Centigrade. And on the other hand, if we are talking about the same form of energy for this one here, which is 1340 we can see that, that leads to much higher DBTT of something like close to minus 100.

So, there is a huge jump in the ductile to brittle transition temperature, if we even if we are talking about the same amount of energy consumption for the differently treated steel. We can verify this for some other energy level also for the different categories.

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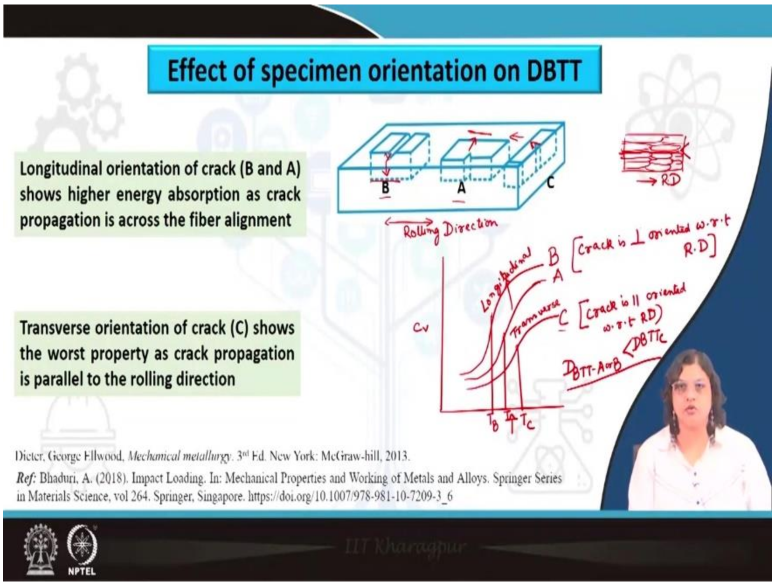

Now, another important way by which DBTT can be controlled or which typically shows some effect on the anisotropy of the behavior is the specimen orientation. Now, this is an example shown here, this is a rectangular billet or some structure which has been rolled along this direction, so, this is the rolling direction. And if we have some rolled structure, we also know that everything like all the grain structure, all the microstructure parameters, inclusions or any kind of defect everything will be aligned along the rolling direction.

So, internally this will have something like this elongated grains or the sausage shaped grains, which signifies that rolling has been obtained or rolling has been performed along this direction and in between, if there are any inclusions, that also will be aligned along this direction because along the direction of the rolling, we have used the deformation we have applied the energy and whatever working that we have applied at a higher temperature. So, everything will be aligned along this direction.

Now, if we are using this sheet or thick rectangular block and we are making some component out of it with the correct orientation being either perpendicular or parallel to the rolling direction, that may have a significant influence on the overall deformation behavior and the fracture behavior the impact toughness properties. So, we can see here three different ways by which components can be designed out of this block, either it could be along the rolling direction, so, you can see that the crack is along the direction of the rolling.

On the other hand, for the case of A and B crack is perpendicular to the rolling direction. So, in this case for the case of B, this is the way crack is supposed to grow and this is the rolling direction, so, it is perpendicular. Similarly, for the case of A also the crack is supposed to grow in this direction and the rolling is perpendicular to that right and because of that, we are going to see some differences in their DBTT curve.

So, let me draw here once again the CV versus temperature. So, this is the impact energy and this is the temperature curve. And what we can see now, is that there could be significant differences in the ductile to brittle transition behavior. Now, this could be for C for sure, the one in which the crack is oriented along the direction or parallel to the direction of the rolling that way it will be quite easier for the crack let us say if we have a crack here, it will find it quite easier to move and to grow along the direction of rolling so that it can grow through these boundaries whatever the defect areas are there and that can lead to early fracture.

So, this one will having or will require lower amount of energy to fracture for sure, an A and B both will be having actually higher or absorbing higher amount of energy for fracturing and there will be some competition between which one will achieve the most and that also depends on the specimen geometry and the specimen dimension as well as the dimension of the microstructure features anything which is there, but this is what we are typically seeing here that both B and A are having higher fracture energy or higher impact energy compared to the one in which the crack is perpendicularly or the crack is parallelly oriented.

Or in other words, we can also say that both for the case of A and B in which crack is perpendicularly oriented with respect to rolling direction, the DBTT will be also low so, this to our for example, for T_B and T_A and for the case of T_C this comes something like this. So, C in which case the crack or notch is parallelly oriented with respect to rolling direction this is what we can see that DBTT for A or B is less than DBTT for C.

So, this is eventually what we are seeing that is what is explained here that in case that it is longitudinally oriented, so, this one here is longitudinal both A and B. And in this case, higher energy absorption will be required as the crack propagation is across the fiber alignment.

Now, fiber alignment is this, the microstructure features the way it is being aligned is like a fiber that is why it is called fiber alignment. And if it is perpendicular to that, or across that, that will lead to higher energy requirement. On the other hand, if there is a transverse orientation, so, C here is having transverse orientation that will show the worst property as the crack propagation is parallel to the rolling direction.

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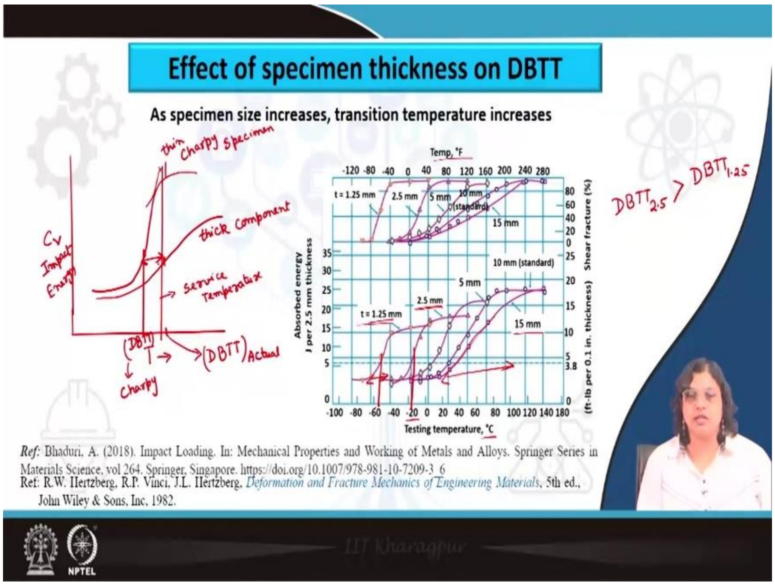

Now, apart from the orientation, thickness also has a major influence on the ductile to brittle transmission temperature and what we can see here from this slide, we can see that there are some experimental results shown for the different thickness of material starting from thickness of 1.25 up to 15 millimeter and very clearly if you look into this the curves below are in centigrade, where the temperature is measured in centigrade whereas, the curve at the top are the same results but in which the temperature is represented in Fahrenheit.

So, let us consider the one which is having a thickness of 1.25 millimeter versus the one which is having a thickness of 2.5 millimeter, so, just twice the value and we can very well see that the ductile to brittle transition temperature increases significantly for the case of 2.5 which is around minus 20 degree centigrade. So, this is just one example, for DBTT of 2.5 is actually much higher than DBTT for 1.25.

And we can verify this for even 5 millimeter 10 millimeter thickness and we can see that there is a huge difference. In this case it is varying from almost minus 60 to -20. So, 40 degree variation in the DBTT just if we are increasing the thickness from 1.25 to 2.5 just the double, but if we are doubling this thickness of 2.5 to 5, we can see that even further jump and not only that, once again the nature of the curve is also changing.

If we are changing the thickness by an order of magnitude, so, 1.25 to let us say 15. We can see that the nature of the curve in this case is completely different, it has much shallower slope, which means that the ductile to brittle transition is happening over a huge range of temperature compared to this 1.25 which is happening over a very narrow range of temperature.

Now, this leads us to a problem in the sense that if now, we are talking about the experimental results that we are getting from lab scale testing versus the service requirement, let us see that how it will look like. So, this is the typical Charpy impact test result that we can get, let us name this as thin Charpy specimen, this is what we get. And in case we are talking about the component which is much thicker now, thick and thin are once again a relative term we have already seen that how thick and thin could be different.

If we are changing the perspective, but what I mean here is that if we are using much bigger and thicker component in service, it will show something like this, thick component and in comparison to that if we are talking about a lab scale testing of a Charpy or the impact energy for that matter, we can see that there is a huge difference in the ductile to brittle transition behavior overall.

And now, if we are talking about a service temperature something like this, for example, this is the service temperature can we need to apply this component at a certain temperature something like this. Now, if we are predicting the value from the lab scale testing, what we can see is that the DBTT is somewhere here. As per this 50% deformation concept, so this is the DBTT for the thin one for the Charpy one.

And on the other hand for the thick one, the DBTT could be actually even higher than that. So this here could be the DBTT for the actual component and this one is for the Charpy. Now, if the service temperature is higher than the DBTT, as we are seeing this for the Charpy, we can see that there are significant differences between the DBTT that means that at service temperature, it is not supposed to fail in a brittle manner.

And we expected that behavior, but in the actual practice, what we can see is that if you are using a thicker component, the DBTT is actually even more than the service temperature or almost comparable to the service temperature. So, that means that it has a total chance of failure as a brittle mode in the service and that can lead to a significant failure catastrophic even which is always undesirable situation. So, we have to be careful about these factors while designing a component and while doing the testing in the lab scale.

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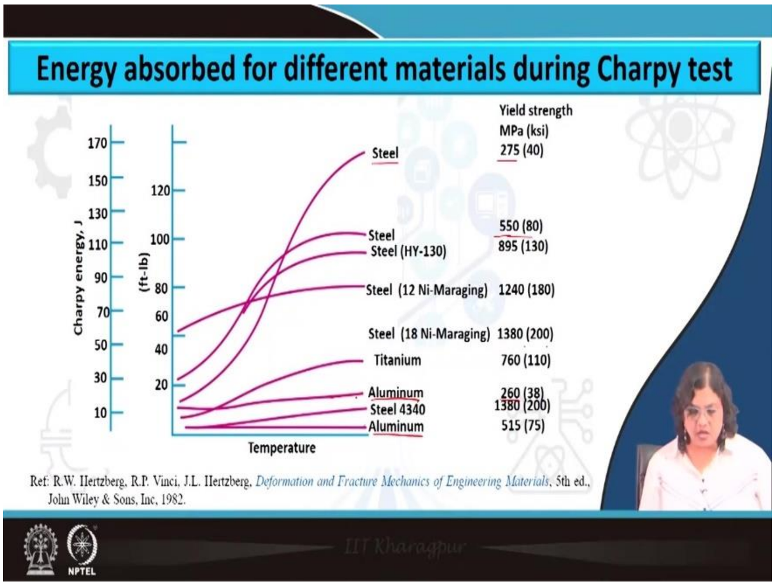

So, this is an example of the experimental results for different categories of material. And what we can see in general is that if the yield strength of the material is increasing, that means that it will require lesser energy to fracture or it will have lower fracture energy or lower toughness. For example, even for the same categories of material for example, steel, we can see that the one which is having the yield strength of 275, this one here shows a very decent ductile to brittle transition behavior.

And in comparison to that if we are just checking for the next one, which is having yield strength of double that value, what we can see is that it requires lesser energy even in the highest temperature range which means that it is fully ductile even then it requires lesser energy or the fracture toughness value is lesser for the steel and this we can keep on verifying.

Of course, these are experimental results. So, there could be some discrepancies, but I thought of showing this just to give an idea that how things are changing. Similarly, for example, Aluminum if we are seeing this the one at the bottom curve is Aluminum and you can see that there is not much difference in the ductile to or ductile or brittle mode of failure this is actually whatever is the mode that is consistent with the enhancement in temperature it is not varying at all.

And it is anyway quite lower value that we can see here. However, if the yield strength of this is half the value, we are seeing that it is absorbing higher amount of energy. So, this depends on how much energy is required for fracture that depends on the inherent structure of the material, but if you are comparing between the same material, we can see that higher the yield strength lower will be the fracture energy.

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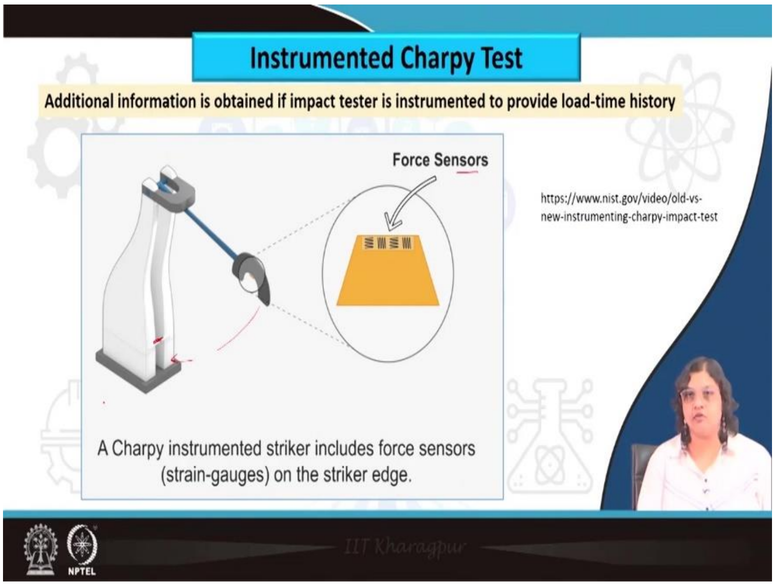

So, this is how we can figure out the ductile to brittle transition temperature and how we can change that based on the service requirement. Now, we have also seen that the way that we are predicting it in the lab scale may not be always appropriate. So, we need further and further information. So, we will be elaborating a little bit more on what are the different ways by which the impact energy can be determined.

So, this one here shows an instrumented Charpy test. So, this is once again a Charpy test, but this is an instrumented one. So, when I say instrumented, it basically means that it has some sensors, some additional sensors, which are typically there at in the pendulum section itself. And the reason that the sensor or the purpose of the sensor is that it can figure out the amount of load that is varying with the time we can see the specimen also kept here.

So, this is the specimen and this is what the pendulum is going to hit the specimen and then it will absorb the energy and it will fracture and from the fracture mode or from the fracture surface appearance we can say what kind of deformation it is.

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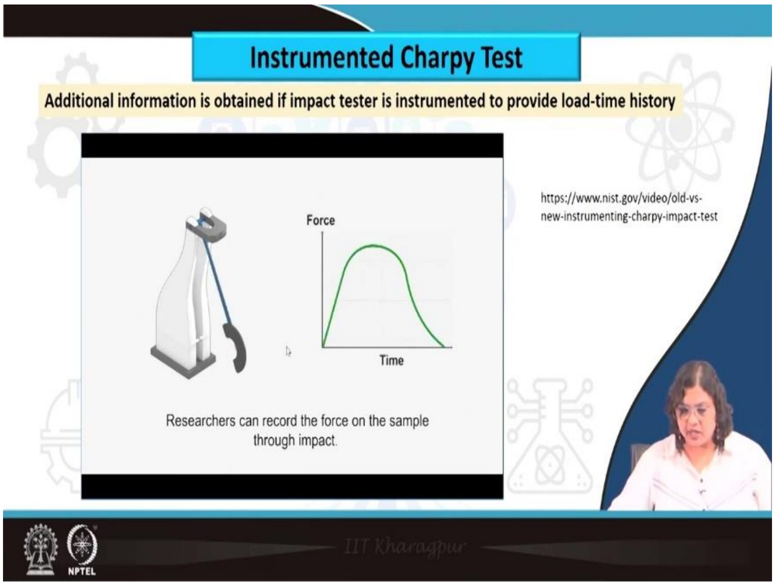

So, we can see that because of the presence of this sensor, we can get the force versus time curve, and if we are getting this force versus time curve, we actually can get a lot of other information from there.

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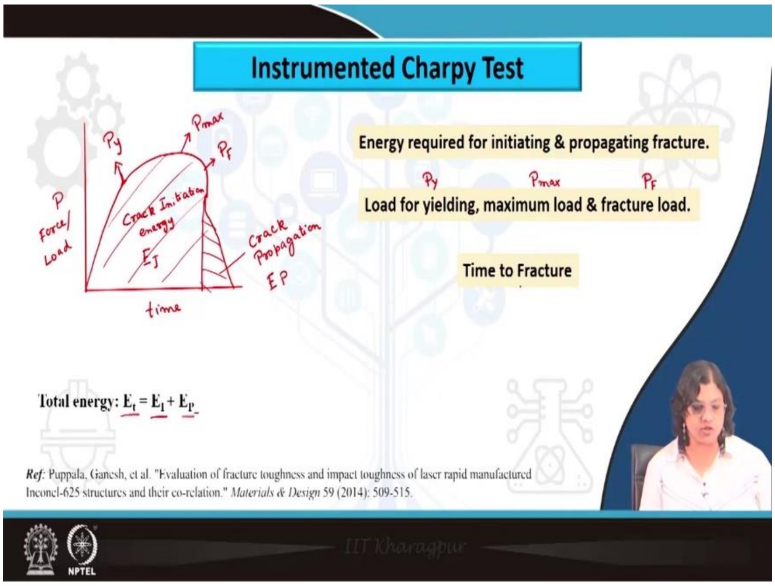

First of all, what we can determine if we are getting the force versus time curve is something like this. So, we can see that if we are having this load or force versus time what we can see is a behavior something like this and can fracture. So, basically, we can find out the load that is required for yielding, let us name this as P_Y. So, this is the load for yielding at which the yielding behavior of the specimen has started.

And then we can also figure out the maximum load that has been absorbed by the specimen, and the load at which the fracture has started fracture means the elastic kind of fracture that will happen here. So, that is the P_F and all this can be precisely quantified from this load versus time curve. Not only that, we can also figure out the amount of energy that is required for the crack initiation, initiation means, the machine notch will initiate to grow so, that is the crack initiation and the area under the curve will give you the energy.

So, this is the overall crack initiation energy let us name this is E_I, this overall area under the curve and on the other hand, this one here will give us the crack propagation energy. So, we can very well quantify this term and we can also obtain the total energy we can see that major part of the energy is being used for initiating the growth of the crack and a minor part is actually used for propagation because this is more or less like an elastic fracture, it takes no time to fracture almost no time to fracture, but we can figure out the total energy and of course, the total time to fracture.

So, that means from the simple Charpy test that we have done so far that has been discussed, so far, we could have obtained only just the energy value and then we can do all the associated investigation based on the fracture surface and we can determine the fracture mode. But if we are doing this in the instrumented way, we can get this additional values and we can quantify in a much detailed manner and accordingly we can obtain the results and we can predict the situation in a better way.

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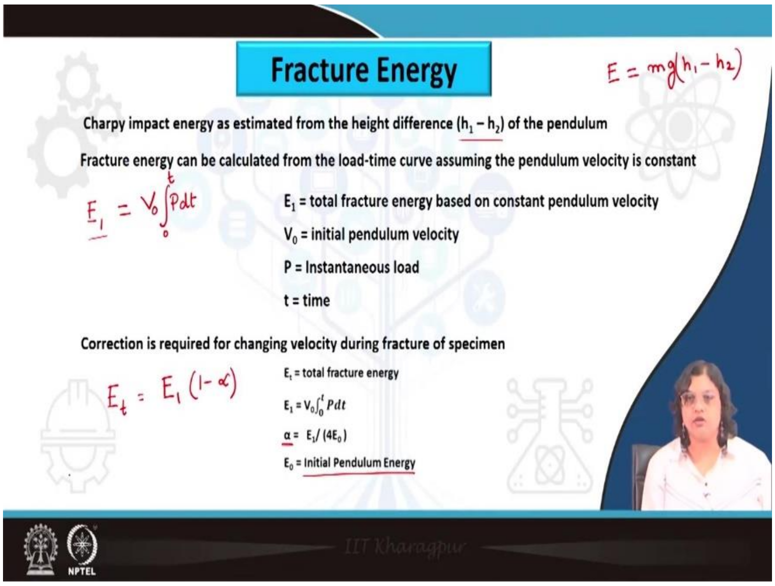

So, let us see how this energy is now calculated. The typical Charpy impact energy is dependent on the height difference of the pendulum we have already seen that how that energy is determined is based on this $E = mg(h_1 - h_2)$, h_1 and h_2 is the initial height of the pendulum and the final height of the pendulum. But in case we are having this instrumented one, then we can actually find out the energy in a more detailed way like we have this E_1 is given by the velocity of the pendulum multiplied by this area under this curve.

So, if we are doing this $E = V_0 \int_0^t pdt$ that will give us area under this curve multiplied by V_0, the initial pendulum velocity will give us the overall energy and P at any point is the load at that point of time, but this will require a correction because velocity is, velocity of the pendulum is not going to be constant right it is continuously changing, we also have to take that into account and for that we need to implement a correction factor.

So, basically we will be getting this $E_t = E_1(1 - \alpha)$, where α is the correction parameter and this is nothing but a ratio of E_1 / 4 E_0 , where E_0 is the initial pendulum energy. So, initial pendulum energy we will get from the instrument itself and if we have that we can figure out all the other parameters we can calculate the E_1 and from there we can get the alpha value and if we have that, we can get the Et value also, quantify each and every term there to figure out the amount of energy required.

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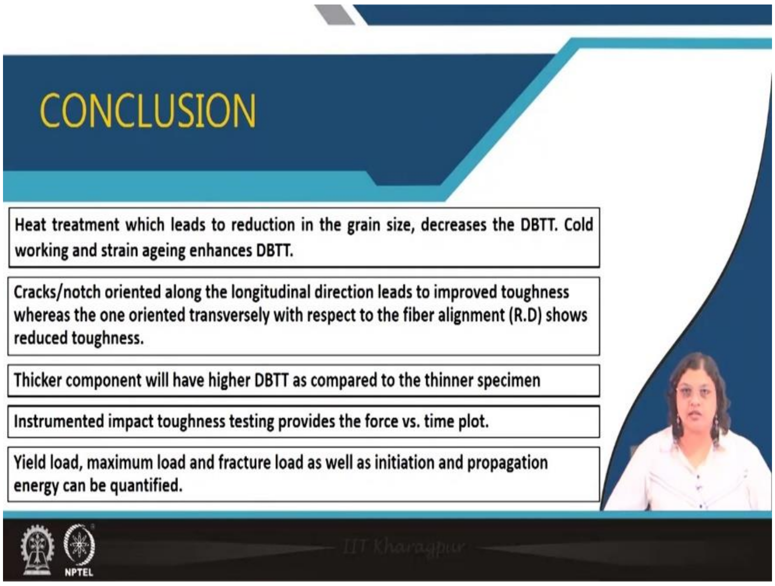

So, as a conclusion to this lecture, we have seen that any kind of heat treatment which leads to reduction in the grain size or grain refinement actually leads have a positive effect and it leads to reduction in the ductile to brittle transition temperature.

So, for that matter if we are pursuing the hot rolling at a comparatively lower temperature or if we are performing the normalizing treatment after the hot rolling or quenching or cooling it at a higher rate after normalizing all this can refine the grain size and lead to a reduction in the ductile to brittle transition temperature.

On the other hand, if you are performing cold working or any kind of ageing treatment, which can coarsen in the grain structure, and that can lead to an enhancement in the ductile to brittle transition temperature.

If we have the cracks or the notches oriented along a direction, which is along the longitudinal direction that means perpendicular to the direction of rolling or any other kind of processing that has been applied, then, that will require a higher amount of energy for the crack to propagate and finally, lead to fracture.

On the other hand, if we have the notch or the defect oriented transversely with respect to the rolling direction or the direction along which the microstructure has been aligned, that practically leads to a lower value of toughness or the lower amount of energy it can absorb. So, while designing a component or a structure we have to keep this in mind and we have to consider this so that we do not obtain anisotropy in the behavior.

We have also seen that a thicker component will have higher ductile to brittle transmission temperature as compared to the thinner specimen the one that we are using typically for the lab scale testing. So, this is a very important factor while designing a component to consider the right size for the testing even when we are doing this in the lab scale and not only the ductile to brittle transition temperature that is getting affected by this even the trend for the ductile to brittle transition is also getting affected.

We have seen that a thicker component will have a larger span of temperature over which this ductile to brittle transition is changing. We have also seen that in case we are pursuing the test or executing the experiment using an instrument or instrumented machine that can provide us the force versus time plot.

And if we can obtain that we can quantify all the different parameters such as the amount of load required for yielding and the maximum load as well as the fracture load when the fracture has actually commenced and the propagation energy and the initiation energy all this can be determined from such kind of instrumented test.

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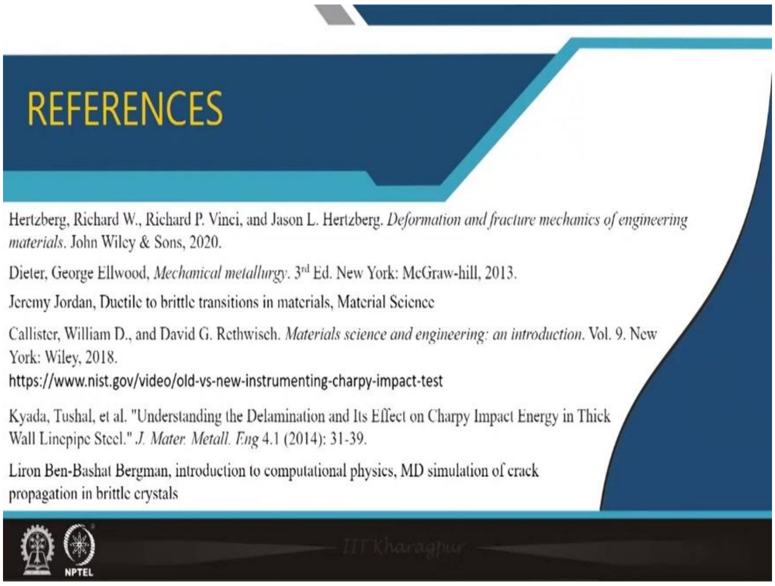

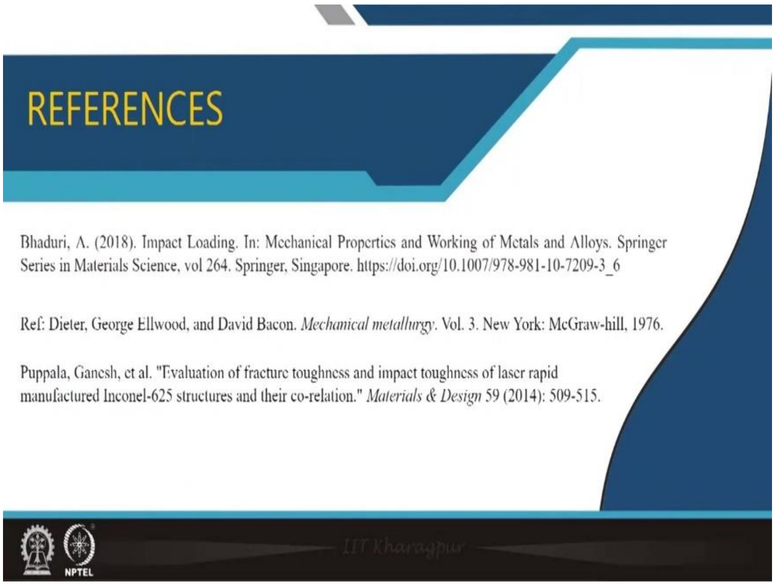

These are some of the references used for this lectures. Thank you very much.