Fracture, Fatigue and Failure of Materials
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Lecture No 22
Fracture Toughness

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NPTEL ONLINE CERTIFICATION COURSES

Fracture, Fatigue and Failure of Materials

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Module 01: Fracture

Lecture 22 : Fracture Toughness

Hello everyone, we are here with the 22nd lecture of this course Fracture, Fatigue and Failure of Materials. And in this lecture, we will be talking more about the fracture toughness of the material.

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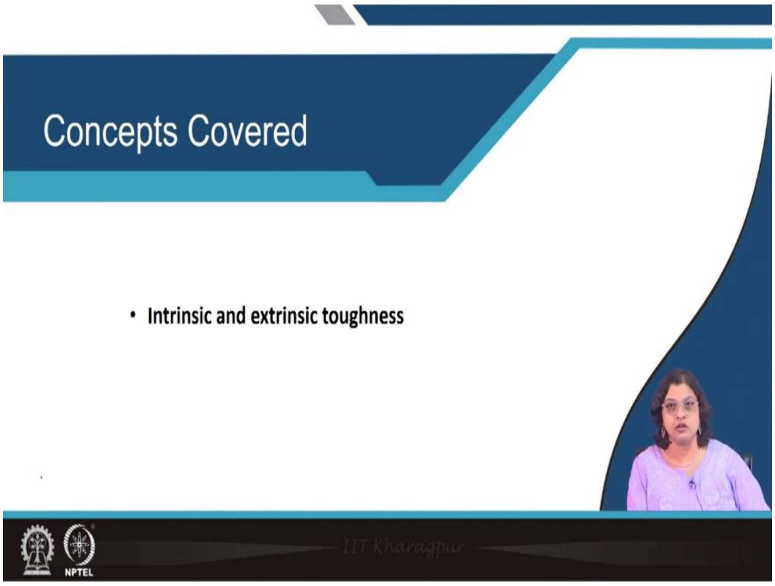

Concepts Covered

- Intrinsic and extrinsic toughness

So, far we have seen, fracture toughness of a material does vary under different condition for example, under plane strain condition, which is valid for a thicker specimen for plane stress condition which is valid for a thinner specimen there is variation in the overall magnitude of fracture toughness, we have seen that the plane strain condition actually gives us the lowest and the constant value of fracture toughness that is why it is considered as constant and materials property.

On the other hand, in plane stress condition, we have seen that fracture toughness continuously decreases, if we are enhancing the thickness of the specimen. We have also seen that in case we are applying a higher strain rate of deformation along with the presence of crack or a notch and at lower temperature, there is a possibility that the material can undergo fracture from the ductile to the brittle mode.

So, basically after all these things that we have seen, we still aim to achieve higher and higher toughness of a material higher fracture toughness of a material depending on the particular application. And we always aim to engineer the strength or ductility or toughness or fracture toughness, any such things the mechanical properties, we try to control so, that we can use it for any particular application.

And for that, what we need to understand is the way by which it can be controlled and basically this can be realized or more insights can be developed on this if we can assess the intrinsic or the extrinsic ways by which the fracture toughness of a material can be modified. So, this is what will be covered in this lecture today, where we will see that how the intrinsic toughness and the extrinsic toughness of a material vary and what are the factors which particularly controls the toughness of the material intrinsically as well as the extrinsic factors which can help us modify the overall fracture toughness of a component.

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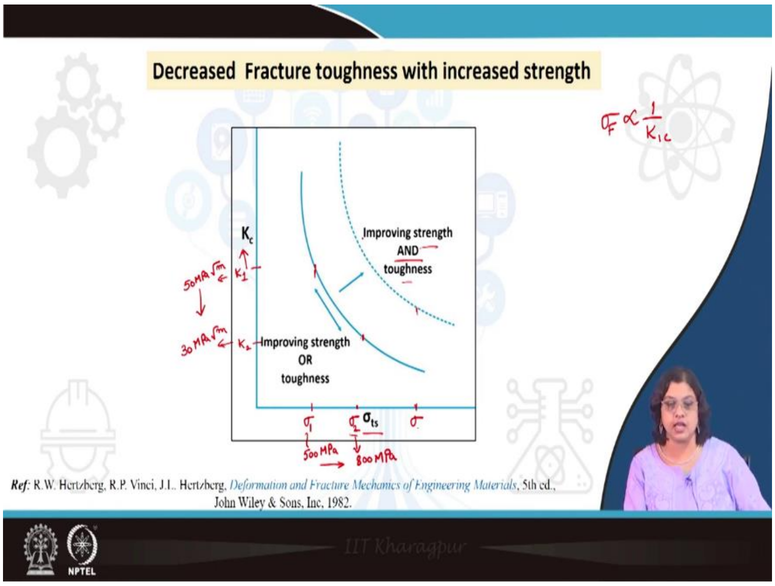

Decreased Fracture toughness with increased strength

$\sigma_F \propto \frac{1}{K_{1c}}$

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

So, let us look into the very basic idea that fracture toughness and the strength let us say the ill strength of a material, these are inversely related. So, if we are using any kind of strengthening mechanism, it is supposed to or it is expected to reduce the fracture toughness or even the tensile toughness of a material.

So, we have seen that fracture strength is typically inversely proportional to the fracture toughness, we have also seen that, as we tried to increase the strength of the material, in this case, the tensile strength is along the x-axis and y-axis is the fracture toughness and we can see that this is the kind of relation that is applicable between fracture toughness and tensile strength, which means that let us say we are talking about a condition one in which it has a certain value of tensile strength. Let us name this as σ_1.

Let us take an arbitrary value something like 500 MPa, and this is equivalent, or this gives us a fracture toughness value, which let us name this as K_1. And let us say this is around 50 $MPa\sqrt{m}$. Now, by any of the strengthening mechanism, if we are able to enhance the tensile strength of the material, to the point two such that the tensile strength now is let us say, σ_2, which is 800 MPa.

So, these are some arbitrary numbers I am giving. So, for this amount of strength, we can see that the corresponding fracture toughness will be something like K_2, which could be a having a lower value of course, let us say this is 30 $MPa\sqrt{m}$. So, it is very clear that although we are able to enhance the strength, so, that is a good news at some point that we are able to enhance the strength by 300 MPa, but it could be a bad news if we are considering the toughness as the prime factor controlling the failure of this component.

So, we cannot always increase the strength or increase the toughness without cutting on the corresponding counterpart of that and our target again being an engineer is always to improve both the strength and the toughness, such that we can shift this curve to the dashed one and we can now see that for example, this 30 $MPa\sqrt{m}$, we can, if we are able to shift this curve to the right to the dashed one, we can see that now, for this amount of K_{1C} of the fracture toughness, we are able to get much higher value of σ.

Or the in the starting value we can see that the relation between K and σ are giving us a higher value of both. So, this is what is the target and as I said that for that to assess that we need to appreciate the intrinsic and extrinsic toughness of the material.

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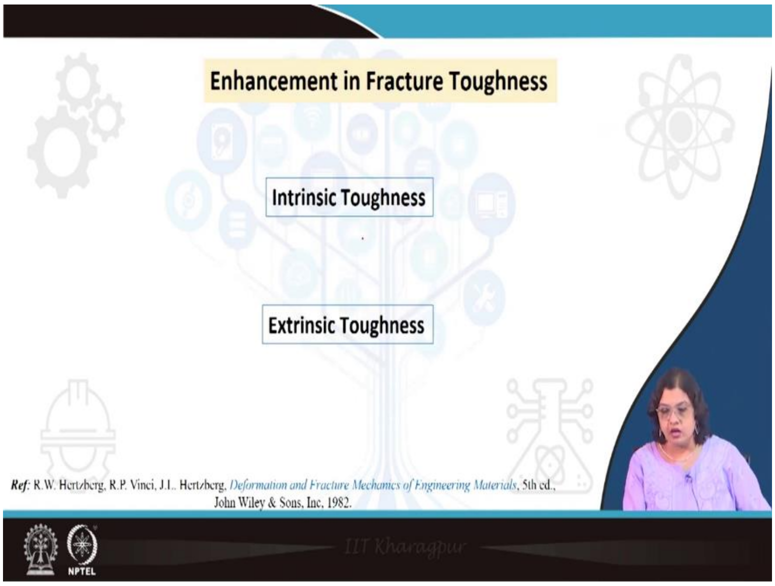
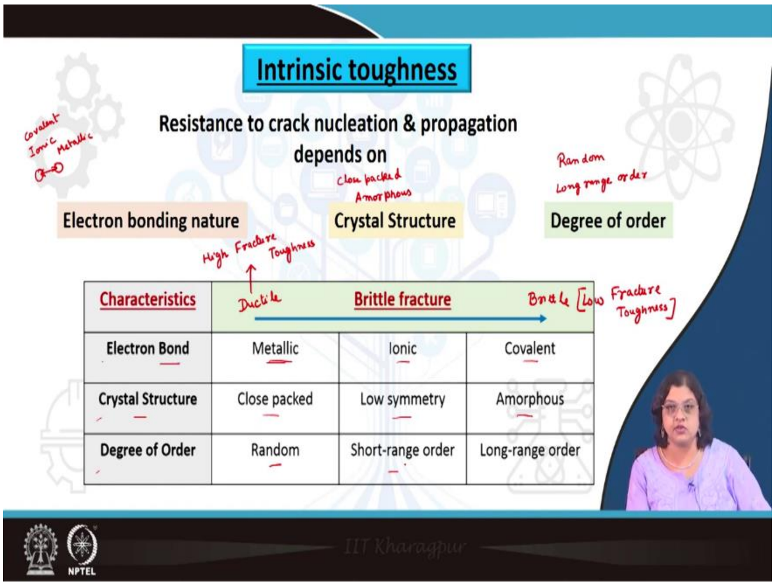


Enhancement in Fracture Toughness

Intrinsic Toughness

Extrinsic Toughness

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.



Intrinsic toughness

Resistance to crack nucleation & propagation depends on

Covalent
Ionic
Metallic

Electron bonding nature

Close packed
Amorphous

Crystal Structure

Random
Long range order

Degree of order

High Fracture Toughness

Ductile

Brittle [Low Fracture Toughness]

Characteristics	Brittle fracture		
Electron Bond	Metallic	Ionic	Covalent
Crystal Structure	Close packed	Low symmetry	Amorphous
Degree of Order	Random	Short-range order	Long-range order

Now, let us go through this one by one coming to the intrinsic toughness, this is the inherent resistance of a material to the crack nucleation as well as the crack propagation and it particularly depends on several factors for example, the electron bonding nature. If we have the atoms how these are being bonded, what kind of energy is associated with this bonding how easy or difficult it is to break the bond this kind of factors that dictate whether the material will have enough ductility or higher toughness or not.

So, let us say we have different kinds of bonds such as covalent, ionic, metallic. So, covalent one is a very strong bond and that means that it is very difficult to break the bond and if it is so, then it is very difficult for the dislocations also to break the bonds continuously and move and if it is difficult for the dislocations to move obviously, the ductility will be less and if the ductility is less, since ductility is related to the toughness of the fracture toughness, which means that for the case of let us say covalent bond, the bond strength is high then toughness is reducing.

So, that is one of the example on the other hand it is also related to the crystal structure. For example, if we have close packed structure, we know that for the case of close packed structure, it is easier for the atoms to move and it is easier for the dislocations to move there are enough number of slip systems and that will lead to easy motion of the dislocation which means that ductility will be higher and if ductility will be higher than that means that fracture toughness will also be higher.

On the other hand, if we are having an amorphous structure for example, that will obviously, there will be no dislocation motion at all and that means that that ductility will be less and the toughness of the fracture toughness will also be less. Apart from that degree of order is also very, very important if we have a long range order or a short range order or a completely random without any kind of order that will also dictate how the behavior will be for example, in case there is no particular order, it is easier for the dislocations to move through and that means that the toughness will be higher.

On the other hand, if we are having a long range order, so, there is a particular sequence that needs to be maintained and that is difficult to be broken. So, that will lead to a reduction in the ductility and in turn reduction in the fracture toughness of the material. So, all these factors are summarized here as we have seen that these are the different characteristics on this column here and we are seeing that how the brittle fracture or the brittle mode is increasing.

So, this one on the left is actually giving us the ductile behavior and on the right is the brittle mode of failure. So, for the case of electron bond the metallic one which is the most random there is no particular sequence. And here we can see that it is very easier for the dislocations to move through and that means that metals are always ductile that is one of the reason that for most of the structural applications, we use the metallic or the metal based components, so, that there is enough ductility and higher toughness

So, that it is not going to fail in a catastrophic manner, that is the one thing that we always try to avoid, when we are talking about failure analysis and failure analysis as part of this course, we always aim to have something or the structure should be like that, it can give us some indication before the actual catastrophic failure and ductility is one such thing, any kind of change in shape, which is permanent can be tracked and we can understand or we can predict that failure is about to happen.

So, for that sense metallic bonds are always easier for the dislocation to move through and more ductile on comparison ionic one which is having a higher bond energy compared to the metallic one, but kind of in between the metallic and the covalent they are having or lower fracture toughness. So, and the covalent one where it is very difficult for the bonds to be broken because it is having very high bond energy.

So, that will lead us to lower fracture toughness. So, brittle one is associated with low fracture toughness on the other hand ductile one is giving us higher fracture toughness, coming to the crystal structure, again the close pack structure where it is easier for the slip to move through is giving us higher fracture toughness and giving us a ductile behavior on the other hand a low symmetry one or particularly an amorphous one when there is no symmetry at all that can give us a brittle fracture with a very little fracture toughness value.

If the degree of order is random, then it is obviously easier for the dislocation to move through and we are getting a ductile behavior on the other hand, even if there is a short range order, it is quite difficult to break that order. And in case of long range order, it is even more difficult and that leads to make it a completely brittle behavior a bit kind of failure with very low value of fracture toughness. So, these are all the intrinsic properties of a material and this is how the fracture behavior is being controlled inherently by the materials characteristics.

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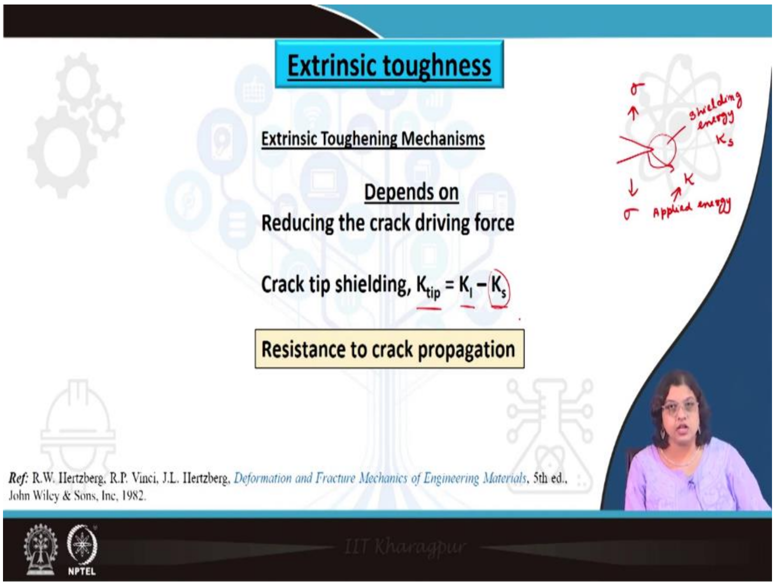

Extrinsic toughness

Extrinsic Toughening Mechanisms

Depends on

Reducing the crack driving force

Crack tip shielding, $K_{tip} = K_I - K_s$

Resistance to crack propagation

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

But, we always as I said that we try to engineer the properties and for that, it is very important to understand or appreciate the external conditions that can lead to an enhancement in the fracture toughness. So, these are not typically the intrinsic factors not inherent to the material property, but this we can make it behave in a different way if we can modify the structure in a different way.

So, particularly this extrinsic toughness the main target is to reduce the crack driving force such that even if there is a defect, it should not grow further. So, we have to restrict the growth of the crack and for that, let us say we have a defect or a crack here and what we are supplying is some kind of stress and basically at the tip of the crack we are or for that matter at any point we are supplying the energy for fracture and that is equivalent to K or K_1 or K_C at the point of c the critical value it will fracture.

So, this is the available energy and let us write this as the applied energy is given by K or G or whichever is convenient for us to determine this. On the other hand, if there is some other mechanism some alternate mechanism is going on in the zone ahead of the crack tip, which is kind of shielding the growth of the crack stopping the growth of the crack or consuming part of the available energy for some other kinds of mechanism that can lead to stopping that or that can lead to either stop or slow the growth of the crack.

So, this is basically leads to a shielding and for the energy required for this shielding mechanism, this is let us say K_S. So, if the applied energy is K_1 and then the shielding energy is Ks, we can term this as stress intensity factor in this case. So, the overall stress intensity factor that is available at the tip of the crack which will be used for growing the crack or fracture that is reduced getting reduced by this amount here.

So, the available one will be just K_1 - K_S. So, we need to find a way, such that the growth of the crack can be shielded and there should not be any growth and that will lead to a resistance to the propagation of the crack. So, let us see how this can be achieved.

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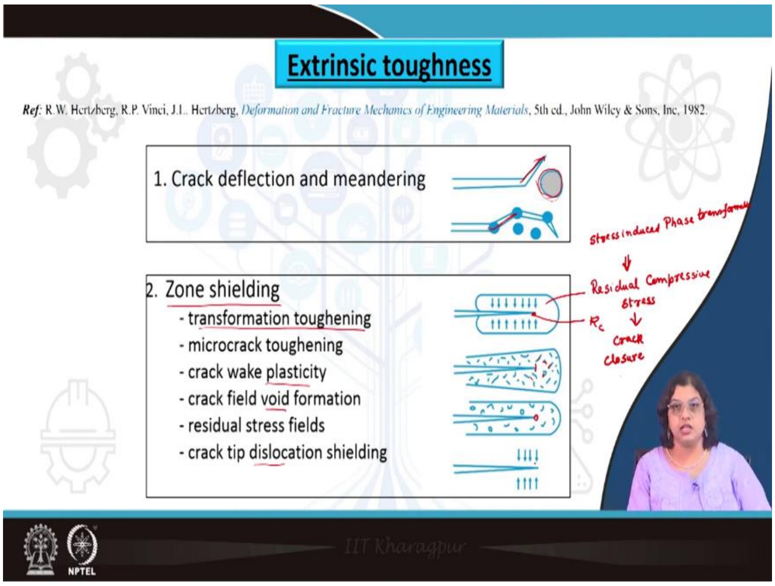

Extrinsic toughness

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

1. Crack deflection and meandering

2. Zone shielding
   - transformation toughening
   - microcrack toughening
   - crack wake plasticity
   - crack field void formation
   - residual stress fields
   - crack tip dislocation shielding

Stress induced Phase transforma
↓
Residual Compressive stress
R_c
↓
Crack closure

One of the very interesting way to do that is to deflect the crack, in case we are having a second phase here inclusion or precipitates or any kind of other structures, which the crack will find it difficult to pass through it has to either cut it or it can deviate its path. So, if it is deviating the path, part of the energy that was available, so, K_1 that will be used up in this energy to deviate the crack right to deflect the crack obviously, that means, that more and more energy needs to be applied needs to be supplied such that the crack can grow and lead to fracture.

On the other hand, if there is such that the crack can go pass through this inclusions or precipitates, it has to still cut through that and that will consume some more amount of energy. So, obviously, once again, we need to apply more amount of energy for the crack to cut all these barriers and overcome all those barriers and to move forward and lead to final fracture that will decrease the growth rate and that will enhance the fracture toughness of the material.

One of the other way is zone shielding, this is a very interesting way and the first example given here is the transformation toughening. So, in some cases which in which the material is capable of having a transformation of phase transformation, because of the presence or because of the availability of some amount of stress or energy to it, what happens is that, because of the presence of a crack or a defect or a notch we know that there is a stress concentration factor this K_C that is a maximum value of the applied stress that is developing there.

And because of the stress concentration factor, if it exceeds the stress value that is required for the phase transformation to occur stress induced phase transformation, then that will lead to a phase change. Now, the second phase for example, it can change in some cases from one phase to another, which may have a different volume most of the cases if it is changing from austenite to martensite for example, which is having a higher volume fraction and because of this higher volume, actually it occupies more space and that will lead to a residual stress and more importantly a residual compressive stress that will be generated.

And this residual compressive stress will then act to close the crack. So, that will lead to crack closure, first thing that I have I should write now is the stress induced phase transmission. So, there are several materials like that which can undergo stress induced phase transformation, in case of the TRIP condition or for example, in shape memory alloy or nickel titanium based alloy which undergoes a phase transformation from austenite to martensite just because with the presence of stress.

So, in such cases because of the availability of higher amount of stress at the tip of the crack this zone ahead of the crack or adjacent to the crack is very much prone to be transformed. And as I mentioned that, because of the change in the volume, there can this residual compressive stress can generate and which can assist in crack closure. So, if the crack is getting closed, that means that we still need to apply higher and higher energy to first of all to open up the crack and then to move forward. So, that will eventually lead to enhancement in the fracture toughness values.

Similarly, if there are micro cracks present adjacent to the notch or the defect, then each of this micro cracks are acting as the barriers to the growth of the crack. So, this are nothing but free space. So, whenever a crack is interacting with a micro crack it the tip is getting blunt, the energy is kind of getting released. So, that means that we need to add more energy for the crack to overcome this barrier and move forward.

Similarly, if there is any kind of plasticity that is generated at the crack wake or the crack tip, that can also further consume the part of the energy for this plastic deformation to occur and that means, that we need to supply more and more energy if there are voids to the forming, so, voids are also discontinuities and which means that these are also the free spaces that are forming.

So, if there are void ahead of the crack tip, and if the crack comes in contact with this void again the tip gets blunt, when if the tip gets blunt means the energy available at the tip is getting reduced the stress concentration value reduces and that means, that we again need to apply higher energy to overcome this barrier and for the to make the crack sharp enough again to proceed for further fracture. So, in some cases there could be dislocations that can generate again with the available stress that can be used up in generating the dislocations and which in turn will act as shielding the crack growth.

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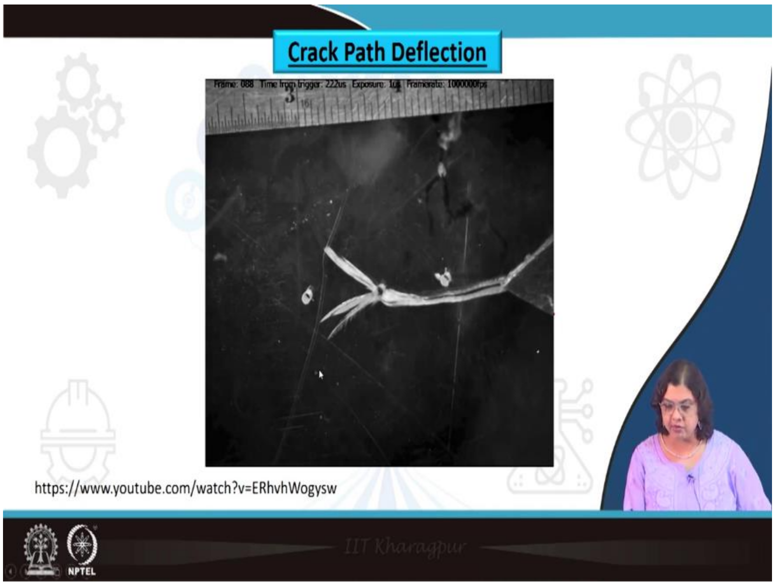

Crack Path Deflection

https://www.youtube.com/watch?v=ERhvhWogysw

So, here is a small video that you can see and what we can see here is that there is a notch, machined notch and we can see that it has the tendency or it can increase from in this direction and then there are some holes here and we will see in this video here that how the crack will behave when it comes in contact with these holes.

So, you can see the crack is interacting and when it comes here, we can see that since the crack is coming at this hole, the energy is getting dissipated and we can see that there are several direction in which the crack is propagating which means the energy for each of this crack direction is getting reduced and overall the way that it or the amount of energy that is required for the overall fracture, catastrophic fracture the growth rate of the crack will reduce and that in some way could be beneficial.

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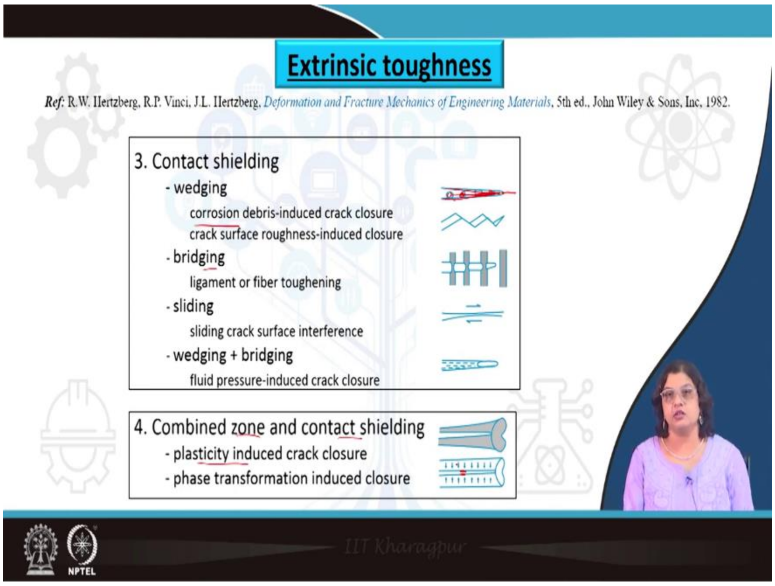

Extrinsic toughness

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

3. Contact shielding
    - wedging
        corrosion debris-induced crack closure
        crack surface roughness-induced closure
    - bridging
        ligament or fiber toughening
    - sliding
        sliding crack surface interference
    - wedging + bridging
        fluid pressure-induced crack closure

4. Combined zone and contact shielding
    - plasticity induced crack closure
    - phase transformation induced closure

So, there are other ways also for extrinsic toughness, for example, contact shielding, in case of contact shielding what happens for example, one of the example is for corrosion. So, what happens is that whenever there is corrosion, the corrosion debris that are forming corrosion products that falls on the wake of the crack as we can see, and if it falls between the two free surfaces of the crack, it kind of closes the crack wick. It blocks it and as a result, that also acts as a crack closure mechanism and we need to further apply energy such that it generates enough amount of energy to propagate any further bridging in case there are fibers that can act in bridging the crack there are mechanisms like fiber pool of which can lead to enhancement in the fracture toughness value.

So, often composites are designed such that the crack propagation will be restricted because of the presence of these fibers in the matrix such that the higher toughness can be obtained. Sliding of the crack surface interface: so, again in case of sliding, the two free surfaces are coming in contact and if that is the case that can also lead to an enhancement in the toughness.

Similarly, there could be a combination of both zone and the contact shielding, which could be because of the plasticity induced crack closure if there is some plastic deformation happening, as I mentioned that that will consume part of the energy and because of the phase transformation also, there is a change in the volume and once this are in contact, so, the zone and the contact will also be acting simultaneously leading to an overall enhancement in the fracture toughness behavior.

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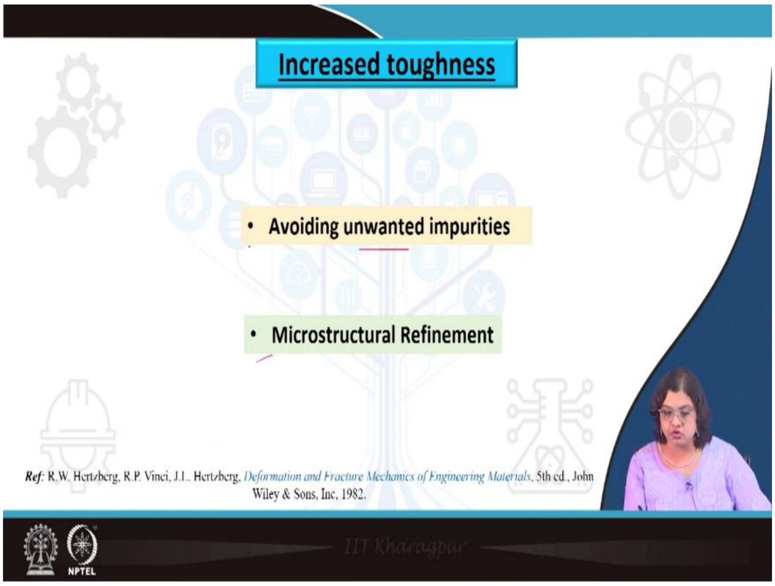

Increased toughness

- Avoiding unwanted impurities
- Microstructural Refinement

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

So, if we aim for increased toughness of material, we can do so, by several ways, the most important couple of ways by which we can do so are by reducing the impurities content. Whatever second phases which are unwanted can be termed as impurities often we add second phase is to enhance the strength of the material for example, precipitates on dispersers etcetera, but are inclusions also sometimes.

But in case that those are unwanted those are not serving our purpose and those are leading to early fracture or unpredicted factor, those can be considered as impurities and if we are able to remove those, we should be able to enhance the fracture toughness of the material. The other way by which fracture toughness can be enhanced is through microstructure refinement. So, this two of the factors we will be discussing in more details.

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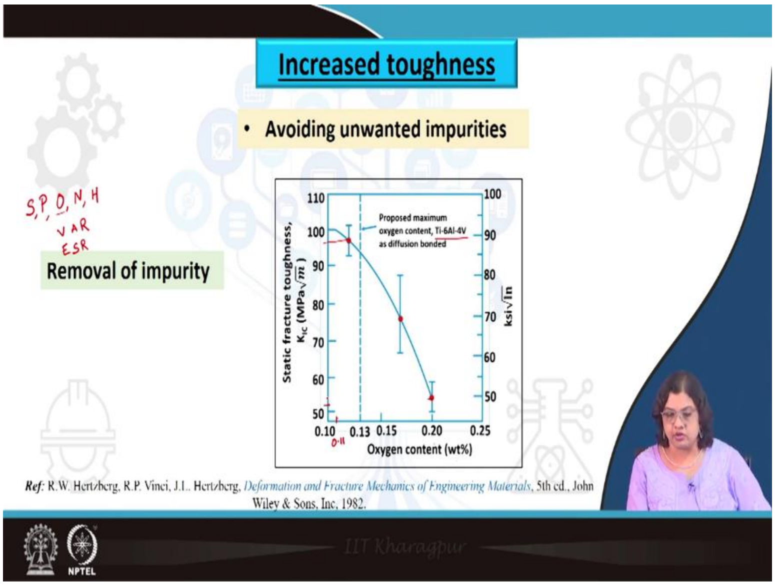

Increased toughness

- Avoiding unwanted impurities

S, P, O, N, H
VAR
ESR

Removal of impurity

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

Let us talk about the unwanted impurities first. So, there are three ways by which we can get rid of the impurities. First one is of course, removal of the impurity. So, there are certain interstitial atoms and impurities in case of steels for example, we know that sulfur, phosphorus and then this presence of oxygen, nitrogen, hydrogen, all this serve as the impurities. The presence of sulfur actually forms the sulfides and disulfides or inclusions are often very much detrimental for the stigma component and we need to get rid of this.

Hydrogen we know that hydrogen leads to an embodiment and often we want to get rid of the hydrogen content to avoid the early fracture or the brittle fracture mode. Similarly, oxygen also is something that needs to be removed for most of the metallic system. And for that, we can use different kinds of technique for example, we use the vacuum arc re-melting for repeatedly melting it and get rid of the oxygen or we can use the electro slag re-melting kind of process to get rid of the oxygen content.

So, we need to have a killed condition where the oxygen content is reduced. This is not only valid for steel, but for other materials particularly for example, titanium or steel which are used for biomedical application, we often need to get rid of the oxygen to achieve higher strength and toughness.

So, this is an example experimental data for the titanium this is a Ti6Al4V material which is often used for biomedical as well as aerospace applications also. And we can see here that if we are varying the oxygen content, if we are increasing the oxygen content, the fracture toughness values decreases significantly for example, if we are talking about the oxygen content of around 0.11 wt. %, we see that the fracture toughness value is close to 100 around 97 $MPa\sqrt{m}$ and just by making the oxygen content twice as if from 0.1 to 0.2, the fracture toughness values comes to almost half.

So, this is like 50 MPa or maybe 51 $MPa\sqrt{m}$. So, there is a significant reduction from 100 MPa to 50 $MPa\sqrt{m}$ just by increasing the oxygen content from 0.11 to 0.2 %. So, obviously, this is not acceptable if we are talking about biomedical application and aerospace application and we often go for extra low interstitial grade or ELI grade where we do not have such contents of the impurities.

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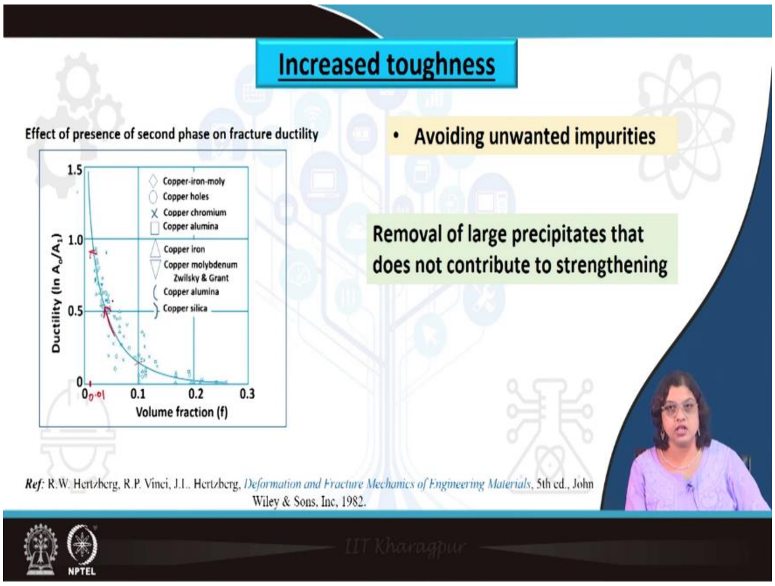

Increased toughness

Effect of presence of second phase on fracture ductility

- Avoiding unwanted impurities

Removal of large precipitates that does not contribute to strengthening

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

Now, the second way by which these impurities we can get rid of is by removing the precipitates which are large enough which are not adding much to the strength rather which are acting as the sites which are prone to defect initiation the crack initiation we should be removing such large precipitates or design the manufacturing process in such a way that no such large precipitate should form because those are always bad news for the fracture toughness of the material.

So, here is once again an experimental results for the volume fraction of different kinds of defects and different contents of copper and iron and molybdenum, chromium, aluminum, etcetera and we can see for any such cases the ductility reduces drastically if we are changing the volume fraction from very close 0 let us say 0.01 to 0.1 percent. We can see that the ductility which in this case is taken as the ratio of the ln A_0/A_1, we can see that there is a huge reduction in this ratio itself, if we are changing the volume fraction or reducing the volume fraction and ductility will increase significantly.

So, that is our target we often want to get rid of these unwanted impurities. So, that the ductility is increasing and as we have discussed earlier the ductility is directly proportional to the fracture toughness of the material. So, higher ductility means obviously, higher toughness.

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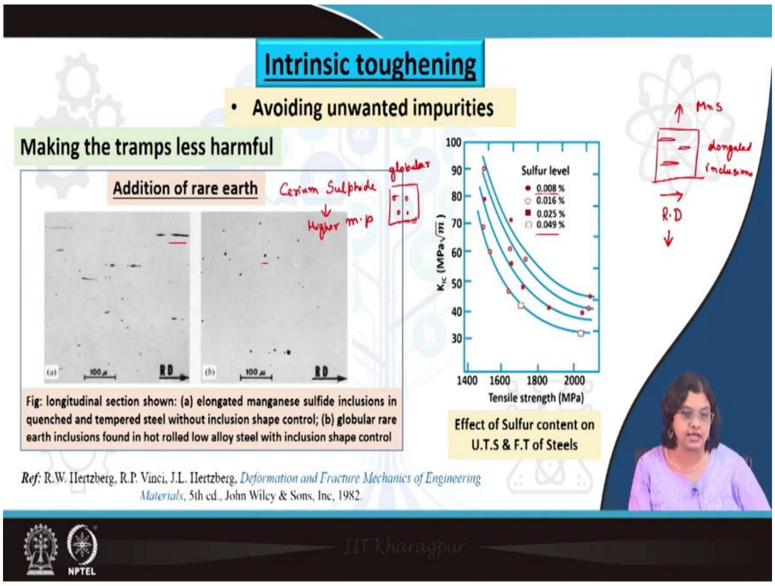

Intrinsic toughening

- Avoiding unwanted impurities

Making the tramps less harmful

Addition of rare earth

Fig: longitudinal section shown: (a) elongated manganese sulfide inclusions in quenched and tempered steel without inclusion shape control; (b) globular rare earth inclusions found in hot rolled low alloy steel with inclusion shape control

Effect of Sulfur content on U.T.S & F.T of Steels

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc, 1982.

Now, the third way is that, if we are not able to remove the unwanted impurities or if in case the removing the impurities is making it too much expensive, so, that it cannot be used for practical application, we want to make those impurities less harmful, we do not want it to be very much effective in reducing the fracture toughness. So, here is a smart way an example of how we can do that.

So, we all know that sulfur content in steel is bad news and this is particularly because it forms sulfide let us say MnS, we know that there are Mn that are added to steel, we have also seen in case of intellectual for impact toughness that addition of Mn is good for reducing the ductile to brittle transition temperature. So, Mn is of course added for that.

Now, this manganese when it comes in contact with the sulfur, it forms a MnS and this MnS inclusions are big and they could be detrimental in the sense that this MnS inclusions are having lower melting point. So, in most of the cases for machining operations or for fabricating operations, we often employ hot rolling or any kind of hot deformation or hot forging such kind of steps there.

So, at that temperature what happens is that this MnS comes to a semi molten state and it attains the direction of the ruling or whatever deformation that has been added. So, accordingly we get the kind of elongated inclusions of MnS and this elongated inclusion are actually what is making the properties of the component an isotropic.

So, in case we are rolling this along this direction for example, and we have the inclusions arranged around this direction. So, that will give a dissimilarity in the properties particularly when we are talking about the longitudinal versus transverse property. So, if the loading axis is perpendicular to the direction of the inclusions, the elongated inclusions that will lead to early crack initiation and that will lead to early failure.

Now, since these are used for let us say for making automobile or car sheets, so, often we have to bend it at the time of fabrication and then it is not advisable to have an isotropic behavior at the different directions. This is an example where the experimental results are being shown for different sulfur level from starting from 0.008 which are these elongated points here and for example, 0.049 percent or close to 0.5 percent we can see that how the fracture toughness versus tensile strength is going on the left side which means that both are reducing if we are having higher content of sulfur.

And one of the smart way to get rid of that is to add some rare earth. Now, what happens is that in presence of this rare earth, they actually form for example, if we are adding cerium they now form the cerium sulfide instead of the MnS and this cerium sulfide has higher very high melting point. And as a result, when we are doing this hot rolling kind of operations, they are not getting rolled along this direction and they are not forming such kind of elongated inclusions rather it is forming just globular inclusions.

So, in this case we are seeing elongated inclusions in case we have done MnS in case we have the cerium sulfide we are seeing that they are having globular. So, we are seeing the globular precipitate or inclusions for the case of the cerium sulfide presence of the sodium sulfide, this is what exactly is being shown here, this is what we see for the case of MnS we can see the elongated inclusions leading us to anisotropy in the property and this is for the cerium sulfide the real pictures here, but, we can see that these are very, very small and this also are globular in shape and that gives us an isotropic property.

So, that is one of the motto that if we are not able to remove the impurities or if removing the impurities are making it inconvenient in terms of in adding the cost to it, then we should better make it less harmful or less effective.

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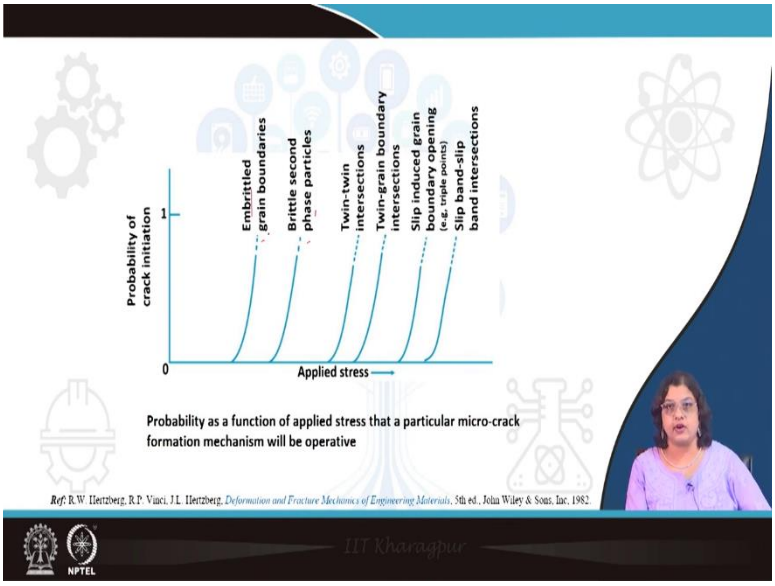

Probability as a function of applied stress that a particular micro-crack formation mechanism will be operative

Ref: R.W. Hertzberg, R.P. Vinci, J.L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 5th ed., John Wiley & Sons, Inc. 1982

So, this graph here shows application of stress how the crack initiates which other locations which are most probable for the crack to initiate. First of all the grain boundaries which are embrittled that is the location where the cracks are always easy to initiate. And secondly, if there are some brittle second phase particles, those can also act as the next probable one for the crack to initiate and then there are the twin-twin interactions or twin grain boundary interactions in which the crack can generate afterwards and then there are the sleep induced grain boundary opening or sleep band sleep band interaction, those are the locations whether crack can initiate at the end. So, the grain boundaries and particularly if those are embrittled these are the most detrimental sites for the crack to initiate.

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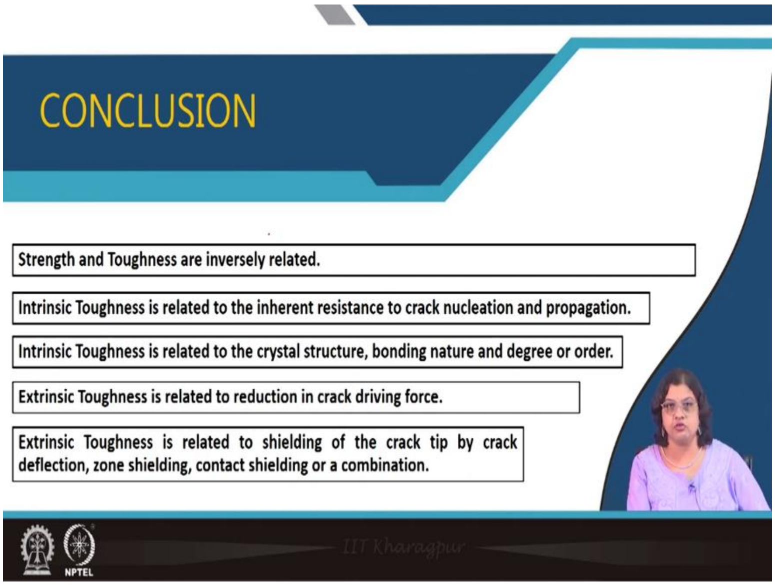

CONCLUSION

Strength and Toughness are inversely related.

Intrinsic Toughness is related to the inherent resistance to crack nucleation and propagation.

Intrinsic Toughness is related to the crystal structure, bonding nature and degree or order.

Extrinsic Toughness is related to reduction in crack driving force.

Extrinsic Toughness is related to shielding of the crack tip by crack deflection, zone shielding, contact shielding or a combination.

So, let us conclude this lecture that we have seen here that strength and toughness are always inversely related and we target to achieve both higher and higher combination of strength and toughness simultaneously. And to achieve that, we need to understand that how the toughness or the fracture toughness of the material can be increased either intrinsically or extrinsically.

Now, intrinsic toughness is the inherent resistance of the material to crack nucleation and propagation. So, this intrinsic toughness is related to the crystal structure or the nature of bond or the degree of order whether this is randomly ordered or there is a short or high range order those dictates that how tough the material will be whether it is the fracture mode will be ductile or brittle.

And extrinsic toughness on the other hand is related to the reduction in the crack driving force. So, that means, that part of the energy will be used up in some other mechanism to shield the crack and such that the growth of the crack will be restricted. And this is particularly related to different kinds of mechanisms such as the crack deflection, zone shielding, contact shielding or a combination of both zone and the contact shielding.

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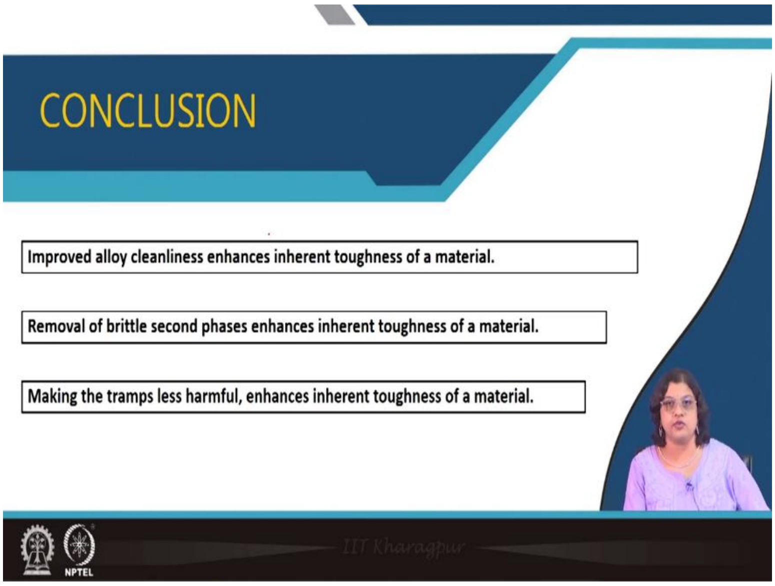

CONCLUSION

Improved alloy cleanliness enhances inherent toughness of a material.

Removal of brittle second phases enhances inherent toughness of a material.

Making the tramps less harmful, enhances inherent toughness of a material.

There are other ways to achieve higher fracture toughness one of this is to make the alloy clean improved alloy cleanliness by removing the impurities or in some cases we can get rid of the brittle second phases of bigger size particularly bigger size which act as a possible other of which are most prone to crack initiation that can lead to early fracture or in case that we are not able to remove the inclusions or the impurities, we can at least try to make it less harmful. And the example has been shown that how we can enhance the toughness in or the reduce the anisotropy in the behavior if you are adding rare earth that can form the rare at sulfide in case of steel.

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