Fracture, Fatigue and Failure of Materials
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Lecture 24
Fracture Toughness (Contd.)

Hello everyone and welcome back to the 24th lecture of the course Fracture Fatigue and Failure of Materials.

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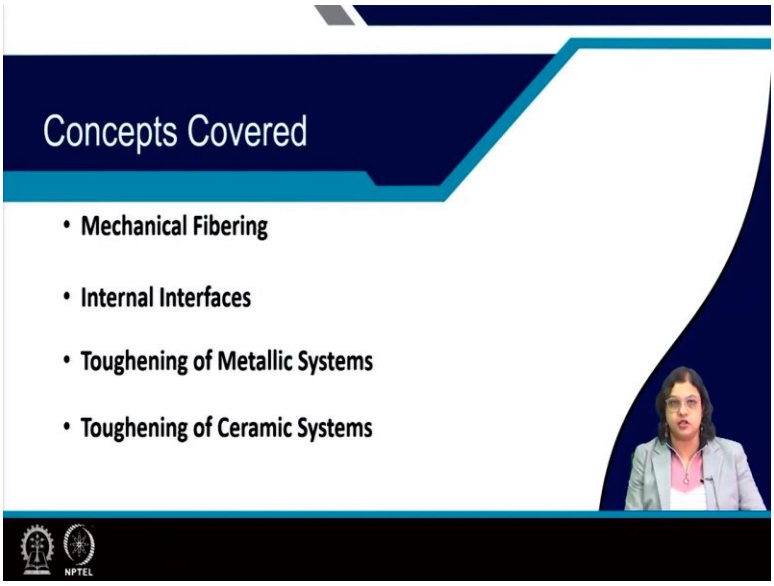

Concepts Covered

- Mechanical Fibering
- Internal Interfaces
- Toughening of Metallic Systems
- Toughening of Ceramic Systems

And in this lecture, we will be talking about the mechanical fibering and how that can influence the fracture toughness of material particularly metallic systems as well as the presence of the interfaces internal interfaces that can modify or increase the toughness particularly the extrinsic ways by which fracture toughness of a material can be increased. And then we will see that, how for typical metallic system, how the toughening can be achieved and same for the ceramic systems how we can achieve higher and higher toughness.

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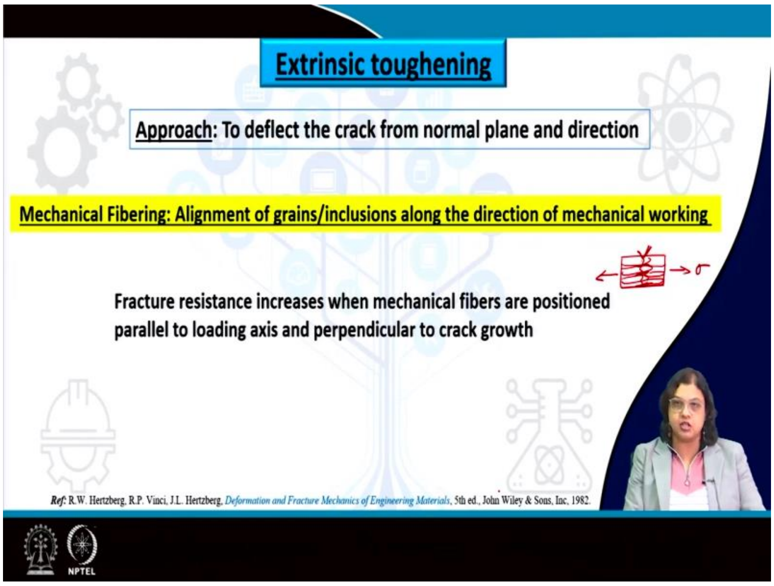

Extrinsic toughening

Approach: To deflect the crack from normal plane and direction

Mechanical Fibering: Alignment of grains/inclusions along the direction of mechanical working

Fracture resistance increases when mechanical fibers are positioned parallel to loading axis and perpendicular to crack growth

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, coming to the point of view from the extrinsic toughening, we know that this is the way by which we deflect the crack from its original plane and direction of motion to another one we kind of diverted and part of the energy is consumed in all this diversion, which enhances the total energy consumption and that means, the fracture toughness of the material increases.

In the earlier lectures we have seen how by removing the impurities or by making the impurities less harmful or by simply defining the microstructure size, we can enhance the toughening of the material intrinsically. On the other hand, if we still try to have a higher and higher toughness of the material, we can employ any other way by which the crack path can be deflected or diverted and we can still achieve higher and higher toughness.

So, let us see what are the typical ways which are followed? one of the very interesting way is when mechanical fibering, so, mechanical fibering means that, it is the way by which the grains or the microstructure features including even the inclusions all those are aligned along the direction of mechanical working. So, we often need to employ some kind of mechanical working to fabricate some component to give it a particular shape or simply to modify the microstructure or have different kinds of properties, we need to employ some kind of processing of the material or working of the material.

Accordingly, along the direction of those working the microstructure features are also supposed to get oriented and that leads to a variation in the properties also. So, that variation can be actually employed in a beneficial way in case the mechanical fibers are positioned parallel to the loading axis and perpendicular to the crack growth.

So, for example, if we have a structure like this and due to some reason due to the mechanical fibering we have the elongated grains like this. And if we know that there is a crack, which is at the edge and it is supposed to grow on this direction, so, that means that the applied stress is perpendicular to that, then each time the crack comes in contact with these interfaces, it will be hindered by those interfaces and more the number of days those hindrances, more will be the toughness of the material. So, the crack somehow needs to overcome those barriers and to move forward and that will lead to an enhancement in the energy requirement for fracture to occur to materialize and that will lead to an enhancement in the fracture toughness in turn.

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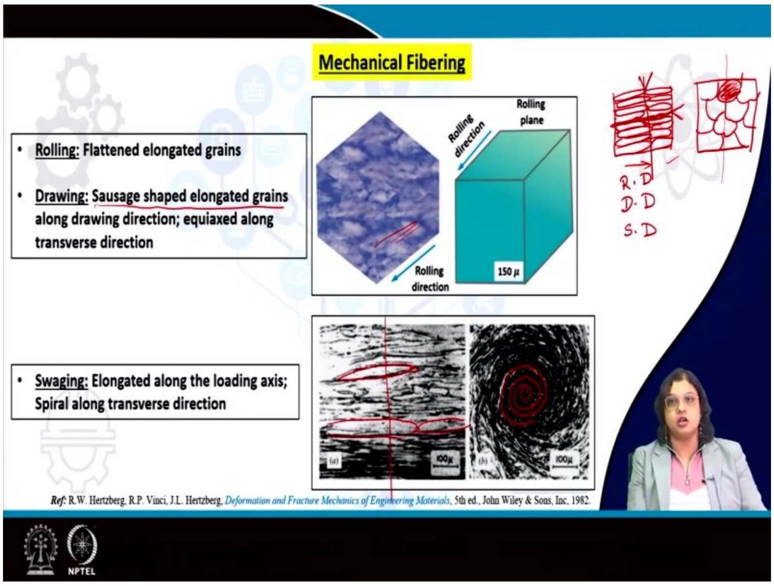

Mechanical Fibering

- **Rolling:** Flattened elongated grains
- **Drawing:** Sausage shaped elongated grains along drawing direction; equiaxed along transverse direction
- **Swaging:** Elongated along the loading axis; Spiral along transverse direction

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 see how this mechanical fibering looks like? the typical operations that we do the mechanical working that we do are rolling and due to the rolling, what we achieve is elongated grains along the direction of the rolling. On the other hand, one that we otherwise use other than rolling is drawing we often need to draw for example, for wires or rods, we often need to draw it along some particular direction.

And for that this is an example of 3d structure of a rolled one. So, we can see that this is the rolling direction and we can see some elongated grains along this direction. And most interestingly, if for example this is the rolling direction or for that matter the drawing direction, along with it has been drawn.

We are supposed to see the elongated grains which are referred to here as sausage shaped grains which are nothing but the one which are having very high aspect ratio and which are oriented along the direction of the rolling or drawing and not only the grains, but the inclusions are also supposed to be oriented along the direction of the rolling and that makes all the differences and that can lead to particularly an isotropy in the property.

Now, as I mentioned that if we have a crack along this direction, it such kind of orientation of the grains could be beneficial, but on the other hand, if we are having the crack along this direction, then the crack will be it will be easier for the crack to move through these boundaries itself. So, in that case such kind of orientations of the grains will not be favored at all.

So, it gives us an isotropy in the property, but knowing that we have the grains oriented along certain direction, we can make it work in such application which we know that the crack or the stresses will be applied perpendicular to those directions and we can employ it for a beneficial reason. So, but if we are looking this on the other direction like the transverse direction.

So, if we are cutting it along some plane then we are going to look it as if there are equiaxed grains. So, all this sausage shaped or the elongated grains will be actually on the other side and we are seeing just the cross section. So, if we are cutting it through we can through the plane of this computer, we can see that those are the elongated grains that are there.

So, just by looking on the transverse direction, we can still think that this is supposed to be in the ones which are having isotropic properties, but which may not be the case if we know the working history of the material we should be able to understand or if we are looking into the microstructure 90° to this plane again we will be able to see that there are elongated grains along this direction.

So, this is one of the ways by which the toughness of the material can be modified as I mentioned that that depends on the position of the crack perpendicular to the direction of the grains or the microstructure features or along the direction of the microstructure features. So, based on that we can use it for both a positive effect or a negative effect we have to be careful about this.

Other than rolling and drawing there is another mechanism which is commonly used is swaging. And in this case also we are going to see elongated grains like we have seen for the case of rolling okay if we are looking along the swaging direction, but interestingly we can see here those elongated grains if you can look into that. So, that way it looks very similar to that of rolling one, but if we are looking into the cross section if we are cutting in this plane and then looking through the cross section, instead of the equiaxed grains that we have seen for the case of rolling here, we are seeing this spiral shape one.

So, we are looking into it like the whirlpool that are forming and that signifies that swaging operation has been done on this. So, if we are looking into a different kind of microstructure, which shows such kind of spiral behavior, we know about the processing history of the material and such kind of processing history are very, very important when we are talking about the failure analysis if something has already failed and we are looking into the broken components, then we have to know that whether what kind of operations has been done previously to estimate or to understand the differences in their behavior. So, that is one of the ways by which mechanical fibering can be used to have a better or improved toughness.

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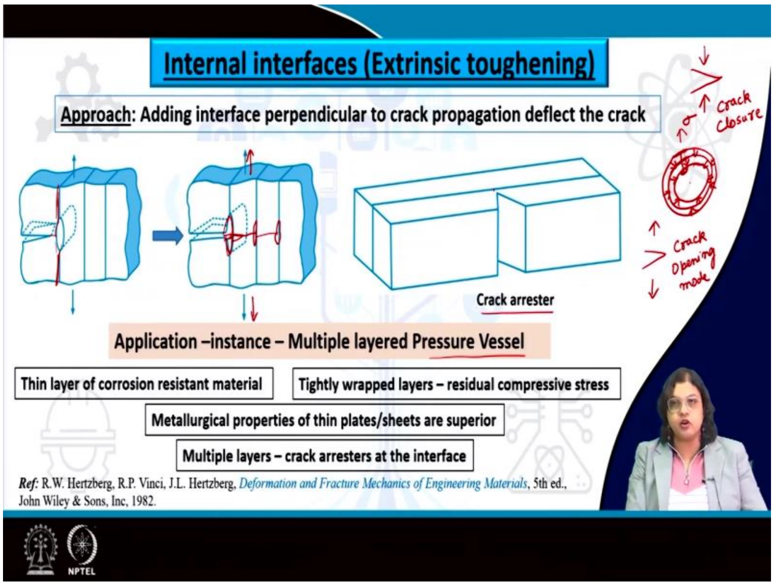

Internal interfaces (Extrinsic toughening)

Approach: Adding interface perpendicular to crack propagation deflect the crack

Application –instance – Multiple layered Pressure Vessel

Thin layer of corrosion resistant material

Tightly wrapped layers – residual compressive stress

Metallurgical properties of thin plates/sheets are superior

Multiple layers – crack arresters at the interface

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

And the other very interesting way by which toughness can be enhanced extrinsically is by adding some surfaces, free surfaces which means that if we are making some layers in the component, then we can still achieve higher toughness providing that those interfaces or those layers are perpendicular to the crack propagation direction and that essentially will lead to deflection of the crack.

So, this is one example when we have a crack here and we are adding the interfaces which are perpendicular to the direction of the growth of the crack. So, we can see that as soon as the crack comes in contact with these interfaces, the part of the energy is getting released because these interfaces are nothing but a free surface intermediately present right.

So, as a result the crack tip is supposed to release some of the energy are getting blunt. So, now, the sharp crack which was supposed to have a sharp tip is now getting blunt here and as we all know that as the crack tip is getting blunt so, that means, the stress concentration at the tip of the crack is getting reduced to a lot extent and that means that the amount of energy that is required or the amount of stress intensity factor that is required for the bones to be broken to have to achieve fracture is not being achieved in such condition and hence catastrophic fracture will not occur.

Now, we that means that we need to apply more and more stress to overcome this barrier to gain further energy such that the crack can propagate and reach till the next interface. Now, when it is coming to the next interface, again the repetition will be there and once again the tip of the crack will be blunt by these interfaces, because the part of the energy will get released there and every time it comes in contact with such kind of interfaces, it is will be getting blunt, and we need to apply more and more energies to reinitiate the growth of the crack. Obviously, the fracture toughness essentially will increase from such behavior.

Now, it has a very smart applications of course, these are applied in many of the ways, but I thought of showing you a way by which this can be employed in a pressure vessel. So, what is being done as you can as you know that pressure vessel is the one which is used for storing pressurized fluids. So, it is a cylindrical vessel typically, so, what is being done is that the cylinder the volume of the cylinder is made of a series of or different multiple layers of metallic sheets.

So, it gives something like this when so, this kind of orientation of the crack with respect to the laminates or the interfaces are known as the crack arrestor because the crack has been arrested by each of these layers. So, for the case of pressure vessels, if it is a cylindrical one this is how it is so, it is made of the concentric layers, and we finally, store the fluid in this section.

Now, the benefit of using these concentric layers instead of a single layered one for pressure vessel is the following we do not need to have a corrosion resistant material for the entire wall thickness we have already seen the importance of wall thickness and the importance of the critical thickness that need to be maintained to have the leak before break condition.

But, in this case, since we are having the multiple layers, we do not need a single material to be used here since in most of the cases pressure vessels are used for storing the corrosive fluid and we need a highly corrosion resistant material as the cylinder material. So, we can achieve that by using a very thin layer of the corrosion resistant material.

Only the inner one in the innermost layer can be made of that material which are supposed to be expensive in most of the cases, but the rest of the layers can be made with some other kinds of material which may not need to be that much corrosion resistant as well. Then this makes it actually economic, but the other technical or the scientific reason, why we prefer such kind of multiple layers is that each of these layers are actually applying some kind of compressive stresses.

So, it applies a residual stress and we also know that residual stresses are good news for the crack if there are any existing crack residual compressive stresses will act to close the cracks. So, if there is a crack, we know that this is the most dangerous mode, this is the crack opening mode when we are applying the stress normal to the crack propagation direction and those are the tensile stresses.

But on the other hand, if we have a crack and we are applying compressive stresses near its tip on the way, so that will lead to crack closure. So, compressive stress is always preferred to close the crack and that means that the fracture incident will be delayed. So, all these multiple layers are actually acting to have these compressive stresses as a residual one and that will lead to have even if the crack generate along this in any of the internal layer this will be compressed and that will help to close the crack.

Now, we have also seen when we were discussing about the ductile to brittle transition and also some other cases that a thin specimen versus a thicker specimen thicker specimen has lot of non uniformity in the properties there will be plane strain condition that will be active and there will be triaxial shear amount of stress even if the presence of a smallest amount of crack and that will lead to some detrimental properties in the sense that properties of the thin sheets are always superior compared to the thick version of the plates.

But most importantly, why is it preferred to have multiple layers and pressure vessel is because of the crack arrestor dimension that even if the crack generates at any point on the internal surface, which is perpendicular to the thickness or which is along the hoop stress is being active, we know at the circumference.

So, that way, each time this crack has to overcome this barrier, it will get affected by these internal layers and that means that the crack tip will get blunt at every stop there at every hindrance and that means that we will require higher and higher amount of energy for the fracture to materialize. So, overall the fracture toughness of the pressure vessel cylinder will increase.

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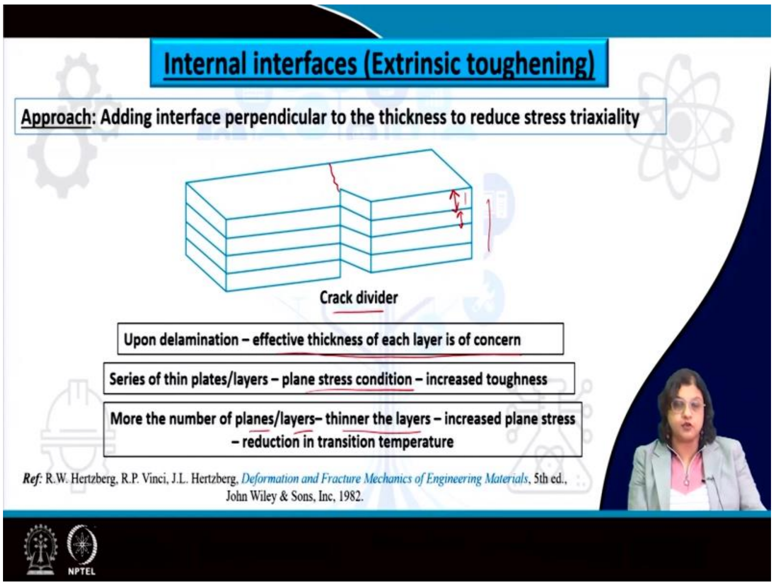

Internal interfaces (Extrinsic toughening)

Approach: Adding interface perpendicular to the thickness to reduce stress triaxiality

Crack divider

Upon delamination – effective thickness of each layer is of concern

Series of thin plates/layers – plane stress condition – increased toughness

More the number of planes/layers– thinner the layers – increased plane stress – reduction in transition temperature

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

Another way by which these internal layers can actually lead to an enhancement in toughness is by adding this interface perpendicular to the thickness direction and this is known as crack divider where you see that instead of having the layers along this direction, we are having the layers which are perpendicular to the thickness direction and that is also beneficial in the sense that in this case, the crack growth direction is not being hindered by the interfaces.

Rather what is happening is that that if even if it gets delaminated, the effective thickness of each of this layer is what is very important. Now, each of this layer will act as the individual layer and we already know that for the case of thin layer planes stress condition gets active and we have also seen that the fracture toughness under plane stress condition is higher than that under plane strain condition.

So, while figuring out the fracture toughness values in the lab scale, we always prefer to find out that value the lower bound value in the lab scale for the plane strain condition, but in actual service, we want it to have a plane stress condition such that we achieve a higher fracture toughness value.

So, that is what is being achieved here in case of the crack divided morphology, where each of these laminates even if it gets it is getting delaminated we can see that each of these plates are having higher toughness and more or the number of those planes or layers and thinner are the layers more will be the plane stress condition will be very much active and that will lead to even a reduction in the transition temperature.

So, if we are using a component at a lower temperature knowing that DBTT will be of significance, there we can use such kind of morphologies we can design it in this way in the crack divider way such that we can achieve higher toughness or lower DBTT in such case for cryogenic applications particularly.

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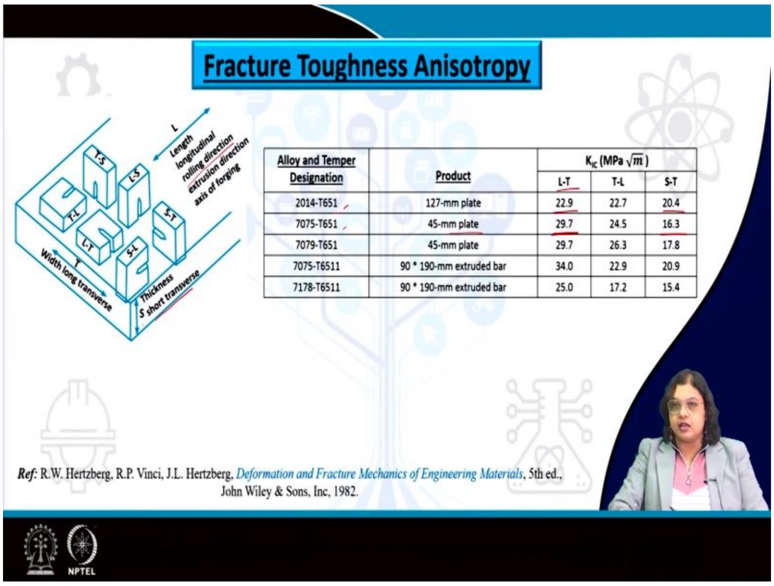

Fracture Toughness Anisotropy

Alloy and Temper Designation	Product	K_{IC} (MPa $\sqrt{m}$)		
		L-T	T-L	S-T
2014-T651	127-mm plate	22.9	22.7	20.4
7075-T651	45-mm plate	29.7	24.5	16.3
7079-T651	45-mm plate	29.7	26.3	17.8
7075-T6511	90 * 190-mm extruded bar	34.0	22.9	20.9
7178-T6511	90 * 190-mm extruded bar	25.0	17.2	15.4

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 is just an example of an aluminum alloy where specimens has been made along different direction and we can see that the L here signifies the length and this is the longitudinal rolling direction or the extrusion direction or the axis of forging whichever kind of operation has been made. And then there is the S which is the short transverse direction as well as the T which is the transverse direction and specimen has been made with different configurations of the crack growth path with respect to those directions.

And we can see that there is a huge change in the numbers of the fracture toughness that have been achieved. For example, we can take any one and you can see that the one here with the 44-millimeter plate has the L-T configuration has a fracture toughness values of 29.7 are close to 30 MPa√m whereas along the S-T direction it has the list which is only 16.3 MPa√m.

So, that is a huge jump in the values. Not All the cases are for all the different kinds of alloys will behave in the same way of course not what we can see here that there is not much change in the properties for this 2014-T651 condition, but for other cases or for other shape we can see there is a huge differences in the values.

So, depending on the kind of material that we are working depending on the kind of operations that has been done, we have to find out that which way can give us the best fracture toughness behavior and we can use that for the practical applications.

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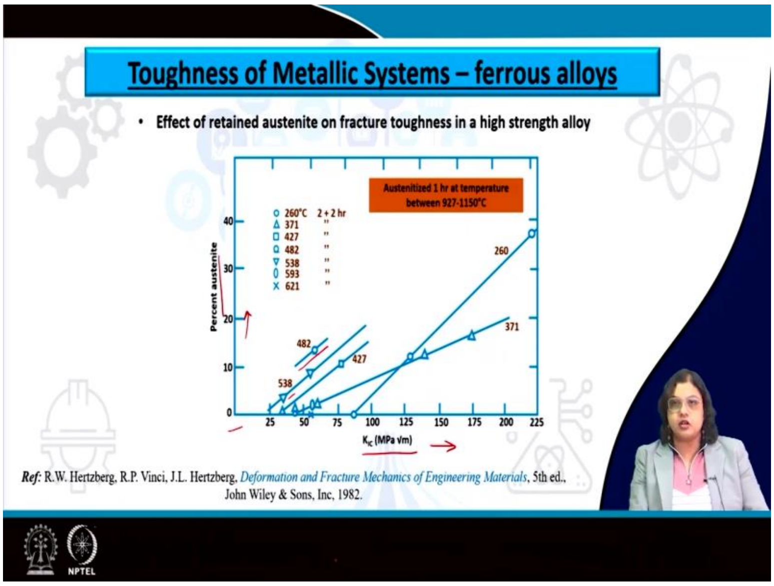

Toughness of Metallic Systems – ferrous alloys

- Effect of retained austenite on fracture toughness in a high strength alloy

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, for the case of metallic system, if we try to enhance the fracture toughness of metallic system, let us first go with the ferrous alloys, because this is the one iron base alloys are the one which are most commonly used to structure materials for the metallic segments. And for that one of the ways by which the toughness can be enhanced is by having higher amount of austenite retained austenite phase.

Now, austenite having an FCC structure is any way having more number of slip systems. So, that means that its toughness is more so, by any kind of operations, if we are having higher amount of retained austenite. We can have achieve higher fracture toughness values also. So, this is what is shown here in experimental results that as the percent of austenite increases the fracture toughness value plain strain fracture toughness value of K_{IC} increases.

Now, this is happening for almost all the temperatures, as you can see here, the first one is at 482 °C and this one here is at 538. So, these are varying in a different way of course, the trend is not always the same at the different temperatures or different kinds of operations, but at least we can always say that, as the percentage of the austenite increases, fracture toughness also increases. So, this is a straightforward relation that we have seen

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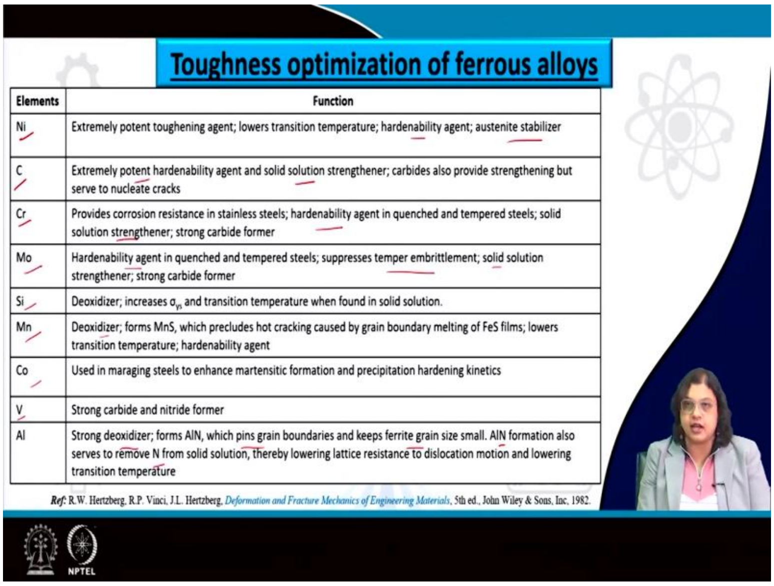

Toughness optimization of ferrous alloys

Elements	Function
Ni	Extremely potent toughening agent; lowers transition temperature; hardenability agent; austenite stabilizer
C	Extremely potent hardenability agent and solid solution strengthener; carbides also provide strengthening but serve to nucleate cracks
Cr	Provides corrosion resistance in stainless steels; hardenability agent in quenched and tempered steels; solid solution strengthener; strong carbide former
Mo	Hardenability agent in quenched and tempered steels; suppresses temper embrittlement; solid solution strengthener; strong carbide former
Si	Deoxidizer; increases σ_{ys} and transition temperature when found in solid solution.
Mn	Deoxidizer; forms MnS, which precludes hot cracking caused by grain boundary melting of FeS films; lowers transition temperature; hardenability agent
Co	Used in maraging steels to enhance martensitic formation and precipitation hardening kinetics
V	Strong carbide and nitride former
Al	Strong deoxidizer; forms AlN, which pins grain boundaries and keeps ferrite grain size small. AlN formation also serves to remove N from solid solution, thereby lowering lattice resistance to dislocation motion and lowering transition temperature

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

And based on such different kinds of observations that has been made by different scientists all across the globe, people have come to a conclusion that some of the elements that should be added to achieve higher fracture toughness in iron-based alloys and some which should be avoided.

Now, strength and toughness again being two very competitive properties, we have to be careful of either enhancing the strength or enhancing the toughness practice toughness or in case we need both we have already seen in the last lecture, that microstructure refinement is the one way by which we can achieve both higher strength and toughness. But other than that, most of the cases we have to rely on one of the properties either yield strength or fracture toughness.

So, here are some of the elements which are more commonly used for example, nickel. Nickel is a very potent toughening agents it increases the toughness and it most importantly it lowers the transmission temperature also and it hardens the system and it stabilizes the austenite content and as we have seen in the last slide that more is the austenite content more will be the toughness in that way also nickel is acting beneficially.

Carbon, now carbon is very much very widely used in case of steel in case of iron alloys for several reasons, one of them being it is a very good hardening agent. So, it increases the strength through solid solution strengthening and but above all, it also all these carbide particles are the potential sites from which the cracks initiate. So, we have to be careful, if we are talking about both strength and toughness requirement, we have to be careful about the amount of carbides or carbon that can be added.

Chromium as we all are aware that it provides corrosion resistance particularly used in stainless steel and it has a lot of influence as an harden ability agent for strengthening for as per the solid solution strengthening, but it also forms a carbide and chromium carbide is something that are not always very much preferable. Particularly when we are talking about the crack initiation sites.

Molybdenum is once again a hardening agent and it suppresses the temper embrittlement it also acts as a solid solution strengthener but at the same time it has a carbide formation ability also. Now, Silicon is often added as its a role to be a deoxidizer we have seen that how oxygen content needs to be minimized to achieve higher toughness and, in that sense, silicon acts as a beneficial one and but it also increases the yield strength, but the transition temperature as well when found in the solid solution.

Manganese on the other hand is a deoxidizer. And we have also seen the influence of manganese in lowering the ductile to brittle transition temperature, manganese is the one which reduces the DBTT and we still have to maintain this carbon is to manganese ratio to obtain a particular property set of properties.

Cobalt is often used to enhance the martensite formation and we also know that martensite has a very higher strength or hardness of the materials. And for that sense cobalt acts as a beneficial one particularly if we are talking about the strengthening mechanism. Vanadium, on the other hand is a strong carbide and nitride former, so, in case those carbide or the nitride particles are acting as a potent crack incision sites then we have to be careful about adding the vanadium content.

Aluminum on the other hand is once again acts beneficially it is a deoxidizer but it also forms aluminum nitrate, which means the grain boundaries and it helps in the grain refinement it arrests the grain growth particularly for the ferrites and as we have seen that grain refinement has a significant influence on the enhancement in both strength and toughness. So, that sense it can be a benefit have a beneficial role. On the other hand, by forming the aluminum nitride, this nitrogen is being removed from the system and then from that sense also it can act to enhance the toughness and also for lowering the transition temperature.

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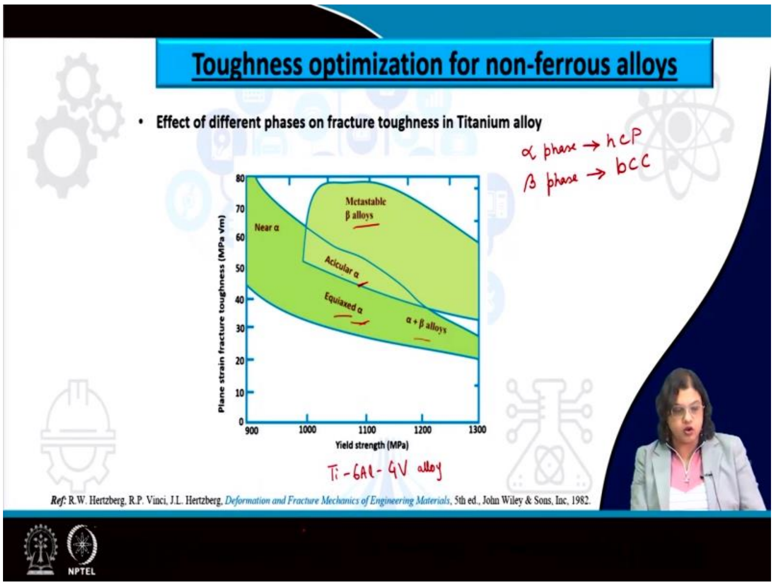

Toughness optimization for non-ferrous alloys

- Effect of different phases on fracture toughness in Titanium alloy

α phase → hcP
β phase → bcc

Ti-6Al-4V alloy

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, for the case of non ferrous alloys, here is one example of titanium alloy, now titanium alloy so, this one is actually a Ti-6Al-4V alloy that has been shown here and there are different phases in this titanium system also for example, the α phase which has a hexagonal close packing structure as well as the β phase which is having a body centered cubic structure and it is seen that the β phase particularly the metastable β phase has the highest toughness.

So, if we want to have achieve higher strength and toughness we should go for this β alloys particularly at high temperature so, that we can achieve higher strength and toughness. On the other hand, the α phase which is having an equiaxed structure and even the α + β alloys are also suffers from lower plane strain fracture toughness.

Now, amongst the β also there are the differential shapes or size of the grains that can also affect in the fracture toughness behavior for example, the acicular α versus the equiaxed α we can see the acicular one which is having a longer aspect ratio that actually works better and has higher values of fracture toughness compared to the equiaxed one. So, we have to be careful about the phase content and as well as the shape and size of the different phases in the different material system.

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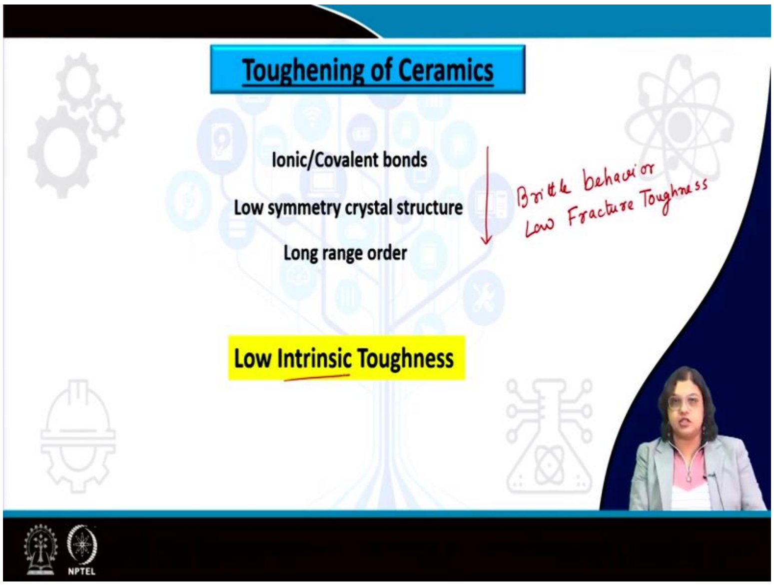

Toughening of Ceramics

Ionic/Covalent bonds

Low symmetry crystal structure

Long range order

Brittle behavior or
Low Fracture Toughness

Low Intrinsic Toughness

Now, coming to the ceramics moving on from the metallic system, let us see what is there what is the toughness mechanism for ceramics and for that, we have to again recap, the one that we have mentioned in the very first lecture on fracture toughness, how we can enhance this intrinsically or extrinsically. There we have seen that in case there the bones are ionic or particularly covalent the inherent fracture toughness of the material will be very, very low it will be brittle by default, because of this bonding nature.

And this is what is there in ceramics there are mostly ionic or particularly covalent bonds, it also has very low symmetry crystal structure as well as long range order now, all this actually act for brittle behavior and brittle behavior means low fracture toughness so, that means that ceramics are anyway having lower values of intrinsic toughness.

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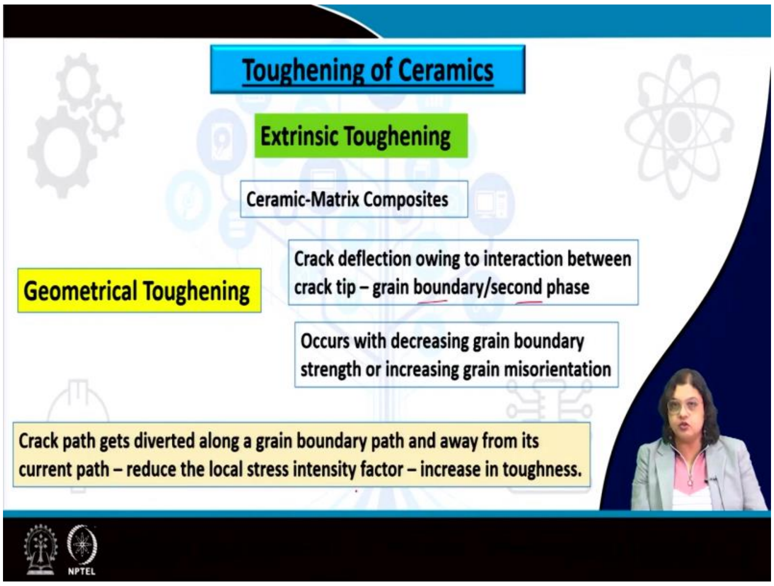

Toughening of Ceramics

Extrinsic Toughening

Ceramic-Matrix Composites

Geometrical Toughening

Crack deflection owing to interaction between crack tip – grain boundary/second phase

Occurs with decreasing grain boundary strength or increasing grain misorientation

Crack path gets diverted along a grain boundary path and away from its current path – reduce the local stress intensity factor – increase in toughness.

So, if we want to toughen a ceramic, we need to employ some kind of extrinsic toughening mechanism and this is particularly applied for the case of ceramic matrix composites, and one of the way by which we can achieve this is by geometric toughening. So, what it is meant by is that, if there is a crack and we have a composite, so, we have a matrix as well as a fiber phase or particle phase and in that the crack deflection can occur owing to the interaction between the crack tip as well as the grain boundary or the second phase.

So, any kind of interfaces those are there the crack can interact with such interfaces and based on that the energy of those interfaces and other mechanisms there can be a crack deflection now, if the crack is being deflected or diverted to any other direction apart from its regular growth direction, it can lead to higher toughness and with decreasing grain boundary strength or increasing grain misorientation this deflection can be even more significant and that can lead to even higher and higher toughness.

So, if the crack path is getting diverted along the green boundary or it gets away from its current path, so, that means that every time it is being hindered by such kind of interfaces, be it a grain boundary or it be the second phases and because based on the misorientation between these two phases, it has to that the local stress intensity factor gets reduced and eventually that means that we need to apply more and more energy and the toughness basically increases.

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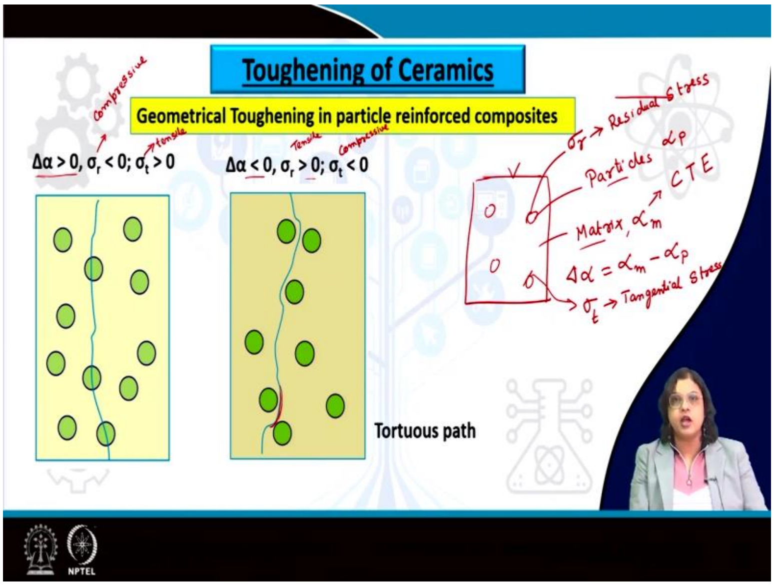

Toughening of Ceramics

Geometrical Toughening in particle reinforced composites

$\Delta\alpha > 0, \sigma_r < 0; \sigma_t > 0$

$\Delta\alpha < 0, \sigma_r > 0; \sigma_t < 0$

Tortuous path

Now, in case of the particle reinforced composite, let me draw it here. So, if we have such kind of behavior where we have a matrix phase as well as these are the particles or precipitates. So, what is of interest here is the coefficient of thermal expansion for these particles as well as the matrix. So, if we denote this with the symbol α, so, this signifies the coefficient of thermal expansion.

So, this is for the matrix this can be signified as α_m for particles, this could be α_p and the difference between the coefficient of thermal expansion can be written as Δα which is nothing but α_m minus α_p. Now, because of this coefficient of thermal expansion and because of the differences in the properties between the matrix phase as well as the particle or the other reinforcement phases, there is also some kind of residual stresses that are generated here.

So, this is nothing but σ_r or termed as the residual stresses as well as there could be a tangential stress particularly at this interface in the matrix and this is termed as σ_t or tangential stress. There is an interaction with all these different kinds of stresses as well as the coefficient of thermal expansion and based on the nature of the stresses like be the tensile stress or a compressive stress, we can find out that how the any kind of crack which is available there how this can behave, how this can move.

So, this is one of the condition when we have this coefficient of thermal expansion greater than zero. So, it has a positive value as well as the residual stress is compressive. So, what we can see here is a compressive residual stress because it is less than 0 value. And the tangential stress on the other hand is tensile. So, if such is the case, then the crack will be attracted by these particles and as a result the crack can move or crack and cut pass this particle.

And this again depends on the nature of the particles and this nature of the particles is being dictated by the Δα, the coefficient of thermal expansion and all those are correlated all the other stresses, the residual stress as well as the tangential stresses, those are all correlated with those properties of those individual phases and if that is so, the crack can move through this particle. So, cut through this particle.

On the other hand, if we have the second case where the coefficient of thermal expansion difference is less than 0, so, it has a negative difference and so, that means that the matrix phase is higher alpha value as well as the residual stress is a tensile one. So, in this case, since it is more than 0, so, that means the residual stresses tensile one as well as the tangential stress is a compressive one.

So, if such is the case, then the crack will be rejected by the particles so, it will be deflected it will not be allowed to cut through the particles rather it will deflect it will get away from the particles and that means that every time there is a particle, it has to change its course or its path and that will consume more and more energy. It will make the crack path very much tortures or rough and that eventually will require higher fracture energy or the fracture toughness of the material will increase.

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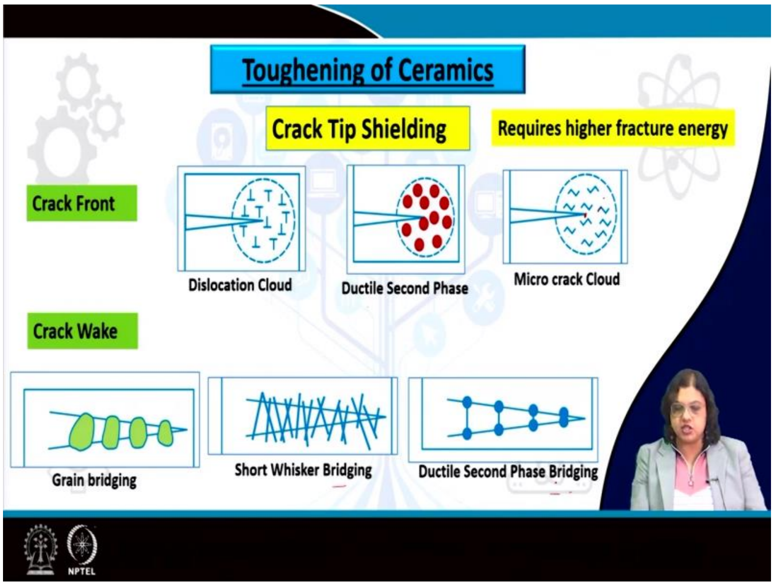

Toughening of Ceramics

Crack Tip Shielding

Requires higher fracture energy

Crack Front

Crack Wake

Now, other mechanism of toughening in ceramics include crack tip shielding. So, this means that we if there is a crack already existing and if the tip is being shield by some other mechanisms such that the available stress intensity factor is getting reduced, then obviously, the fracture toughness of the material will increase.

So, this is what we have seen, there could be two ways either the crack front. So, if there is a crack and there is some dislocations, which is happening in the matrix phase or in the material ahead of the crack tip that can lead to using up some of the energies and that will lead to an enhancement in the fracture toughness or if there is a second phase which is ductile and that again can have some deformation and as a result the fracture toughness of the material can increase.

But this took the particularly the dislocation cloud are hardly seen for the case of ceramics because there are hardly any presence of dislocations if we are having a ductile second phase of course, this could be a valid point, but mostly what is seen here is because of the differences in the coefficient of thermal expansion or because of the high amount of energy that is available at the tip of the crack that leads to formation of microcracks.

Now, these micro cracks here ahead of the crack tip are nothing but the free surfaces. So, every time a crack tip is comes in contact with this micro crack it the energy is partly getting released and as a result it has to again reunite and grow further and that eventually leads to an enhancement in the fracture toughness of the material.

So, other than crack front there could be some activity on the crack wake. So, this part here and this is one mechanism, where a grain bridging has been shown. So, you can see that there are different grains which are being bridged, by the part of the crack or if there are whiskers kind of present there, then that can also lead to fiscal bridging. Or in case of the second phases, those can be also breached as the ductile second phase bridging and any kind of operations any kind of mechanisms like this will lead to an enhancement in the fracture toughness.

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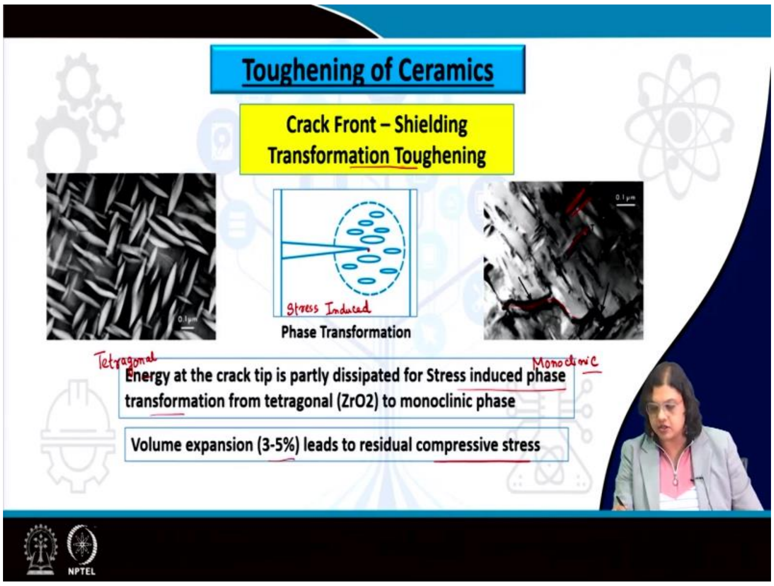

Toughening of Ceramics

Crack Front – Shielding
Transformation Toughening

Tetragonal

Energy at the crack tip is partly dissipated for Stress induced phase transformation from tetragonal (ZrO2) to monoclinic phase

Monoclinic

Volume expansion (3-5%) leads to residual compressive stress

So, we will look into two of these different ways by which the fracture toughness can be increased one is the crack front shielding that we have seen this one is very important particularly for ceramics, but also seen for metallic system which is the transformation toughening. So, what happens here is that at the tip of the crack because of the presence of high amount of energy there that can lead to some stress induced phase transformation.

So, this is seen also for different metallic system. For example, in case of steels we have seen the tip steel transformation induced deformation and transmission induced phase transformation there or we have seen this also for nickel titanium-based shape memory alloy or pseudo elastic alloys which undergoes a stress induced martensite transformation.

So, this is also seen for ceramics, particularly one of the example is zirconia base ceramics. Here is an example. So, this one we have a tetragonal ZrO2 or zirconia and because of the presence of a crack here as you can see that this is the crack path and because of the presence of high amount of energy there, there is a transformation from this tetragonal phase to a monoclinic phase.

And as a result, as you can understand that part of the energy that is available for at the crack tip will be used up for this stress induced phase transformation to occur. And also, not only that, because of this phase transformation, there is a volume expansion. Considering that the monoclinic one has a higher volume, so, there is a 3 to 5 % volume expansion and if there is a volume expansion considering the constraints at the surrounding is apply, we can understand that there could be a compressive residual stress.

And as I mentioned that any kind of compressive stresses are always beneficial in kind of closing the cracks. So, that will be helpful to achieve higher toughness of the material. Also, interestingly, we can see that although the transformation is happening near to the crack front, but if we are talking about the at a distance other apart from the crack tip, we can see that there are still these elongated tetragonal phases which are present. So, that leads to an increased toughening of the material.

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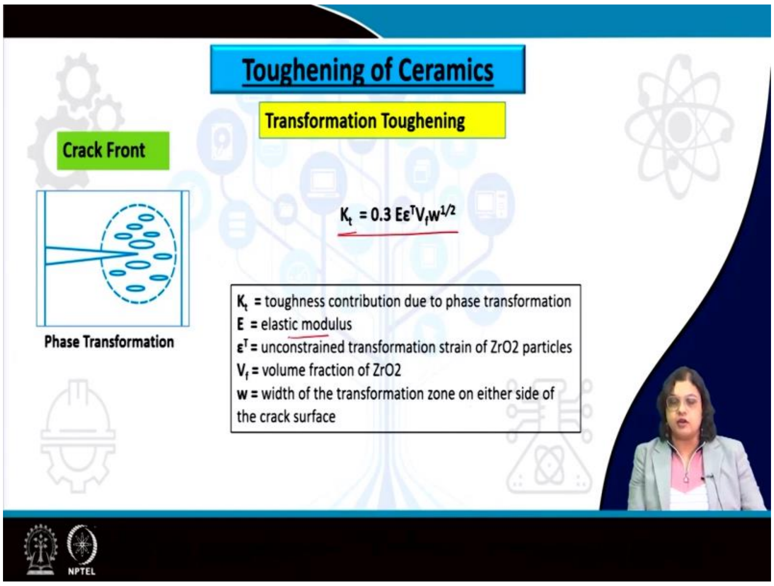

Toughening of Ceramics

Transformation Toughening

Crack Front

Phase Transformation

$K_t = 0.3\, E\varepsilon^T V_f w^{1/2}$

K_t = toughness contribution due to phase transformation
E = elastic modulus
ε^T = unconstrained transformation strain of ZrO2 particles
V_f = volume fraction of ZrO2
w = width of the transformation zone on either side of the crack surface

And we can also figure out the contribution of this toughening because of the phase transformation based on this kind of relation, which is related to the elastic modulus of the system as well as the unconstrained transformation strain of the ZrO_2 a typical transformation strain the volume fraction of the ZrO_2 particles those are there. The width of the transformation zone on either side of the crack surface based on this we can also figure out the contribution of phase transformation on the toughening behavior.

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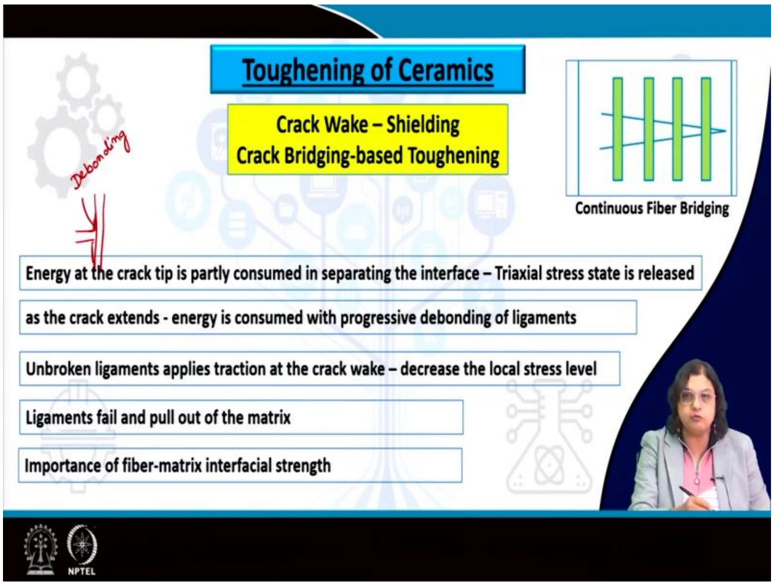

Toughening of Ceramics

Crack Wake – Shielding
Crack Bridging-based Toughening

Energy at the crack tip is partly consumed in separating the interface – Triaxial stress state is released

as the crack extends - energy is consumed with progressive debonding of ligaments

Unbroken ligaments applies traction at the crack wake – decrease the local stress level

Ligaments fail and pull out of the matrix

Importance of fiber-matrix interfacial strength

The other way by which ceramics can be toughened is through the crack wake shielding and that is by the crack bridging. So, what happens here is if we have this is particularly for the fiber reinforced composite, if we have a fiber like this and then there is a crack coming. So, it is possible that it is getting D bonded here at the interfaces and because of this D bonding once again the toughening the fracture toughness of the material is going to increase.

So, each time the crack is coming in contact with this interface with the fiber, the triaxial stress state of the crack will be released and as the crack extents energy is consumed with progressing D bonding of the ligaments. So, every time it is coming in contact with each of these ligaments and there is a D bonding that is happening, there will be an enhancement in the requirement of energy. So, for the progression of the crack.

And this unbroken ligament applies traction at the crack rate and that decreases the local stress level. Finally, the ligaments fail and pull out of the matrix. So, these are all sequentially happening and it is also related to the interfacial strength between the fiber and the matrix interfaces because, if there is a higher strength if the interfacial strength is too high, then it will not even break the bond or D bonding may not even happen, but rather the fiber will rupture on its own. Or on the other hand, if this interfacial strength is very low or weak on that case, actually, the energy release will not be of much significance and that will not lead to a significant enhancement in the fracture toughness as a whole.

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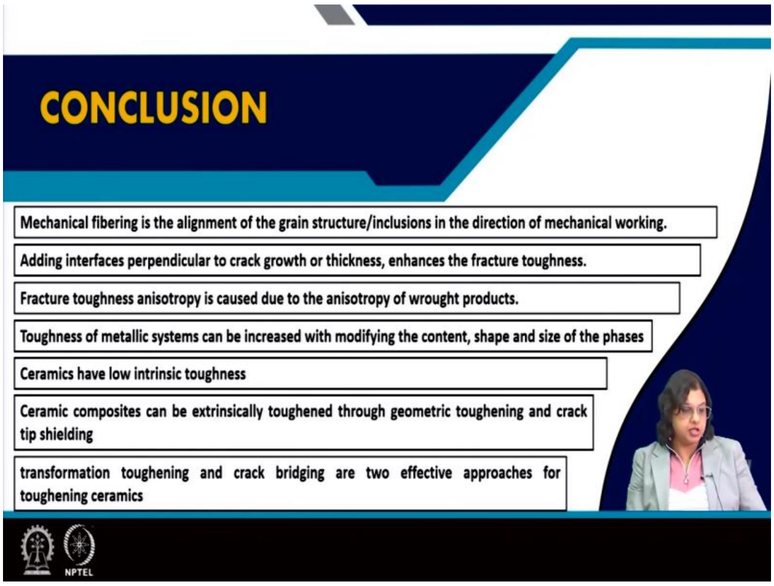

CONCLUSION

Mechanical fibering is the alignment of the grain structure/inclusions in the direction of mechanical working.

Adding interfaces perpendicular to crack growth or thickness, enhances the fracture toughness.

Fracture toughness anisotropy is caused due to the anisotropy of wrought products.

Toughness of metallic systems can be increased with modifying the content, shape and size of the phases

Ceramics have low intrinsic toughness

Ceramic composites can be extrinsically toughened through geometric toughening and crack tip shielding

transformation toughening and crack bridging are two effective approaches for toughening ceramics

So, let us conclude this lecture with the following points here. What we have seen is that mechanical fibering is means that it aligns the grain structure or the micro structures in general including even the inclusions along the direction of the mechanical working and adding interfaces perpendicular to the crack growth or to the thickness direction enhances the fracture toughness.

We have seen the crack arrestor and crack divider morphologies and fracture toughness an isotropy is caused due to the anisotropy of the wrought products. We have also seen that if we are machining the specimens at different directions we can achieve different values of the fracture toughness.

So, toughness of metallic systems can be increased with modifying the content, the phase fractions the shape and size of the different phases present. Ceramics by default have low intrinsic toughness because it mostly have ironical covalent bonding it has long range order or low symmetric crystal structure, but we can enhance the toughness of ceramics through some extrinsic ways and that could be obtained by geometrical toughening or corrective shielding. And it has been shown that how transformation toughening or crack bridging are the two effective approach for toughening of ceramics.

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So, following are the references use for this lecture. Thank you very much.