Fracture, Fatigue and Failure of Materials
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Lecture 19
Impact Toughness (Contd.)

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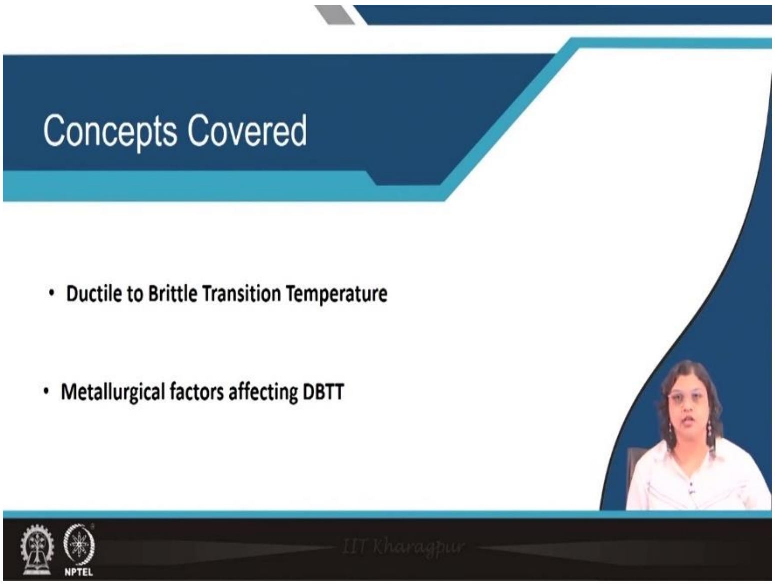

Concepts Covered

- Ductile to Brittle Transition Temperature
- Metallurgical factors affecting DBTT

Hello everyone and welcome to the 19th lecture of this course fracture fatigue and failure of materials. In today's lecture also, we will be talking some more about the impact toughness. The concepts that will be covered in this lecture are the following: we will see that how ductile to brittle transition temperature can be quantified what are the different ways and what is the most conveniently used one and then we will see that what are the factors by which we can control the ductile to brittle transition mechanism or the ductile to brittle transition temperature.

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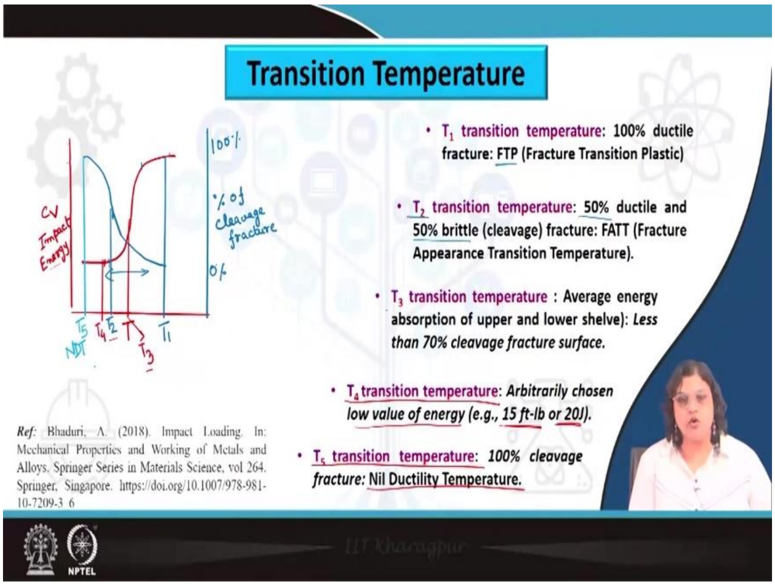

Transition Temperature

- T_1 **transition temperature**: 100% ductile fracture: FTP (Fracture Transition Plastic)
- T_2 **transition temperature**: 50% ductile and 50% brittle (cleavage) fracture: FATT (Fracture Appearance Transition Temperature).
- T_3 **transition temperature** : Average energy absorption of upper and lower shelve): *Less than 70% cleavage fracture surface.*
- T_4 **transition temperature**: *Arbitrarily chosen low value of energy (e.g., 15 ft-lb or 20J).*
- T_5 **transition temperature**: *100% cleavage fracture:* Nil Ductility Temperature.

Ref: Bhaduri, A. (2018). Impact Loading. In: Mechanical Properties and Working of Metals and Alloys. Springer Series in Materials Science, vol 264. Springer, Singapore. https://doi.org/10.1007/978-981-10-7209-3_6

So, let us move on to the transition temperature. We have seen that there are some materials which undergo severe change in the failure mechanism from the ductile behavior which is at higher temperature and at low temperature it fails in a brittle manner. And we have also seen that, if we perform the Charpy impact test, we can figure out the energy that is required for failure in the ductile mode as well as that under brittle mode at the different temperatures and from there, we can figure out that there is a transition happening over a range of temperature.

So, let me just draw this curve, so, the y-axis here is the energy we can also use the term C_V for the energy and the x-axis is the temperature and we have seen that for those materials which undergoes ductile to brittle transition, it shows S shaped curve, we have also seen that from the fracture surface, we can quantify the mode of brittleness, the extent of brittle failure, we can find out the shear lip width or the percentage of cleavage and by that way also we can try to find out the transition regime.

And we are putting the y_2-axis as the percentage of cleavage fracture. So, cleavage fracture signifies that it has failed in a brittle manner that means, that at lower temperature it is supposed to have 100 % cleavage fracture whereas, at higher temperature when it fails in a ductile mode there will be no cleavage fracture at all. So, if we are plotting this over a range of 0 to 100 % this will look something like this. So, this is 0 % and this is 100 %.

Now, if we try to find out the temperature the first one is already written here, we can do it in several ways. First of all, we have seen that the temperature range over which this ductile to brittle transition is happening is varied over this range. So overall, a temperature range of something like this, when this transition is happening, where there is a significant difference in the amount of energy that is consumed for the fracture.

So, it is quite difficult to specify one particular temperature as the ductile to brittle transition. So, there are several ways to do that, there are standards which are followed worldwide, so, that there is no confusion in that. There are actually five different ways by which this ductile to brittle transition can be quantified the first one known as the T_1 transition temperature is based on 100 % ductile fracture.

So, that happens at in at the higher temperature when there is complete ductile failure, which means that there is 0 % cleavage at all. So, that makes us this temperature as the T_1 also known as fracture transition plastic. So, if we just use this term that the FTP of a material is some temperature we will obviously know that that means a complete ductile failure totally 100 % ductile failure and that is the maximum energy that this material can consume to fail. So, that is the highest value of toughness that we can obtain at this temperature.

Secondly, the next mode is to find out the T_2 transition temperature and this is based on 50 % ductile and 50 % brittle failure. So, if we are then considering this blue curve based on this we can find out the exact temperature at which there are 50 % has failed by ductile mode and 50 % by brittle mode which means that there is a mixed mode kind of transition.

So, this signifies the T_2, the exact nature of this curve and the exact shape of this curve may vary from material to material and we have to do the experiments to figure this out more precisely. Coming to the next way by which the transition temperature can be obtained, there is the T_3 transition temperature which is based on the average energy absorption. So, that is based on the red curve.

So, let me change the color of the pen once again which means that if this is the amount of energy consumed, when it is fully ductile and this is the amount of energy consumed when it is fully brittle, then what is the intermediate the average of the energy, 50 % of the energy that is consumed based on that that T_3 temperature can be obtained.

So, accordingly this one here represents T_3, now, this T_2 and T_3 typically are quite close, they may be similar, there can be some differences, because these are just two different ways by which we are figuring out the temperature. And obviously, there will be some scatter in the results also we have to take that into account, it is noteworthy that each of this curve this red curve or the blue curve can be obtained if we do multiple number of test.

So, that means that if for the same specimen for the same material, same specimen dimension, if we do multiple number of tests, we can just make one curve. And then again if at each particular temperature if we are using multiple specimens for each conditions, there will be some scatter in the results also. So, when we do the experiments, we have to take care of those scatters also if it is too much, we often need to repeat the experiments to come to a final conclusion.

We often use the mean value and then we also quote or we also show the standard deviation which signifies the range of over which the data has been scattered. So, based on that, there could be some differences in the T_2 and T_3, also the mode by which T_2 and T_3 are determined are also different T_3 is just based on the reading that we are getting from the instrument based on the energy whereas T_2 is based on the microstructural or the fractographic investigations that we have done after the experiments. So, there could be some discrepancies or some differences in these two numbers.

Then comes the T_4 one and practically this one is the most widely used temperature as DBTT. So, in case that nothing is mentioned, whether this is T_1 or T_2 or something like that, it is just mentioned that the DBTT of a material is some temperature, we assume that this is the T_4 transition temperature, this is considered based on an arbitrarily chosen low value of energy. So, this is around 20 Joule or 15 foot pounds.

So, that means that this amount of energy from metallic systems means that this is quite low and this will lead to brittle failure and in case we want to find out that how a material will behave at different temperatures we are interested to know particularly that when it will behave or it will fail in a brittle mode. So, for that this kind of particular energy comes very handy and we often go ahead with this 20 Joule number.

So, again based on this red curve, we can figure out what this T_4 could be. So, let us say this is the T_4 and we can write this as T_4. On the other hand, there is one more way by which we can figure out the transition temperature which is the T_5 transition temperature also known as Nil Ductility Temperature, this signifies a total cleavage fracture. So 100 % of cleavage fracture, which means just the end of this curve that signifies 100 % of cleavage fracture or this is the NDT temperature, Nil Ductility Temperature.

So, this T_1 and T_5 are then the range over which the transition is happening T_1 signifies complete ductile failure T_5 signifies complete brittle failure and T_2 and T_3 is like average of that halfway when there is ductile mode and brittle mode mostly 50 % ductile 50 % brittle and T_4 is most conveniently used as a particular one the DBTT that is required for the brittle fracture to occur. So, now that we know about the transition temperature.

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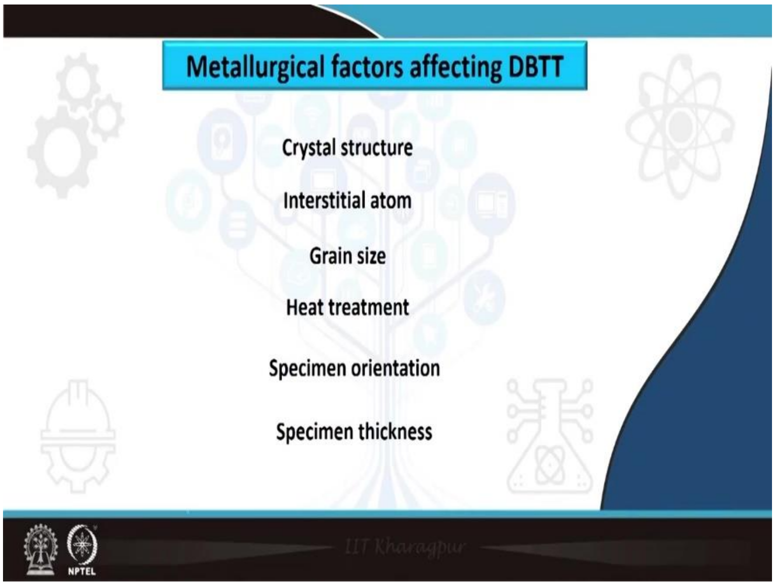

Metallurgical factors affecting DBTT

Crystal structure

Interstitial atom

Grain size

Heat treatment

Specimen orientation

Specimen thickness

Our next target as metallurgist or as an engineer would be to control that, we want to know the mechanism behind any kind of mode of fracture with the primary aim to control that, to manipulate that based on our service requirements. So, that we can change this DBTT as per the requirement and then we can achieve the expected performance of a material. So, of course, there are different ways by which we can control that or we can modify that and the first one is the crystal structure.

Now, crystal structure of different materials are different. There are different kinds of lattices like hexagonal close packed or body centered cubic, face centered cubic etc typically seen in metallic systems and this also is dependent on the ductile to brittle transition temperature in the way that any kind of deformation or any kind of fracture typically occurs if there is change in the crystal lattice itself, because there is a change in the dislocation mode and that is being controlled by the lattice friction.

Different crystal lattices will have different kinds of inherent lattice friction or the peierls stress and that will lead to the fracture behavior being completely different from one another. So, we will see that how different crystal structures lead us to different ductile to brittle transition and the next one is the interstitial atom.

Often interstitial atoms are added and particularly, this is very significant for the case of steel based material and the whole the concept of impact energy as we have discussed in the last lecture that the impact failure or the sudden kind of brittle failure ductile to brittle transition, this has been noticed, when there were failure incidents of this liberty ships, those were all made of steel.

So, a lot of studies has been done during that period and even now, on the steel, different categories of steel which are used for shipbuilding or any such applications which require lower temperature. So, interstitial atoms like carbon for example, are often used in steels to enhance the hardness and several other reasons, and we have seen that this interstitial atoms control the ductile to brittle transition behavior in a big way. And we can actually modify the behavior or the transition if we are changing the content of this interstitial atom.

The third one is the grain size. Now, microstructure or the grains are something which controls almost all the mechanical properties of materials. So, grain size, a finer grain size versus a coarser grain size changes the strength, ductility, toughness, fracture fatigue all different kinds of mechanical properties. So, grain size is something which is of very much significance for the ductile to brittle transition as well.

And then, the next one is heat treatment. Now, heat treatment we often require different kinds of thermal processing or thermal mechanical treatment on the metallic systems or any other systems to achieve the targeted set of properties for the required application required service conditions. And this heat treatments in turn, changes the microstructure as well and as I have mentioned that microstructure controls the ductile to brittle transition. Similarly, by heat treatment, we can modify the microstructure which in turn will modify the ductile to brittle transition behavior of the material.

The next one is a specimen orientation, in which we are making the component out of the big billet that is also very much significant in dictating the behavior. Because, based on the orientations, there could be differences in the arrangement by which the grains or the inclusions or even the defects are arranged and if there is a change in that, that can also lead to variation in the ductile to brittle transition or the failure mode in a way

The next thing is the specimen thickness this we have also seen earlier for example, in the plane strain versus plane stress condition that thickness has a very, very big role very significant role to play in the fracture behavior, we have also seen that if the thickness or the volume of the component changes. For example, from the laboratory scale testing to the actual service condition that can lead to a huge differences in the fracture toughness values that has been determined through the lab, lab scale testing as well as whatever we are seeing in the actual service condition.

So, all these different factors can actually be controlled, so, that we can achieve different values of the ductile to brittle transition and different nature of the curve.

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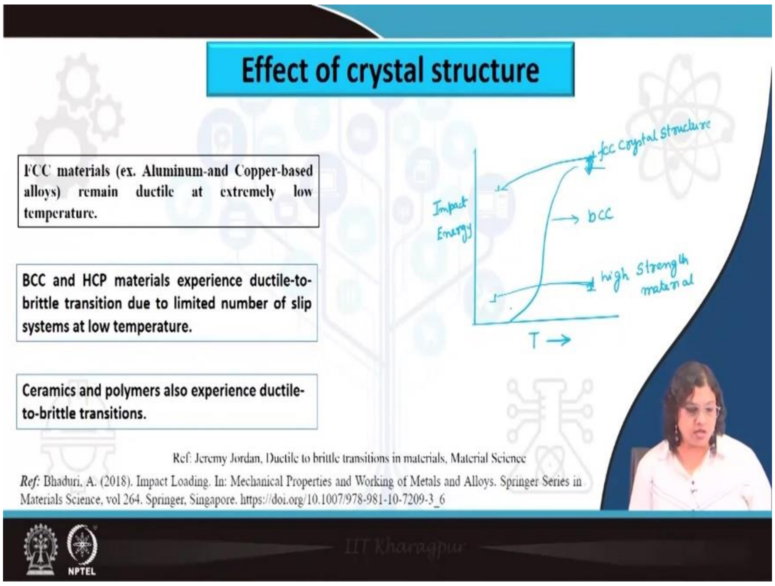

Effect of crystal structure

FCC materials (ex. Aluminum-and Copper-based alloys) remain ductile at extremely low temperature.

BCC and HCP materials experience ductile-to-brittle transition due to limited number of slip systems at low temperature.

Ceramics and polymers also experience ductile-to-brittle transitions.

Ref: Jeremy Jordan, Ductile to brittle transitions in materials, Material Science

Ref: Bhaduri, A. (2018). Impact Loading. In: Mechanical Properties and Working of Metals and Alloys. Springer Series in Materials Science, vol 264. Springer, Singapore. https://doi.org/10.1007/978-981-10-7209-3_6

So, let us start with the crystal structure one. So, once again let me draw the curve. So, the y-axis is the impact energy and this one is temperature x-axis. So, what we see typically for the most commonly obtain crystal structure is FCC or close packed structure for that matter. So, FCC materials typically shows high ductility even at higher temperature as well as lower temperature why because they have enough number of slip systems which makes the movement of the dislocation quite easy and that makes it ductile at almost all the temperature.

So, in such cases, we see a curve something like this. So, this is mostly for FCC crystal structure where FCC stands for face centered cubic, we also can see that there are some changes in the energy consumption or the toughness in general for example, at lower temperature till at higher temperature there is a minute amount of enhancement in the impact energy consumption and that is particularly because at higher temperature it is even more convenient for the dislocation to move it is getting the thermal energy which makes a motion of the dislocation quite easier and at a faster rate and that leads to higher ductility.

But this amount is quite negligible in case of a closed pack structure because they have any way enough number of slip system which makes the motion of the dislocations possible. So, this is something like this range is something like only of this much.

Now, for the other kinds of materials for example, the high strength material, they on the other hand shows very low fracture toughness value or very low consumption of energy because they have minimal flow of dislocation particularly because they have very high strength of the material and that once again is inversely related to the toughness of the material strength and toughness are always most of the cases inversely related except for one condition which we will highlight later on.

So, there also we see a similar kind of trend like we have seen for the FCC, but with the lower consumption of energy. So, this is for high strength material.

And here, what we can see once again is that there is a nominal changes in the total energy consumption from low temperature to high temperature, but this difference is very, very insignificant it is not that much significant one as we notice for particularly for the BCC crystal structure or in some cases some kind of ceramics and polymers also do show the transition, which has a behavior something like this the S shaped curve which are typically seen for the BCC or the body centered cubic crystal structure because they have a complete, they do not have enough number of slip system and that makes all the difference.

The peierls stress value is low and that makes the difference at low temperature versus high temperature. At high temperature anyway, they overcome this difficulty, because the thermal energy is acting positively to enhance the dislocation motion which makes the material ductile. But at lower temperature when this thermal energy is absent the lattice makes it challenging for the dislocation to move through and that makes it brittle at low temperature.

So, this is particularly the effect of crystal structure and that is dictating the ductile to brittle transition. Now, crystal structure of a material are something which are inherent nature of the material whether the lattice will be of FCC or BCC that is an inherent property of the material.

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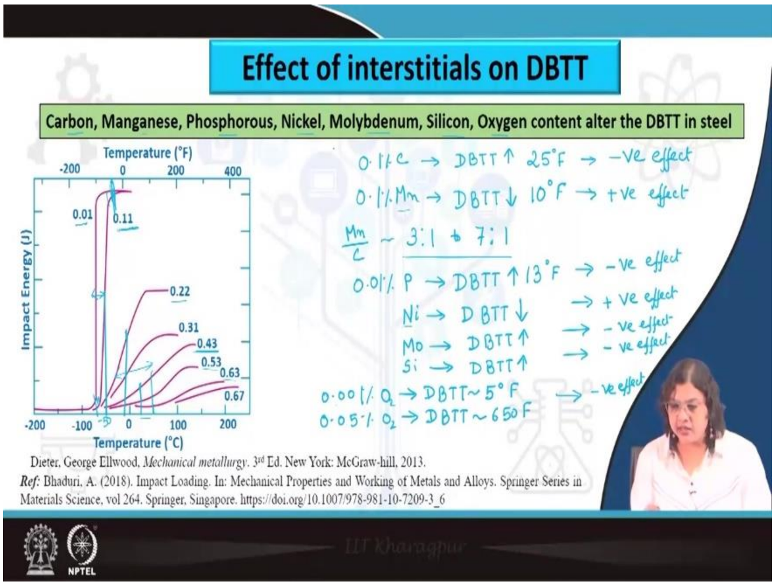

Effect of interstitials on DBTT

Carbon, Manganese, Phosphorous, Nickel, Molybdenum, Silicon, Oxygen content alter the DBTT in steel

$0.1\% C \rightarrow DBTT \uparrow 25^\circ F \rightarrow -ve$ effect

$0.1\% Mn \rightarrow DBTT \downarrow 10^\circ F \rightarrow +ve$ effect

$\frac{Mn}{C} \sim 3:1$ to $7:1$

$0.01\% P \rightarrow DBTT \uparrow 13^\circ F \rightarrow -ve$ effect

$Ni \rightarrow DBTT \downarrow \rightarrow +ve$ effect

$Mo \rightarrow DBTT \uparrow \rightarrow -ve$ effect

$Si \rightarrow DBTT \uparrow \rightarrow -ve$ effect

$0.001\% O_2 \rightarrow DBTT \sim 5^\circ F \rightarrow -ve$ effect

$0.05\% O_2 \rightarrow DBTT \sim 650 F$

Dieter, George Ellwood, *Mechanical metallurgy*. 3rd Ed. New York: McGraw-hill, 2013.

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But, what we have more control on is the effect of the interstitial atoms that are being added for purpose. Now, there are of course, different need for which we add the interstitial atoms. Let us focus on some of the commonly used interstitial atoms which are used particularly for steels different grades of steels and which have some role on the ductile to brittle transition.

So, the commonly used interstitial atom for example is carbon. Carbon is the most widely used one particularly to enhance the hardness. Other than that, there are manganese, phosphorus, nickel all these have specific purposes for addition in the steel, molybdenum, silicon, oxygen, so, all these are being added sometimes, for example, oxygen are already present in the environment and that leads to the presence of oxygen in the structure also.

So, let us see how this influences the ductile to brittle transition temperature. So, coming to the first one the carbon the most commonly present interstitial atom, now carbon is a bad news for ductile to brittle transition, if we add carbon let me give you some numbers. So, let me say that if we are adding carbon by 0.1 % so, that will lead to enhancement of DBTT by 25 °F. So, every 0.1 % of carbon enhancement leads to enhancement of DBTT by 25 °F.

Now, this is again we have to find out the exact content of carbon that should be added, keeping in mind that the primary purpose or the primary reason of adding carbon if that could be hardness, so, if we are talking about both the hardness and the ductile to brittle transition, we often need to optimize the content.

So, overall, we also know that ductile to brittle transition temperature we always prefer to have it a lower value, so, that we can use it safely in service, which means that if it is increasing by any way if the ductile to brittle transition temperature is increasing that is a bad news. So, that means that it is a negative effect that the carbon is addition of carbon to steel is leading us to a negative effect.

And we will see that how much this could be. So, this is some of the experimental data which we can see. And if we just look into the values for example, 0.01 to 0.1 % of carbon enhancement, we can see that there is some change, some definite change in the transformation temperature, but from 0.1 to 0.2, 0.11 to 0.22 you can see that this difference is really drastic.

So, if the DBTT is for the case of 0.22 based on 50 % transformation is something like this, which is let us say minus 50 degree to almost 0 degree. So, that means that there is a very high amount of change in the transition temperature if we are adding carbon. Now, this is one of the thing. The other important observation that we can make from this graph is that the nature of the graph is also changing.

So, if again we are comparing between 0.11 and 0.22 we can see that this one there is a very drastic change from the ductile to the brittle. So, at this temperature it is completely ductile. And if you are changing the temperature by just 10 degree or even less, this could be there is the mode could be brittle. So, this transition is quite drastic.

On the other hand, for the case of 0.22 or this is even more apparent if you are talking about the higher carbon content, you can see that the slope is decreasing to a lot extent which means that the transition is happening over an entire range. Now, that is also sometimes not preferred, if we know the exact service temperature, we should make sure that this should be in the ductile mode.

So that there is no way that brittle failure can occur, but if it is happening over a very wide temperature range, and it is always not possible to control the temperature over such a range, such that there will be no brittle failure. So, for example, if we are talking about the service temperature of 50 degree. So, let us say we are talking about this 0.4 % carbon now, now, if the surface temperature is 50 degree and if there is a slight reduction in the temperature by even 5 or 10 degree we can see that the extent by which the brittle fracture will happen will increase.

So, that means that we have to be very, very careful about that. On the other hand, if we are talking about this 0.1 % and we know that this is the temperature for a complete ductile failure to occur and this is the temperature although the range is very narrow, we can make sure that this has to be used above 0 degrees.

So that no way there could be any brittle fracture occur for this 0.11 % of carbon. So, that makes often the steeper slope being preferred. So that we can have absolute control on the transition temperature and it will behave as per the expectation there will be no unpredicted failure.

Now, coming to the other element, for example, manganese, now manganese is actually a good news in the sense that if we are adding the manganese of the same content like 0.1 % it leads to reduction in the ductile to brittle transition, but only by 10 °F.

So, not as much potential it has as the carbon of course in the opposite way, but at least it is good news, that it reduces the ductile to brittle transition temperature, so, that means that it has a positive effect, which also means that we can use more and more manganese on the steel so that we can achieve lower ductility, but we also have to be careful that this content of the carbon or the content of the manganese is determined or finalized not only based on the ductile to brittle transition, but based on some other factors to other kinds of mechanical properties too and we often need to optimize that.

And for that, typically the Mn:C or manganese:carbon ratio is maintained to from 3:1 to 7:1. If we are increasing the carbon content or reducing the carbon content too much or increasing the manganese content too much, that will also lead to some additional problem and we will not attain the required performance that we were expecting and so, we have to vary this only within this range and not more than that.

Now, coming to the next one phosphorus, phosphorus actually, again some more numbers. So, if we are adding just 0.01 percent of phosphorus that leads to the enhancement in DBTT once again, so, it is like the carbon it is also enhancing the DBTT by around 13 °F. So, once again this is having a negative effect. So, we should be careful of adding phosphorus not too much.

Nickel, on the other hand, is having a beneficial effect. So, I am not giving any farther number because these are just statistics and this will also may vary from different categories of steel as well. So, I just wanted to give some idea about when we are seeing that DBTT is increasing or decreasing how much how effective that is.

So, in case of nickel, actually DBTT decreases. So that makes it once again a positive effect. Coming to the other like molybdenum as well as silicon both leads to enhancement in DBTT molybdenum is almost as potent as the carbon and silicon also typically leads to enhancement in the DBTT. So, both of these are having negative effect.

But nothing beats oxygen, actually oxygen being the most common element and often present in the atmosphere itself, it is almost always present in the steel and oxygen is really adding a negative effect to the DBTT in the sense that if the oxygen content is changing from 0.001 if the oxygen content is something like this DBTT is again I am giving some numbers DBTT is around 5 °F.

On the other hand, if the oxygen content is 0.05. So, that has a DBTT of 650 F. So, there is such a huge jump in the DBTT enhancement in the DBTT if we are changing the oxygen content from 0.001 to 0.05 only, so, definitely it has a negative effect. So, overall we are seeing that almost apart from manganese and nickel, the other elements are typically having a negative effect in terms of increasing the DBTT and we should be careful in adding this.

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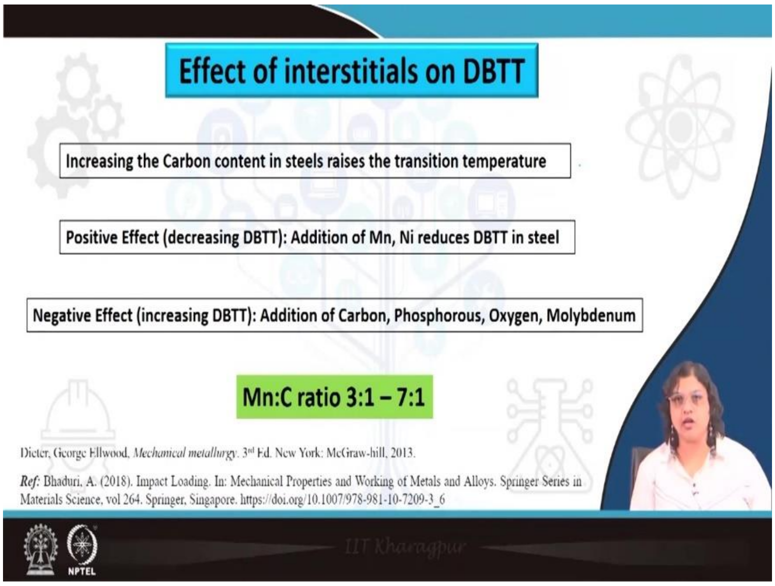

Effect of interstitials on DBTT

Increasing the Carbon content in steels raises the transition temperature

Positive Effect (decreasing DBTT): Addition of Mn, Ni reduces DBTT in steel

Negative Effect (increasing DBTT): Addition of Carbon, Phosphorous, Oxygen, Molybdenum

Mn:C ratio 3:1 – 7:1

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So, in a gist what we are seeing here is that increasing the carbon content in steel raises the transition temperature and there are of course elements like manganese and nickel which has positive effects. Whereas, there are elements like apart from carbon, there are phosphorus, oxygen, molybdenum, which has a negative effect on the ductile to brittle transition which means that it increases or enhances the DBTT.

And the manganese: C ratio is something manganese: carbon ratio we need to control so, that can be varied over a range of 3:1 to 7:1. So, that the typical DBTT the required one can be obtained from there.

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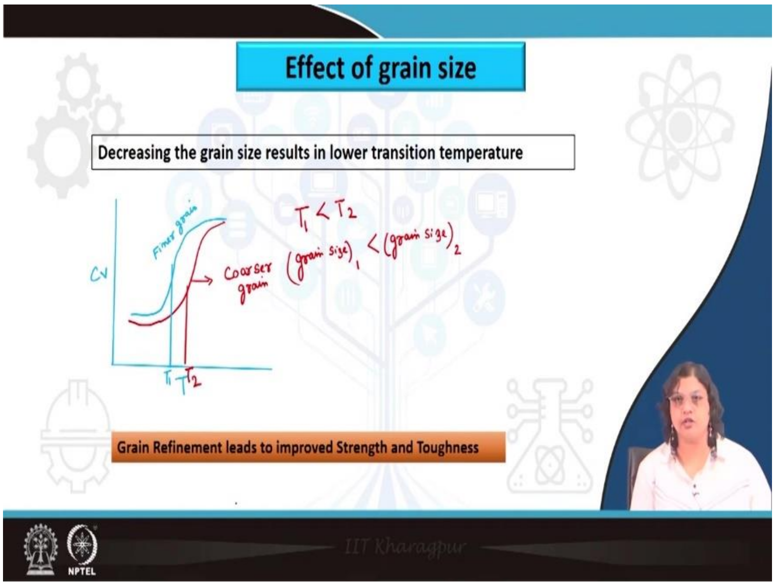

Effect of grain size

Decreasing the grain size results in lower transition temperature

Grain Refinement leads to improved Strength and Toughness

The next effect is for the grain size. In this case what we are seeing is that decreasing the grain size results in lowering the transmission temperature which means that finer grain size is adding a positive effect on the DBTT and this is particularly related to the effect of the correlation of grain size or microstructure size to the mechanical properties. Refinement in grain size actually leads to enhancement in the strength as well as in the ductility and that means that it is enhancing the toughness as a whole.

So, any kind of grain size refinement actually is a good news for toughness for even for fracture toughness and tensile toughness. And this we will see in more details later on in the other concepts of fracture toughness as well, but for impact toughness, we can see that this is what is happening if I am drawing this for the impact energy versus temperature and this is the one that is seen for a finer grain size material then for a coarser grain size material this could be something like this.

So, these are just schematic of course, not on scale, but this is the typical behavior that we can see. So, this is for coarser grain and this is for finer grain or refined grain. So, in this case, we can see temperature based on 50 % is DBTT is something like T_1 and for the case of the coarser one we can see the DBTT as let us say T_2 and we can very well see that $T_1 < T_2$ why because grain size of 1 is lesser than grain size of component 2 and that makes us this difference.

So, for the same material, same specimen dimension or the component dimension everything else remaining same, if we just manipulate the grain size if we just refine the grain size, we can achieve lower values of DBTT. So, that means that for any particular temperature we may achieve higher value of fracture toughness if that could be the reason that we need to refine the grain size.

So, this is an important factor which we often need to control to have some impact on the impact toughness itself, so, that gives the gist that grain refinement leads to improve strength and ductility and toughness in general.

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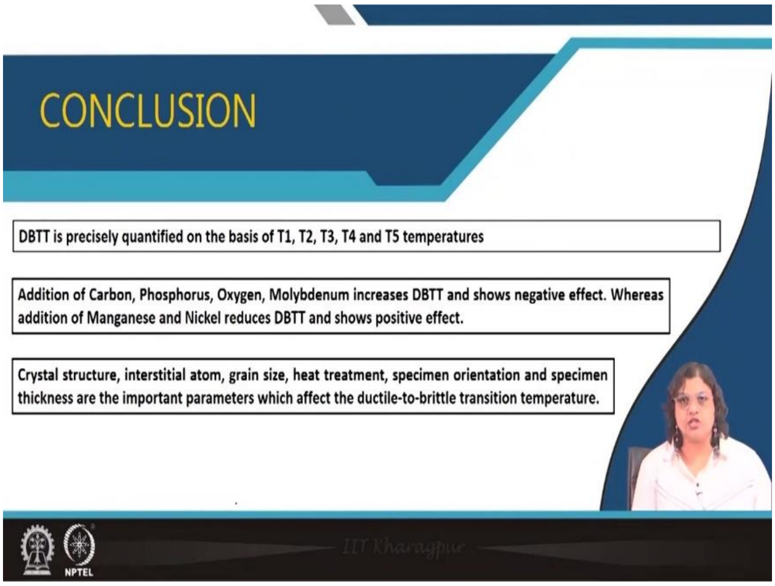

CONCLUSION

DBTT is precisely quantified on the basis of T1, T2, T3, T4 and T5 temperatures

Addition of Carbon, Phosphorus, Oxygen, Molybdenum increases DBTT and shows negative effect. Whereas addition of Manganese and Nickel reduces DBTT and shows positive effect.

Crystal structure, interstitial atom, grain size, heat treatment, specimen orientation and specimen thickness are the important parameters which affect the ductile-to-brittle transition temperature.

So, here is the conclusion for this lecture, that DBTT is precisely quantified on the basis of T1, T2, T3, T4 and T5 temperatures. And addition of different interstitial elements can alter the DBTT particularly we have seen that carbon, phosphorus, oxygen and molybdenum that increases the DBTT and that has a negative effect on the other hand manganese and nickel actually has a positive effect in the term that it reduces the DBTT and we can control that we can vary this manganese is to carbon ratio over a range of 3:1 to 7:1 to achieve the test or the optimized property.

And there are other factors like crystal structure, interstitial atom, grain size, heat treatment, all this can actually alter the ductile to brittle transition behavior which we will see in the next lectures.

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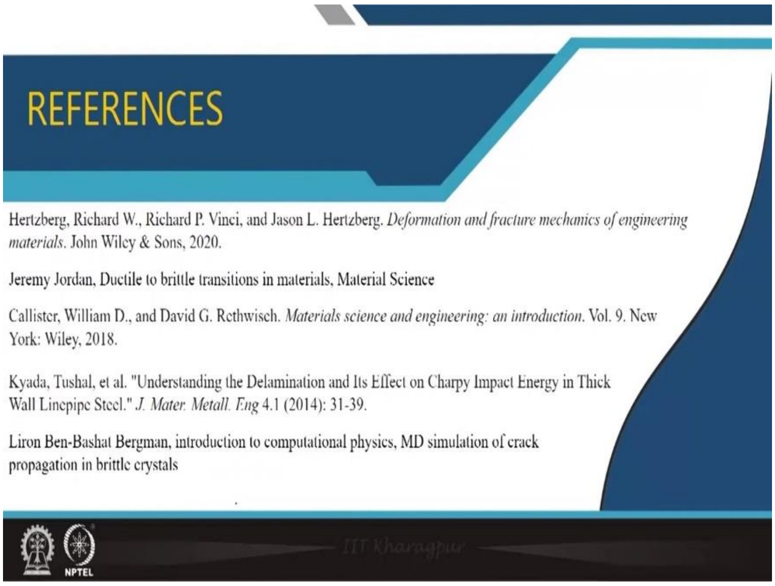

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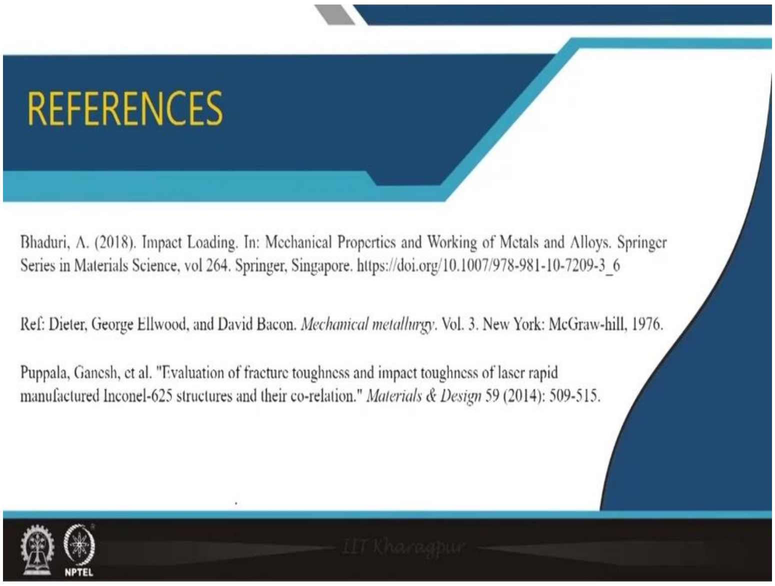

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And these are some of the references used for this lecture. Thank you very much.