Fracture, Fatigue and Failure of Materials
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Lecture 23
Fracture Toughness (Contd.)

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Hello everyone, we are here with the 23rd lecture of the course Fracture Fatigue and Failure of Materials. And today also we will be continuing the module 1 of fracture and the lecture will be typically focusing on fracture toughness of materials.

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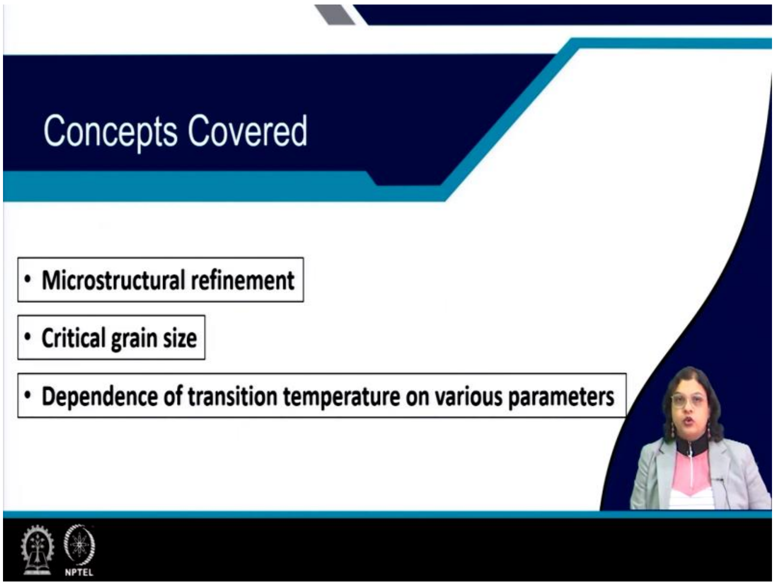

The concepts that will be covered in today's lecture are the following, we will see how microstructure refinement influences the fracture toughness of a material. And from there we will see what is the critical grain size based on which the fracture mode changes. And we will also look into the different factors that affect the transition temperature and how they are correlated.

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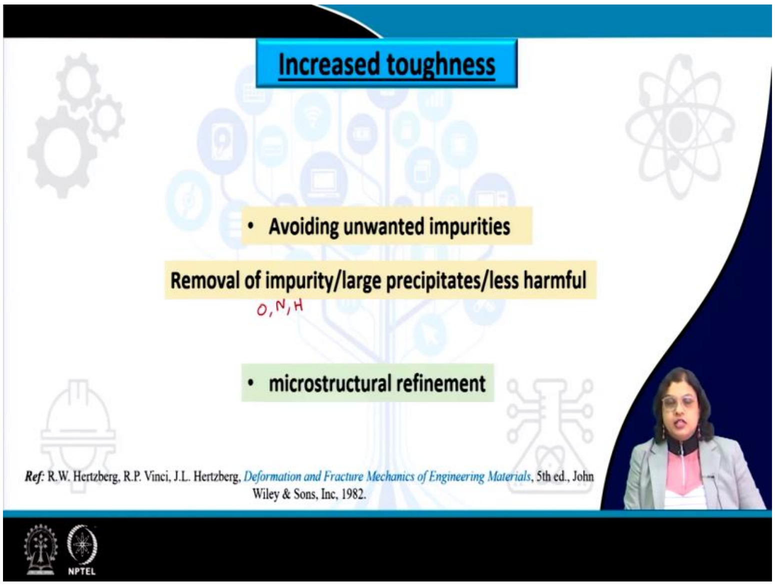

So, in the last lecture, we have seen that extrinsically or even intrinsically toughness of a material can be increased. And one of the way by which toughness can be modified is by varying the impurities which are not of any use particularly for the mechanical properties or the mechanical toughness of the material. And the way by which we can achieve a higher toughness is by removing some of these impurities for example, the oxygen content nitrogen or hydrogen that leads to some embrittlement we need to remove those as much as possible to achieve higher toughness.

On the other hand, we would also like to remove the precipitates which are very much coarser and which do not act as much as strengthening rather they act as the potential sites for the crack initiation and leads to early or unprecedented fracture. So, we also wanted to get rid of such kind of precipitates from the structure and if we are not able to remove the impurities or if it enhances the cost to a lot of extent, the very basic minimum thing that we can do is by making the impurities less harmful.

So, we have seen how we can add a little bit of rare earth in steel to make the rare earth sulfide, which are not melting at the temperature of hot rolling and that overall enhances the toughness as well as remove the anisotropy in the property. So, in this lecture today, we will see that apart from this way, the other way by which we can enhance the toughness of the material is through microstructure refinement.

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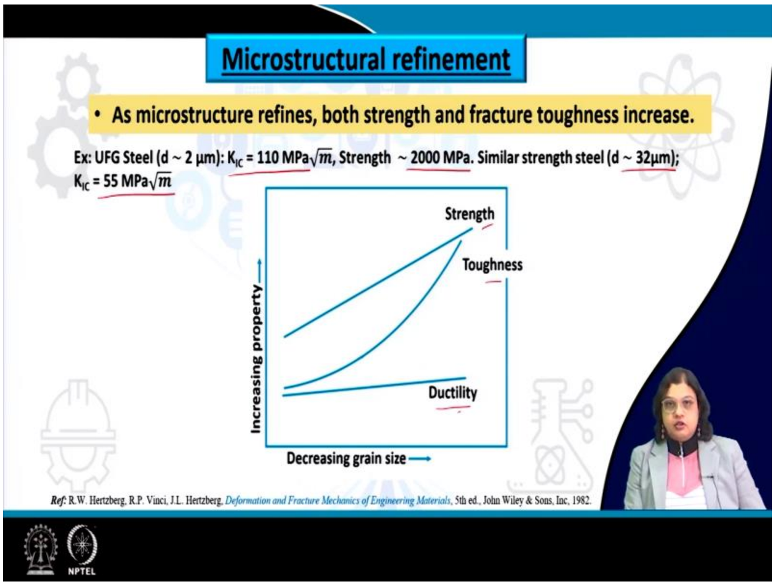

In fact, any kind of microstructure refinement be it a grain size or any other microstructure parameters such as the lab or colony sizes, that affects the mechanical properties of the material, if we are able to refine that, it actually improves not only the fracture toughness, but also the strength as well as the ductility. So, this is one of the mechanism by which we can simultaneously influence or increase the strength of the material as well as the toughness of the material.

And in turn we can get some enhancement in the ductility also and since strength and activity both are combining to give us the effect of toughness. So, we overall can see a enhancement in toughness as well. And just for instance, one example is shown here, which says that an ultra-fine grain steel which has a grain size of something like around 2 micrometer diameter, it has a fracture toughness in the plane strain condition of 110 MPa root meter strength typically the yield strength is around 2000 MPa.

So, that is quite a high strength steel and for a similar strength steel, which has a strength of around 2000 MPa. So, if we are enhancing the grain size to 32 micrometers, the fracture toughness actually has been seen to decrease by almost half the values it has come down to 55 embedded meters. So, that is a huge change in the fracture toughness values that can be achieved just by engineering the microstructural size. And we will look into more details of how we can do this and what are the other factors that control the toughness of the material.

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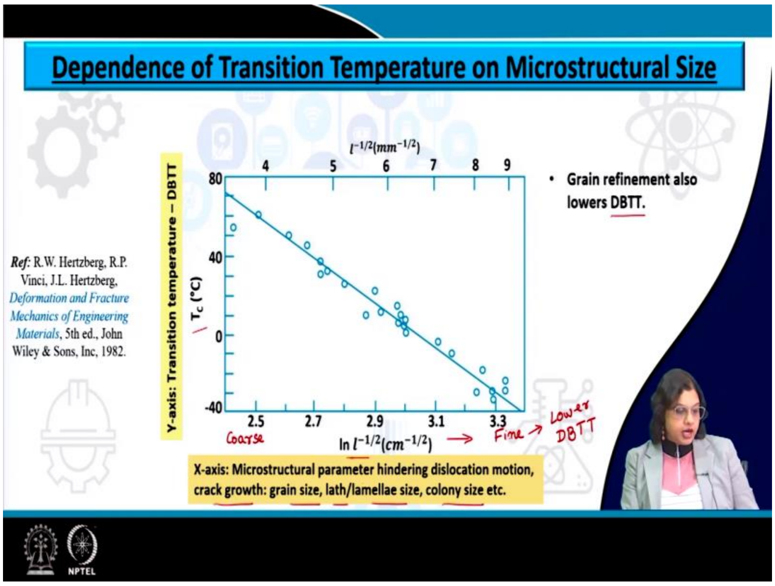

So, eventually fracture toughness and that ductile to brittle transition temperatures are also related. If the toughness is more it signifies that the ductile to brittle transition temperature is less. We always aim for lower and lower ductile to brittle transition temperature. So, that we can use this without the possible fracture in practice in service condition and grain refinement has been found one of a very influential way by which we can lower the ductile to brittle transition temperature also.

So, here is an example, shown here some experimental data, which shows the transition temperature on the y axis in degrees centigrade and the x axis is $l^{-1/2}$ and l here signifies any kind of microstructure parameter that hinders the dislocation motion or even the correct growth now, this could be grain size or lath size or lamella size or colony size whatever size that comes as a hindrance to the crack growth in this case for the case of fracture.

We can consider that as the controlling feature and the size of that is on the x axis. And we see that there is a continuous reduction in the ductile to brittle transition temperature as we are increasing this value of ln $l^{-1/2}$. So, essentially the x axis here means, that grain size decreases along this direction.

So, that means that we have the coarse grain size here as well as the fine grain size there. And what we are seeing is that the finer grain size are having lower ductile to brittle transition temperature compared to the coarser one. So, obviously, this will serve as a beneficial effect and we will look for refining the microstructure size to achieve lower and lower ductile to brittle transition temperature.

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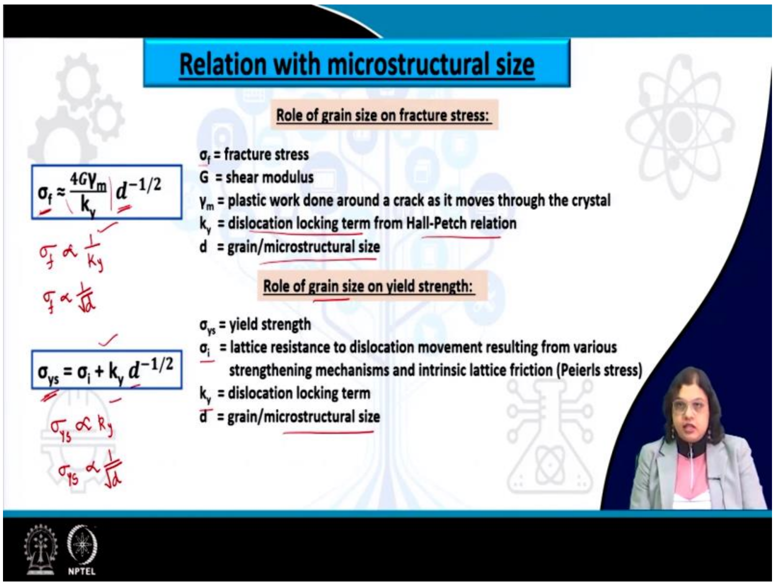

So, how is this related, how is the fracture strength is related to the microstructure size to find out that, we need the help of a relation something like this which says that σ_f which is the fracture stress of a material that is equivalent to $\frac{4G\gamma_m}{k_y} d^{-1/2}$, d here is the grain size or the microstructure size any microstructural size which is of importance here like I mentioned it could be the lath size or the colony size or even the lamellar size whatever size is important here to restrict the growth of the crack that can be considered here as d and the other factors G is nothing but the shear modulus and gamma m is the plastic work done.

So, we have already come across this term earlier also and this is the plastic work that is being done or the energy that is there as the crack moves as the crack grows essentially k_y on the other hand is the dislocation locking term. And we are all already familiar with this k_y term from the Hall-Petch relation, Hall-Petch relation, we will go to that next.

So, essentially what we are seeing here is that the fracture strength or the fracture stress of a material is inversely related to the microstructure size. So, that means that as the microstructure refines the fracture strength of the material will keep on increasing provided the other parameters are kept constant.

Now, we are all familiar with the Hall-Petch relation which explains the relation between the microstructural size as well as the yield strength of the material once again d here could be grain size or for that matter any other kind of microstructural size. And what we are seeing that the yield strength of the material is also inversely related to the microstructure size which means that if we are refining the structure, yield strength of a material is supposed to increase, but this is also related to some other parameters like σ_i, σ_i is nothing but the resistance to dislocation motion.

So, it is nothing but the Peierls Stress that we are aware of it is the intrinsic lattice friction of a material and k_y as I mentioned that k_y is the dislocation locking term. So, the only two parameters which are common for these two relations are k_y in one case for the case of fracture strength we are seeing that the fracture strength of a material is inversely proportional to k_y. And on the other hand, yield strength of a material is directly proportional to k_y.

Apart from that, the other parameter which is same for both the relations are d and , both the cases we can see that is it σ_f or σ_l strain, both are actually inversely related to the $\sqrt{d}$. So, we need to now go through one of one by one through all the parameters to see how they are controlling, but before that, let us also look into the fact the basic differences between these two relations or these two stress.

For example, since, both the sides are representing the stress, but the basic difference is that sigma f is the stress at which fracture occurs. So, fracture means that the bonds break and new surfaces are being formed. On the other hand, yield strength is nothing but when the dislocation starts moving, so, that is the point when the plastic deformation starts and it attains a particular value. So, that is the yield strength.

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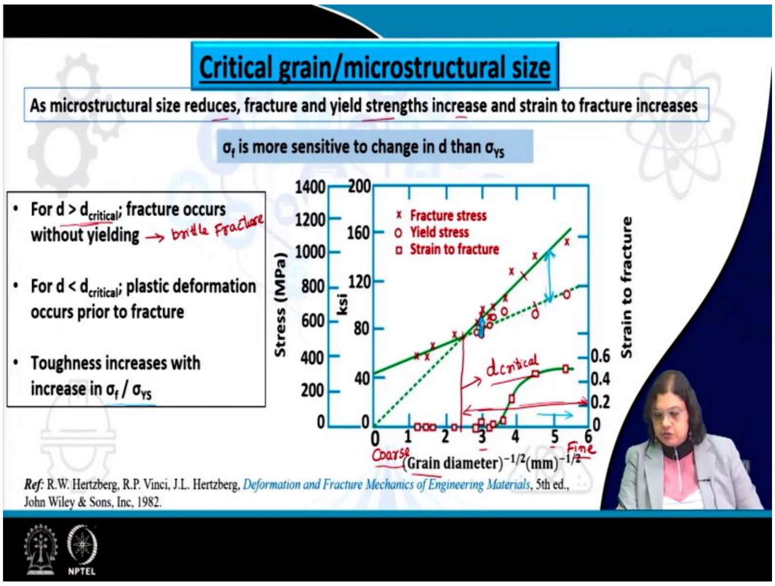

So, that means, that if we try to figure out the critical grain size at which both of these are equivalent σ_f and yield strength are equivalent, we should be able to do that and that is shown here that we are plotting the stress on the y axis as well as the $d^{-1/2}$ in the x axis.

So, $d^{-1/2}$ essentially now, this could be once again instead of the grain this could be any other microstructure parameters, which is of interest, but for most of the cases it is the grain size that controls the mechanical properties and that is the reason that we have used the term grain here, but for your reference, this could be any kind of microstructural size that is of importance.

So, what we are seeing here is that since we are plotting it in this way $d^{-1/2}$ once again this signifies the term 0 or 0 to 1 here signifies the coarse grain and this one here signifies the fine grain. So, we can see that as the microstructural size reduces not only the fracture and the yields strength increase both of these parameters increase as we have seen from the relation earlier, but also the strain to fracture increases, which are represented by the square symbols here.

Now, what else we are seeing here is that the σ_f or the fracture strength is actually more sensitive to the change in d the microstructure size than the yield strength and for the coarser grain size, actually, if we are beyond this point, so, this is the point which can be termed as $d_{critical}$. So, this is the point at which the yield strength as well as the fracture strength both of these lines or both of these curves are intersecting each other.

So, that is the critical microstructure size of interest at which the fracture strength as well as the yield strength are equivalent to each other, and if we are talking about the coarser grain size one which is more than the $d_{critical}$, then we are seeing that fracture is occurring even before yielding so, there is no scope for yielding there is just direct fracture. So, that signifies nothing but brittle fracture. So, there is no yielding at all.

So, that is a brittle fracture. And on the other hand, if we are looking for the finer grain size, so, that means when d is less than the $d_{critical}$ value, so, this half of the curve, we can see that the plastic deformation occurs. So, this dashed line here signifies the plastic deformation and then after the while fracture occurs after certain amount of plastic deformation fracture occurs.

We are also seeing interestingly that final is the grain size so, if you are if we are moving from the point let us say from 3 to 5, we can see that the amount of plastic deformation or the difference between the plastic deformation as the plastic or the yield strength as and the fracture strength actually increases if we are going for finer and finer grain size.

So, while for 3 it is only it spans only for this much for 5 we can see that there is significant amount of plastic deformation prior to the failures more or less the plastic deformation means that a significant part of the energy available will be used up for the plastic deformation and this signifies that the toughness of the material will keep on increase.

So, that is what is referred to here that as we are moving for finer and finer grain size, the fracture toughness essentially increases and that is also represented it by this relation or the ratio between the fracture strength to the yield strength which is signified by this span or the difference between this point here.

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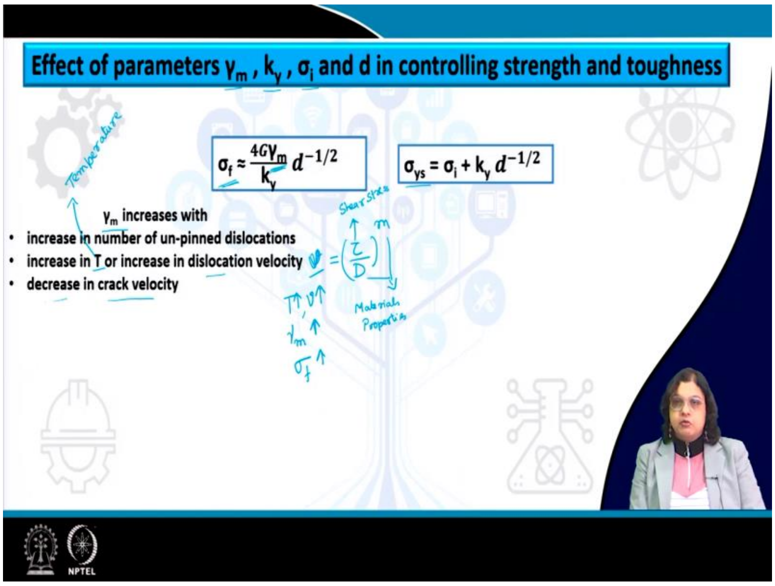

Now, moving to the relations once more and looking into the exact role of each of these parameters, let us focus on how each of these parameters for example, the γ_m and the plastic work energy or the k_y or σ_i the lattice friction, how are they controlling each of the fracture strength as well as yield strength.

So, if we are talking about the fracture strength of the material and its relation, we can see that γ_m is the most significant term here because this is directly proportional to the fracture strength other than the microstructural size this is the most significant term here. So, if we by any chance, if we are able to increase the γ_m that means that we should be able to increase the fracture strength of the material.

Now, this γ_m or the plastic work energy is related to the availability of dislocations, and not only that, it is related to the availability of dislocations which are free to move which means that the unpin dislocations or the mobile dislocations that are available in the system that controls the amount of γ_m.

So, that can be on the other hand being controlled by the T or temperature. So, the T here is temperature. So, as we are increasing the temperature of the system obviously, more and more energy or the thermal energy is available for the dislocations to overcome whatever barrier that comes to its way and that leads to an enhancement in γ_m and as well as the fracture strength of the material.

So, higher is the temperature higher will be the fracture strength of the material and that is also reflected in increasing the dislocation velocity of the material. So, dislocation velocity is actually related to a relation something like this or can term this is $v = \left(\frac{\Gamma}{D}\right)^m$ where this D and as well as m these are nothing but materials parameters and so, and tau is nothing but shear stress.

So, as we are increasing the temperature, this D value actually decreases and that means the velocity increases. So, as we are increasing the temperature eventually what we are seeing is that V increases and that means that more and more dislocations will be able to move and that means that the plastic work energy will increase and eventually the fracture strength will increase.

Now, this is also related to the crack velocity, the plastic work is also related to the crack velocity, how rapidly the crack is growing. So, but in the reverse way, so, if the crack velocity decreases, so, if it is growing slowly that means, more time is available for the plastic deformation to happen ahead of the crack tip and that will lead to an enhancement in γ_m .

So, this is inversely related to the crack velocity whereas, with the dislocation velocity it is directly related. So, as the crack velocity increases, on the other hand, there is not sufficient time for the plastic deformation to happen and that makes the γ_m value a lower one and that actually reduces the σ_f value.

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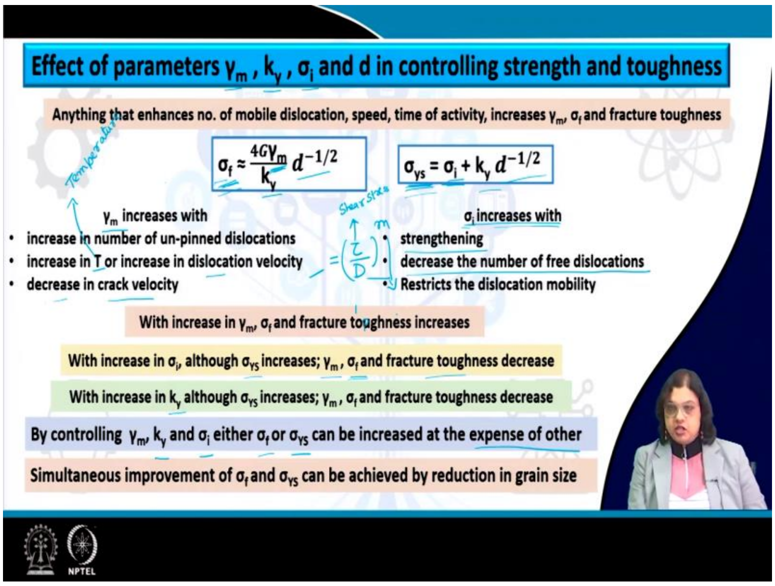

So, what we are seeing here is that with increase in γ_m , σ_f that is the fracture strength as well as the fracture toughness both increases. So, eventually any kind of mechanism that enhances the number of mobile dislocation, its speed time of activity all this can enhance the gamma m term and if that enhances the γ_m then σ_f or the fracture strength as well as the fracture toughness will also increase simultaneously.

Now, looking to the other relation, which is the yield strength, we can see that yield strength instead of the γ_m term here yield strain is directly related to σ_i term, the inherent lattice friction and what we can see is that the σ_i increases with any of these the strengthening mechanism, any kind of strengthening mechanism, actually tries to increase the σ_i the resistance to motion of the dislocation and that leads to an enhancement in the stress that is required to overcome this barrier and for the dislocation to move through.

So, that means the yield strength of the material and eventually the σ_i is related to the number of free dislocations also, but in a reverse way in comparison to that we have seen for the case of fracture strength. So, in this case for the case of yield strength, we can see that σ_i increases with the decrease of the number of free dislocation. So, as the number of free or the mobile or the unpainted dislocation increases, that will actually lead to lowering the value of σ_i and if σ_i value reduces that means, sigma yield strength will also reduce.

So, what it is hinting us here is that, the number of free dislocations are controlling the fracture strength as well as the yield strength in a completely reverse way. So, if by any way, we are able to increase the number of unpinned dislocations, which just means that the fracture strength will increase, but on the other hand yield strength will decrease in case we are able to restrict the dislocation mobility that on the other hand will increase the σ_i and that will increase the yield strength so which is completely opposite to what we have seen for the case of fracture strength.

So, this in turn is telling us that with increasing σ_i although the yield strength increases, but this γ_m and σ_f as well as the fracture toughness decreases, so, there is no direct relation between σ_i and the fracture strength, but, we can see that how these two can be correlated based on the number of unpin dislocations or the dislocation mobility we can say that, we can enhance either yield strength or the fracture strength by manipulating the value of σ_i .

On the other hand, for the case of k_y, we have already seen that this k_y is inversely proportional for the case of fracture strength, but directly proportional for the case of yield strength. So, once again by varying the value of k_y, we can either achieve an enhancement in the yield strength or the enhancement in the fracture strength but not simultaneously so, there can be an enhancement in either yield strength or fractured string at the expense of the other.

So, by controlling any of these parameters, like γ_m or k_y or σ_i , we can enhance only one or the other. So, we can enhance either the fracture strength or the yield strain, but at the expense of the other end, we cannot enhance both of them simultaneously, the only way by which we can increase both the yield strength and the fracture strength of the material is through grain refinement. And that is what we have already seen that for both the cases grain refinement is the one which is directly related to the fracture strength and yield strength of the material.

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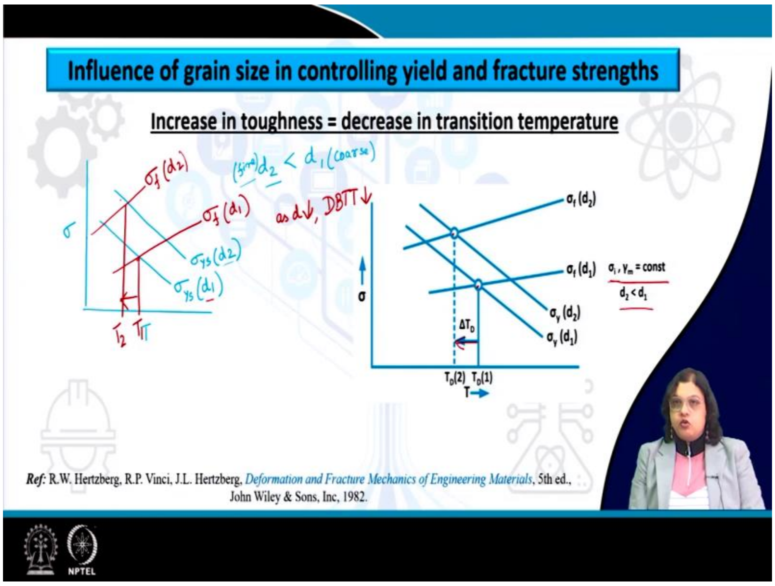

Now, as we have seen that fracture toughness is also related to the transition temperature and we have also seen in the critical microstructure size graph, that the point at which the yield strength as well as the fracture strength are equivalent, if we are having grain size or microstructural size coarser than that, we are seeing the brittle behavior or brittle fracture and if we are having microstructural size finer than that critical size, then ductile behavior will be seen.

So, that is essentially the ductile to brittle transition temperature, temperature corresponding to the critical grain size. So, let's see that how it is varying, if we are varying the grain size, let's find out a relation between the fracture strength, yield strength as well as the microstructural size and the ductile to brittle transition temperature. So, here so, we are plotting the yield strength or the fracture strength. So, any kind of stress here on the y axis and on the x axis we are having the temperature.

Now, yield strength of a material is inversely related to temperature which means that as we are increasing the temperature yield strength will decrease, because it is easier for the dislocations to move and that means that lesser and lesser amount of applied stress will be required to achieve the yielding behavior. And this can be seen if we are plotting the yield strength versus temperature.

So, this is the yield strength for let's say microstructures size of d_1 and this would be the one yield strength following a similar trend, but for the microstructural size d_2. Now, this is also giving us a hint that since the line for yield strength for d_2 is above that of d_1 signifies that d_2 is actually lesser than d_1. So, d_1 is a condition when we have a coarser grain and d_2. So, that means that this is coarse, d_2 is the one when we have fine grain size fracture strength on the other hand is directly related to the temperature which means that as we are increasing the temperature more and more plastic deformation will happen and that means that the stress that is required for fracture will keep on increasing.

So, that means that instead of line which we have seen for the yield strength, in case of fracture strength, we are going to see a behavior something like this. So, this is σ_f for the grain size d_1 and wherever this the yield strength line as well as the fracture strength line cuts each other that is the ductile to brittle transition temperature we have already seen that so, in this case for the case a d_1, we see that, this is the point where the yield strength as well as the fracture strength is same.

So, this T_1 is the point which is equivalent to the ductile to brittle transition temperature for a microstructure size of d_1. On the other hand, if we are talking about a finer grain size material, again this is related to the fracture strength and fracture strength is supposed to increase for finer microstructural size and for that case we are seeing a behavior let's say like this. So, this is the σ_f for d_2 and in this case on the other hand, we are seeing the ductile to brittle transition temperature something like here T_2.

Now, if we are looking into this more carefully, what we are seeing is that with the refinement in the grain size from d_1 to d_2 there is a reduction in the ductile to brittle transition temperature. So, that means that as d decreases DBTT also decreases. So, this is what is shown here and this is a reference plot which also shows the same behavior this will be valid provided we keep the other parameters constant.

So, we are not varying any of the other parameters which are influencing either the fracture strength or the yield strength of the material for example, the plastic work γ_m or the σ_i those parts are constant, but if we are simply refining the microstructure size, we see that there is a reduction in the value of the ductile to brittle transition temperature which is nothing but the intersection point between the yield strength and the fracture strength curve.

We can also do similar kinds of exercise if we are using the reverse relation for example, if we are using d_2 as the coarser grain size materials, you can do that yourself to check out that in that case, actually the ductile to brittle transition temperature will increase if we are talking about a coarser grain size.

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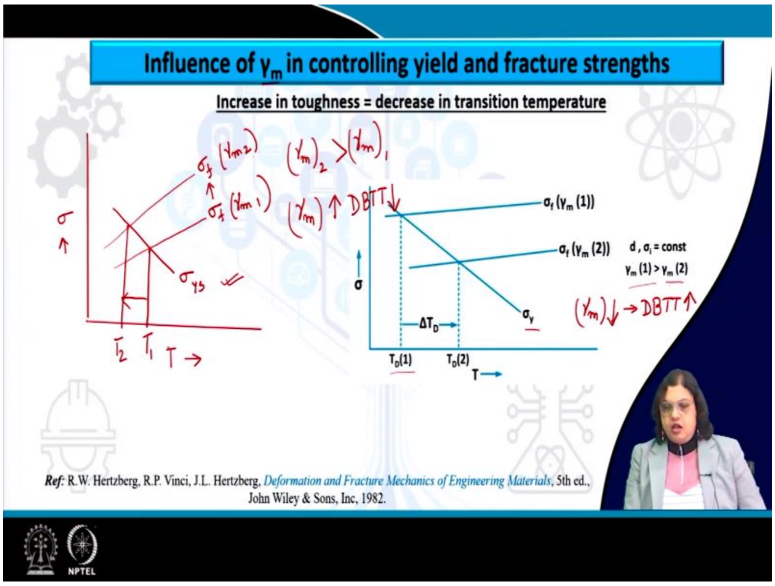

Now, the second thing that we want to find out is the influence of γ_m. Now, γ_m is controlling only the yield strength or only the fracture strength, but not the yield strength of the material, so, once again let us draw this σ on the y axis and T on the x axis. So, in this case what we are seeing is the yield strength curve varying as it is and this is what is the yield strength and this is not varying any further if we are changing the γ_m because γ_m is not directly controlling the yield strength of the material.

On the other hand, fracture strength will be affected by the γ_m . So, let's say this is the fracture strength for γ_{m1} and this could be the fracture strength for γ_{m2} . Now, in this case, since fracture strength for γ_{m2} is higher than that of γ_{m1} . So, this means that γ_{m2} is actually greater than γ_{m1} . So, if that is the case, we can see here that this is the temperature or the ductile to brittle transition temperature for the condition one when the yield strength and the fracture strength curve for γ_{m1} are intersecting on the other hand for the γ_{m2} we can see that this is the T_2 temperature.

So, here also we can see that if we are increasing the γ_m values, so if γ_m value increases, we can see that that ductile to brittle transition temperature decreases. So, this follows an inverse relation with γ_m so, that is what is apparent from here. The same thing is shown here, but only this is shown in the opposite way, where you can see that the yield strength is not varying as usual, but if we are considering the situation where the γ_{m2} is less than that of γ_{m1} so, the reverse of what has been considered here you will see that in this case, the ductile to brittle transition temperature for 1 will be lower than that of the ductile to brittle transition temperature for 2.

So, here also the inverse relation will be maintained. So, what we can see is that as γ_m reduces for the condition 2, we can see that the ductile to brittle transition temperature increases. So, there is a kind of inverse relation that is being seen here.

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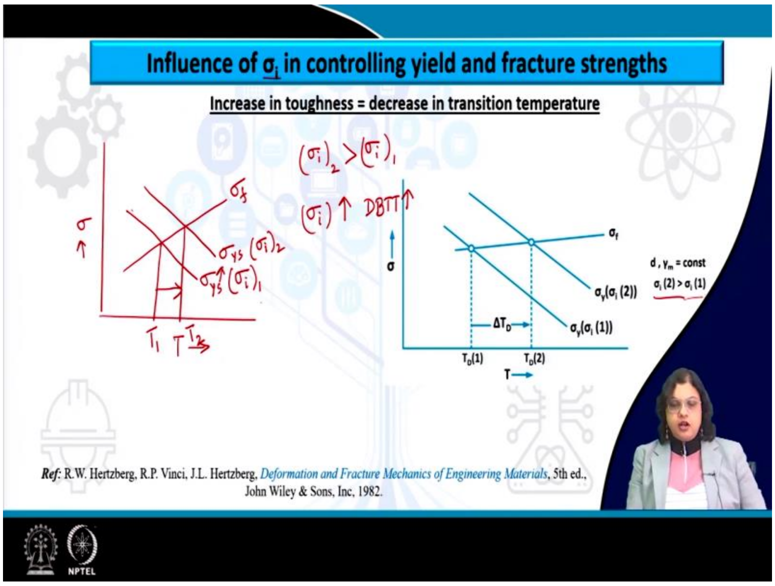

So, let us look onto the other factor which is the σ_i . Now σ_i is the one which controls the yields strength, but not the fracture strength of the material. So, here what we can see is once again by axis is the σ and x axis is T and if the yield strength curve is like this for σ_{i1} then for σ_{i2} this could be the yield strength curve.

Now, since again this is sigma yield strength for a condition 2 is higher than that of sigma yield strength for condition 1 we are seeing here essentially that σ_i for 2 is higher than σ_i for the condition 1 because they are also directly proportional to the yield strength of the material. Now, fracture strength in this case is not going to change.

So, we are seeing a curve for σ_f whatever it is the condition 1 or 2 it is the same curve and what we are seeing the ductile to brittle transition temperature here is the point of intersection. So, this is what is T_1 for the condition 1 and this is what for T_2. So, in this case however, we are seeing that as σ_i for 2 is higher, as it increases, what we are seeing is that the ductile to brittle transition temperature also increases.

So, this is what is seen here as the condition 2 σ_i value is higher than that of σ_{i1} , we are seeing an enhancement in the ductile to brittle transition temperature. Now, since ductile to middle transition temperature enhancement can be also correlated to the reduction in fracture toughness. So, we can essentially say that σ_i , if we are increasing that value, then the fracture strength or the fracture toughness value is going to reduce, although the yield strength of the material will increase.

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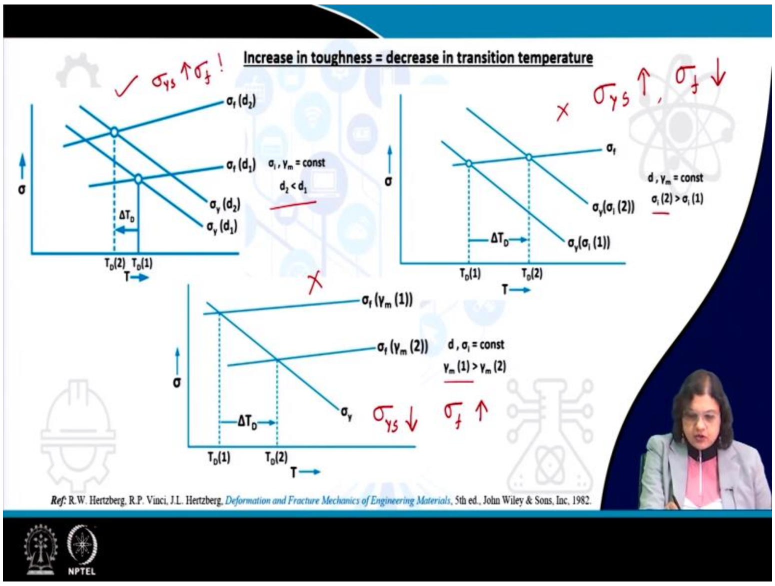

So, that is how a correlation is being set for each of these three conditions and we have seen that how each of them are either directly or inversely proportional. So, apart from the grain size other than the grain size, all the other factors are actually not suitable for increasing both the yield and the fracture strength of the material.

So, if we are talking about the σ_i condition this is will lead to an enhancement in yield strength, but fracture strength will decrease. On the other hand, if we are talking about the γ_m term in this case, yield strength will decrease, but fracture strength will increase, but it is only the grain size, where we can see that both yield strength will increase and fracture strength will also increase.

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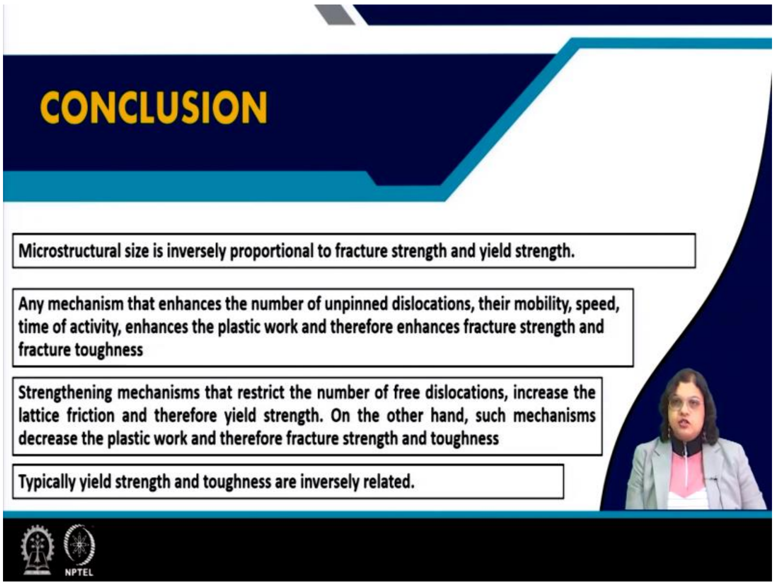

So, that leads us to the conclusion of this lecture that microstructure size is inversely proportional to the fracture strength as well as the yield strength which means, if we are refining the microstructure size, then both the yield strength and the fracture strength will increase and any mechanism that enhances the number of unpinned dislocations their mobility or speed, the time of activity enhances the plastic work and if it does, so, it actually enhances the fracture strength and fracture toughness of the material.

On the other hand, the strengthening mechanisms that restrict the number of free dislocations or in other words that increase the lattice friction, it actually increases the yield strength of the material. On the other hand, such mechanisms decrease the plastic work and therefore, fracture strength and fracture toughness of the material also decrease and typically yield strength and toughness are inversely related we have seen this earlier also, if we are trying to increase the yield strength of the material, we can only do so, at the expense of the fracture toughness or fracture strength of the material.

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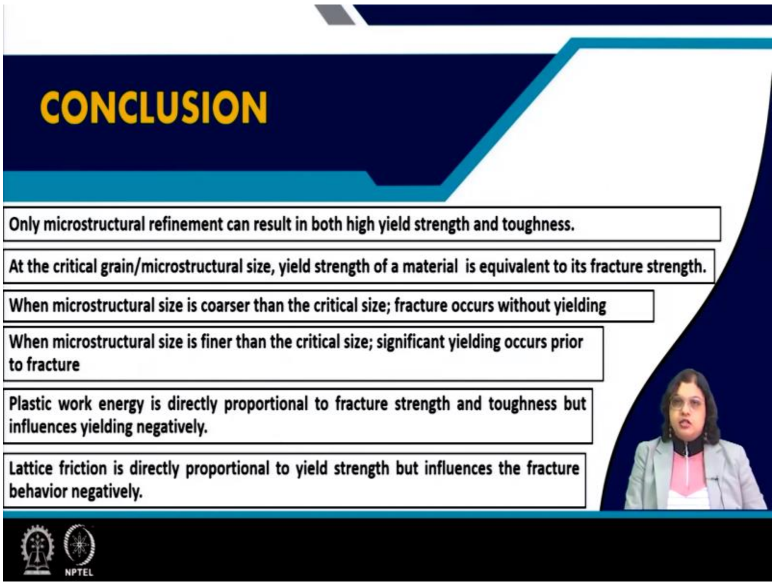

But only microstructure refinement is the one way by which we can achieve both higher yield strength and fracture toughness and fracture strength. So, at the critical grain or the microstructure size, yield strength of the material and the fracture strength of the material will be the same value and when the microstructure is coarser than that critical size, then fracture will occur without a yielding. So, that means, it is a signature of brittle fracture.

On the other hand, when the microstructure size is finer than that $d_{critical}$ that will lead to significant yielding also this amount of yielding prior to fracture will keep on increasing, if we are refining the grain size more and more and plastic work energy we have seen is directly proportional to the fracture strength and toughness, but it influences the yielding behavior negatively although we do not see a straightforward relation between plastic work and the yield strength relation as per the Hall-Petch equation.

But the from the mechanism onward, we can understand that the plastic work energy is actually reducing the yield strength. On the other hand, lattice friction is directly proportional to the yield strength of the material and once again there is no direct correlation that we can establish between the lattice friction as well as the fracture strength. But we can again understand based on the number of the unpinned dislocation that increase in the lattice friction will act negatively to the fracture behavior of the material.

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