Friction and Wear of Materials: Principles and Case Studies
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Lecture - 18
Fracture and Toughening of Brittle Solids

Hello welcome back. So today we would learn the lecture and toughening mechanisms in brittle solids. So every material behaves differently in a loading condition. If you take a tensile loading condition.

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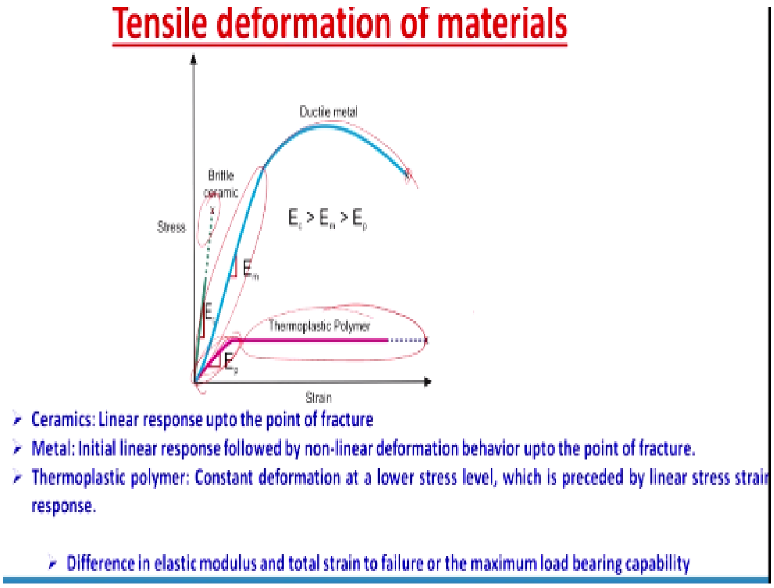

So if you look at the brittle ceramic material there is a linear response up to the point of the fracture whereas in metals there is initially there is a linear response and then this is followed by a non linear response. So if you look at the stress and strain response for a polymeric material, thermoplastic polymer material there is a constant deformation at a low levels of stresses which was proceeded by a linear stress strain response.

So overall the stress strain response for the different classes of material is different. So there is a difference in the linear response with respect to the slope of the stress and strain plot in a linear region. So this slope is nothing but the elastic modulus or we can call it as stiffness parameter. So the elastic modulus are the slope of the stress and strain in the elastic region is different from one material to another material.

So the elastic modulus is higher for the brittle material followed by the ductile material and then a thermoplastic material. In addition to this elastic modulus difference there is also difference in the total strain to failure right. So the failure occurs at a very less strain for the brittle material and a large strain for a ductile material even larger strain for a thermoplastic polymeric material. So there is difference in the elastic modulus, there is a difference in the total strain to failure and there is also difference in the load bearing capability.

So all this differences can be understood by the science behind this mechanical behavior.

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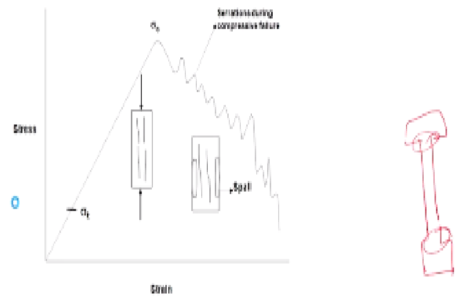
Mechanical behavior of ceramics



Compressive strength is typically 8 times larger than the tensile strength for ceramics

- Greatest significance in many tribological applications!!

- Also, the elastic modulus is the highest for ceramics
  - Also has the great relevance towards Hertzian contact damage resistance.

So let us see the mechanical behavior of ceramic material. So generally ceramics materials are studied for their strength measurement in a compressive loading conditions because ceramic materials are brittle. So the shaping of the specimen to a tensile test specimen like I shape right. So this itself making this shape is itself difficult for the ceramic material. If you somehow make this shape of this material for the tensile testing even while gripping itself, they may break right.

So generally these materials are studied for their strength property in a compressive loading conditions. So compressive strength for a ceramic material is generally 8 times larger than the tensile strength. So tensile strength if at all you can measure the tensile strength it is very less for a ceramic material. So higher compressive strength will be highly significant in a tribological applications right.

So ceramics are mainly used for tribological applications because of the higher strength. So all this tribological applications there is a compressive loading condition so you get a maximum benefit if you use a ceramic material. In addition to that the elastic modulus is also the highest for the ceramic materials if you look at this slope this is highest for the ceramic materials.

So elastic modulus is highest so it has also got great relevance towards Hertzian in contact damage resistance. So both these properties make the ceramic materials attractive for the tribological applications. Let us understand such a behavioral difference from a ductile material to a brittle material.

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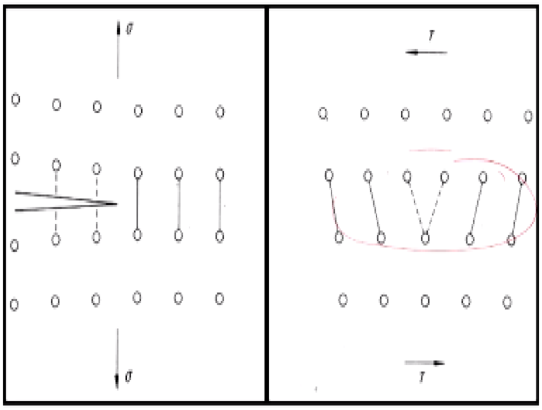
Fracture in brittle materials vs plastic flow in ductile materials



Propagation of crack: brittle fracture   Dislocation motion: plastic flow

So in a ductile material when an external stress is applied there is a resultant shear stress and then because of the shear stress these dislocations will be trying to move in a ductile material whereas in a brittle material the crack will be propagating by breaking the bones between these atoms in adjoin plain. So a propagation of crack will lead to a failure generally it is a catastrophic failure and so it is called brittle failure.

Whereas this dislocation movement in a ductile material will lead to plastic deformation. So you must note down these the dislocation movement and the propagation of crack are present in both materials, but only the propagation of crack is dominant in a brittle material than the dislocation movement so you get a brittle fracture that is a crack is propagating they coalesce each other and then lead to fracture so failure.

Whereas in ductile material the dislocation movement is dominant then the propagation of a crack. So you will have a effect, you will have a result as a plastic deformation right. So the domination of one phenomenon over the other is actually is different from one material to the other material. Let us understand it more clearly why there is a high toughness for the metallic materials right.

So as I told the crack propagation will also be there in a ductile material, but it is not significant. Let us understand how the propagation is not significant in a metallic material that leads to high toughness right.

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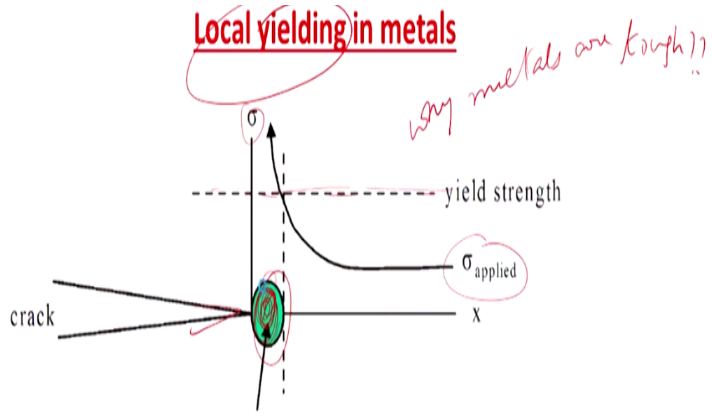

When stress ahead of crack tip exceeds the metal's yield strength, the metal will yield LOCALLY ---Dissipates energy, blunts the tip of the crack and results in toughness

So if you have a crack, crack is nothing but a defect right. Every material has certain defects so we have one of the types of the defects is the crack right. So let us understand a metal which is a ductile material has certain concentration of cracks inside it. Now you are applying a tensile stress over there right externally or applying certain stress sigma right. So this applied stress is the sigma applied.

So the stress ahead of the crack tip this region when the stress ahead of the crack tips exceeds. The metal's yield strength you see every material has a certain yield strength. So applied stress increases and then ahead of the crack tip it exceeds to a larger extent more than the yield strength of that certain material then when happens when the stress ahead of the crack tips exceeds the metal yield strength then the metal will yield locally.

So this region will be yielding locally. So because of this there is a dissipation of energy right. So because of the dissipation of energy so certain fraction of energy is consumed for this local yielding. So there is a dissipation of energy so that blunts the crack tip. So when it blunts the sharpness is reduced so it will not be propagated easily so that eventually leads to toughness.

So why metals are tough so why metals are tough because of the local yielding, this local yielding results in a higher toughness for a metallic material.

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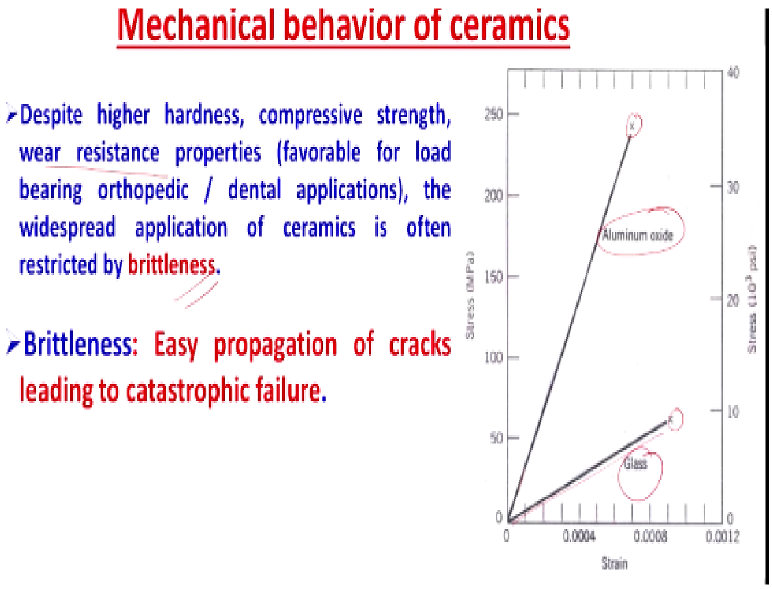

But let us understand the mechanical behavior of a brittle material right. So we have seen there is a highest compressive strength amongst the 3 material categories of brittle material, ductile material and a thermoplastic polymeric material Among this materials the ceramics the brittle material has highest compressive strength and a highest elastic modulus and it also posses highest hardness because of the inherent bonding because ceramics are materials in which the bonding is predominantly iconic or covalent right.

So these bonding are stronger than the metallic bonding. So because of that you get a superior properties of hardness, compressive strength, elastic modulus. So it also gives a wear resistance superior wear resistance. So most of the tribological applications we require higher hardness, higher compressive strength, higher elastic modulus that leads to superior wear resistance.

So but actually despite of having such a superior combination of the properties these ceramics are less used in applications or we can say or we can say the applications are often actually restricted because of the only problem within the brittleness right. Brittleness can be understood as easy propagation of the cracks that leads to catastrophic failure can be understood as a brittleness.

So brittleness so you can see the stress and strain plot for a 2 materials which are brittle one is aluminum oxide and glass right. You can see the stress and strain plot for aluminum oxide and glass. So both material are brittle that means there is a linear response right and then after this there is a fracture again there is a linear response and after this there is a fracture only difference between them is the slope so elastic modulus is different.

So aluminum oxide has a higher elastic modulus than glass. Now what is the common thing here just after the elastic deformation there is a fracture right. So the fracture is occurring because of the easy propagation of cracks. Now let us understand this phenomenon more clearly.

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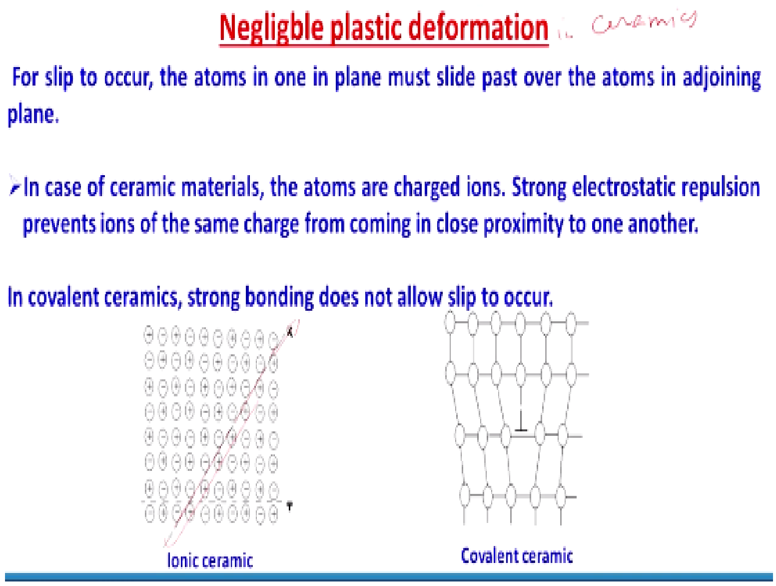

So why there is no deformation in brittle materials so ceramics. So there is or I can say there is a negligible plastic deformation in ceramics. Now the deformation which is a plastic deformation the plastic deformation generally happens by slip mechanism right. So one of the dominant mechanisms for the deformation to occur is a slip. For the slip to occur the atoms in one plane must slide past the atoms in the adjoining plane.

Now look at the ceramic materials so ceramics materials atoms they are actually charged ions right. So the strong electrostatic repulsion prevents ions of the same charge from coming in close proximity to one another. So it is very difficult for the ionic solid right. So if the ceramics are bonded by covalent bonding so those covalent ceramics. The coal and bonding is a directional bonding which is much more stronger than the ionic bonding.

So strong bonding will not allow the slip to occur in coal in ceramics right. So if you have a ionic ceramics this is arrangement of this ionic solid a ceramic so +-+-the chance for having the slip is very, very less. Now we can see only certain plain under direction there is a chance for the slip to occur whereas very less chance for the slip to occur you can see whenever there is a positive and positive charge or whenever there is a negative and negative charge a slip will not occur right.

So there must be some plane under direction combination that we call a slip system. So there must be some slip system where the slip is possible right that means the electrostatic repulsion can be minimum. So very difficult to find such a slip system or numbers of such a slip systems in ionic solids are very, very less. In covalent solids again I told you that covalent bonding is a directional bonding.

So this strong directional bonding will not allow the slip to occur. So in both ionic or covalent bonded ceramic material the deformation by slip the deformation is negligible or you can see absent right. The negligible deformation is because of the difficultly for the slip.

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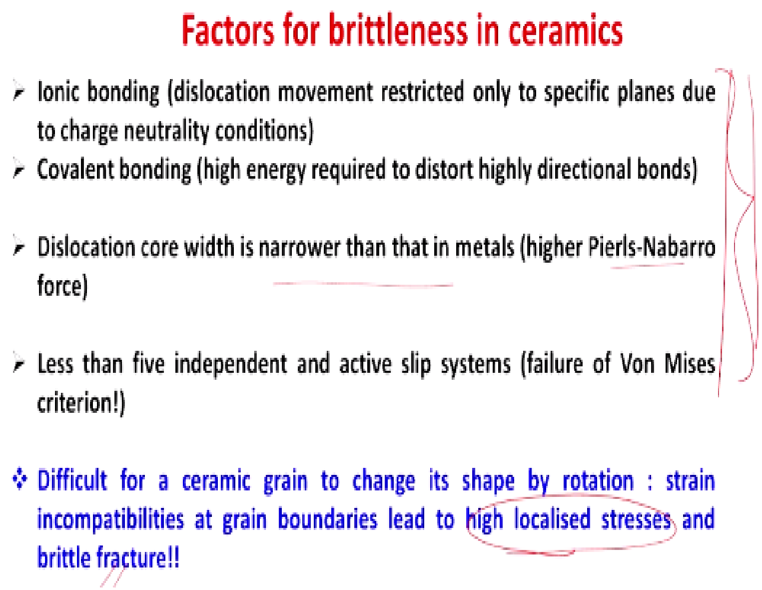

So let us understand the brittleness in ceramic materials what are the factors that actually give rise to such a brittleness. So as we understood ionic bonded ceramic materials right It is very difficult to find a slip system. The dislocation movement is restricted only to specific planes mainly because of the charge in neutrality conditions right. If the ceramic material is covalently bonded highly covalent bonded material. In covalent bonding you require higher energy to distort highly directional bonding again it is difficult.

And if at all there is a dislocation movement right. The dislocation core width is much narrower than the metals. So if you see the shear stress required to move a dislocation to give a (()) (15:19) magnitude deformation. Such a shear stress is called Pierls Nabarro shear stress which is inversely proportional to the dislocation core width right. So the dislocation core width is narrower than the metal.

So the necessary Perls Nabarro shear stress is much higher. So the possibility for the dislocation movement to give a deformation is less right and at the last if you remember the Von Mises criteria which is one of the criteria which tells about the deformation possibility in a material. The deformation by default is a (()) (16:03) is possible only when there are more than 5 independent and active slip system.

In ceramics it is difficult to find even 5 independent and active slip systems. So because of this factor the deformation is much less right. So if you combine all these factors I can state difficult for a ceramic grain to change its shape by rotation. So you have a strain incompatibilities along the grain boundaries that lead to highly localised stresses. So these localised stresses lead to brittle fracture right.

So brittleness in ceramics are govern by these factors right ionic bonding, covalent bonding, dislocation core width and less than 5 independent (()) (17:04) slip systems. So these factors contribute for the brittleness in ceramic materials.

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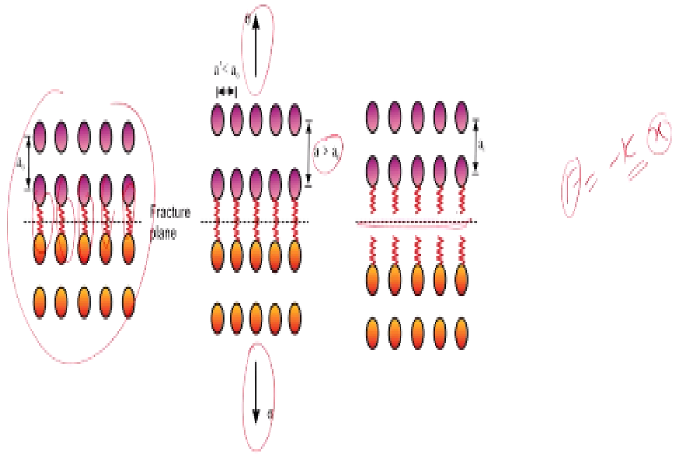
Atomistic view fracture



Let us understand such a brittle behavior from the atomistic point of view right. So if you consider the bonding as like a spring like right as a spring like structure right spring like structure. So you have certain elastic response can be described as F= -k*x where this if F is the force right and k is the spring constant and x is the spring displacement right. So in an equilibrium position there is the atoms are separated by an equilibrium distance.

When they are subjected to external tensile stress right so these atoms will be stretched right. When the atoms are stretching so you have a displacement more than the equilibrium displacement right. So because of the stretching there is a rupture in the bonding that leads to fracture right. So along this plane there is a fracture. If you have the fracture is occurring because of this rupture that leads to cracks right.

The cracks will be having very high concentration at the crack tips. So the crack propagates further and leads to fracture right. Let us understand this crack influence on the brittleness right. So ceramics are processed generally by sintering. So while sintering so you have certain cracks already generated.

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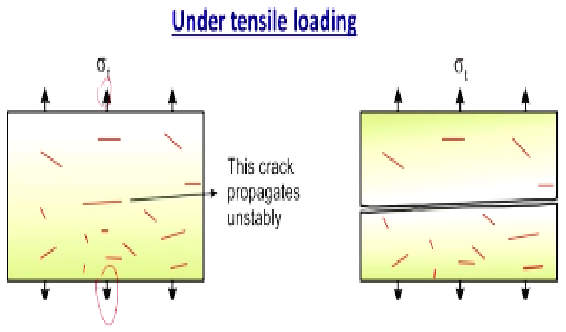
Crack size distribution and orientation influence on fracture



The largest crack with most favorable orientation would propagate in a direction perpendicular to tensile axis

Now when an external stress is applied and the external stress is applied in a tensile manner that means under tensile loading conditions. So the largest crack with most favorable orientation would propagate in a direction perpendicular to the tensile axis right. So this crack will be propagating unstably and then they coalesce each other and then forma fracture plane and then the material will be filled.

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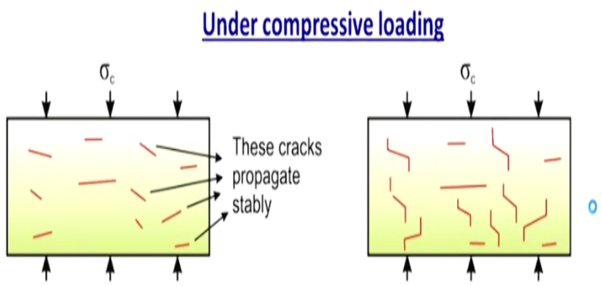
Crack size distribution and orientation influence on fracture



Cracks, oriented closer to the axis of compression, are more likely to grow

In case of compressive loading conditions what happens the cracks oriented closer to the axis of the compression are more likely to grow.

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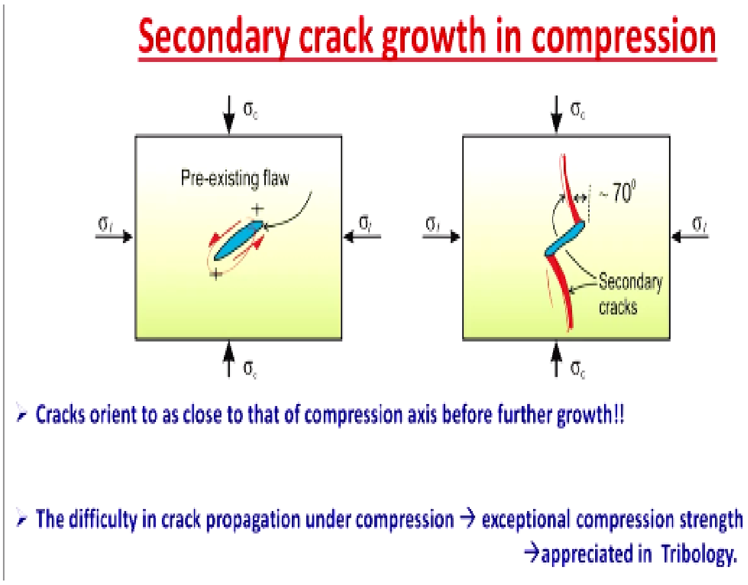

So that means cracks orient to as close to that of the compression axis before further growth. So you see the pre existing crack and because of this orientation there forms a second cracks right. So there is a difficulty in the propagation of such crack right. So the difficultly in propagation of such a crack under compression loading condition also explains the exceptional compression strength that we saw around compressive strength is 8 times than the tensile strength for the ceramics materials.

So generally what happens in the tribological conditions because of the compression loading those cracks will be closed at the surface. So there will not be propagation further or I must say there is a difficultly in propagation of such a crack in compression loading conditions. So they are mostly appreciated in this tribology. So ceramics are used because of their exceptional compressive strength.

Let us understand the behavior of this crack by a fundamental theories right fundamental theories. So there are actually 2 major theories that explains the brittleness of a material right.

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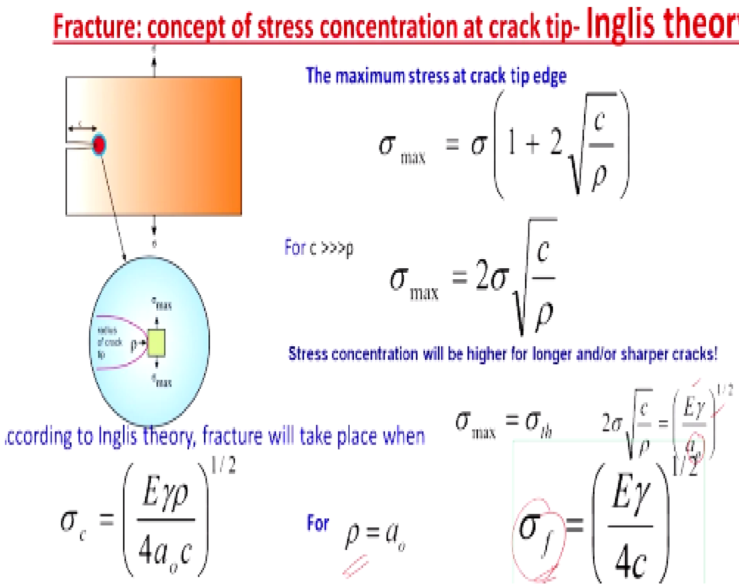

So a brittleness or we can say the fracture of a solid material can be understood by the concept of stress concentration at the crack tip so that was proposed by a Inglis so it is called Inglis theory. Now let us have so a material right and then we have a crack at the edge or there may be a crack inside the material right. So if you take a plate right that means the thickness is negligible so if you apply a tensile stress.

So what happens these crack will be expanding right. So at the crack tip there is a large amount of stress concentration. The stress concentration at the crack tip edge can be described by the external applied stress and the crack size if this is a crack edge c or if the crack is inside the material 2 c right this is 2c. Rho is the radius of curvature at the tip. So for a condition having the c much larger than this rho.

We can actually simplify the simplify the sigma maximum is 2 sigma* under root of c/rho right. This sigma is applied stress. So stress concentration will be higher for the longer cracks or higher for the sharper cracks. If the crack is sharper, we will have stress concentration higher. If the crack length is large then you have stress concentration if the crack is sharp you have higher concentration if the length of the crack is more then you have higher concentration.

So according to this Inglis theory the fracture will take place when this stress concentration is equivalent to the theoretical cohesive strength right. So these theories are based on the mainly the rupture of this bonds at the interatomic level. So the interatomic bonds are broken and then it leads to the crack and covalence of this crack leads to fracture right, but this was studied this was found that every material has a strength less than the theoretical strength.

Why because of the presence of defects. One of the defects is this crack right one of the defects is this crack. So according to Inglis theory the fracture will take place when sigma maximum=sigma theoretical. So if you equate them the theoretical strength to this maximum stress concentration. So you get this E is elastic modulus gamma is the surface energy (()) (24:01) a0 is the interatomic distance right.

So for a condition where the radius of the curvature of the crack tip equal to the interatomic distance this is mostly possible then you get a sigma= E gamma 4c power ½. So this sigma is what we call fracture stress. So you can actually understand the fracture stress is inversely proportional to square root of the crack length right.

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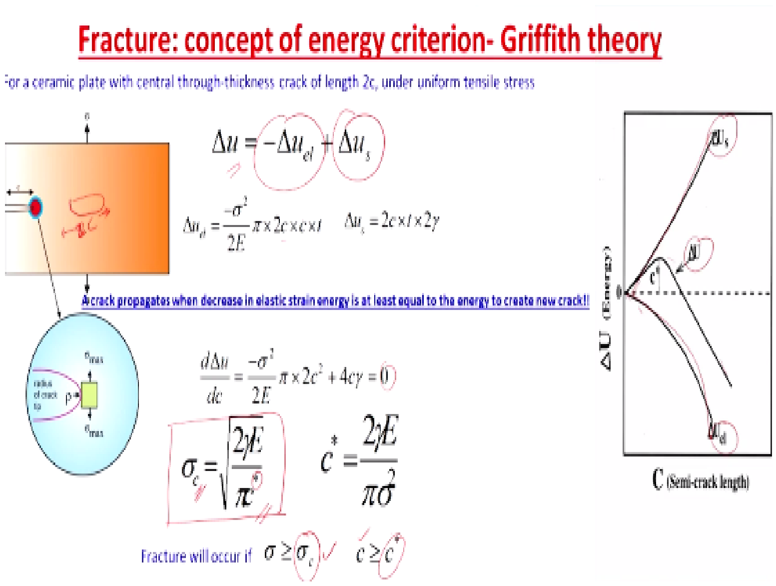

So in another theory which is based on the energy criterion this was proposed by Griffith so it is called Griffith theory. So for a ceramic plate with a central through thickness of crack length 2c. So if you have a 2c crack (()) (24:57) which measure axis length is 2c. So for a ceramic plate with central through thickness crack length crack of length 2c under uniform tensile stress condition.

So the energy the total system energy is a summation of elastic strain energy and then surface energy. This elastic strain energy is released for propagating a crack and then the surface energy is required for creation of a new crack right. So you can see one this delta u yes it is a positive and delta u elastic strain energy negative. So we have resultant of it and if you for a spontaneous propagation of a crack this must be 0 d delta u/dc=0.

Then you will end up with the sigma c. So d delta u/dc-0 so if you can rearrange them then you will get a sigma that is the stress at which the fracture happens (()) (26:10) the critical stress sigma c is the critical stress=under root of 2 gamma E/pi c *. C* is the critical crack length that means you have several cracks the crack which is equivalent are more than the critical crack length that will be contributing to the fracture right.

So I can say in either way fracture will occur if the applied stress is more than the critical stress here right or the crack length c is> or= this critical crack length c*.

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The stress intensity factor

$$K = Y\sigma\sqrt{\pi c}$$

Y is a factor dependent on location/orientation of crack and loading condition.

The stress intensity factor K can be described as this right. K=Y*sigma*under root of pi c. So Y is the factor that depends on the location of the crack or orientation of the crack and even the loading condition. So this K=Y*sigma* under root of pi c right.

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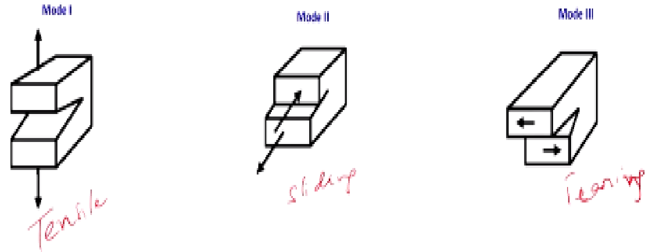
Crack opening modes



Tensile mode is considered to be the most dangerous among the three modes and most failures of brittle solids are largely due to mode I failure.

$$K_{IC} = Y\sigma_c\sqrt{\pi c^*}$$

K_{Ic} : Fracture toughness

In tribological applications, the external force induced K_I value should not exceed K_{Ic} of the material

So there are actually 3 modes of the crack opening. Mode 1 is like a tensile mode opening this is tensile right and mode 2 sliding mode 2 is a sliding mode sliding. Mode 3 is like a tearing. So out of this crack opening mode. So the tensile mode is considered to be the most dangerous right. So because when the crack is opening in a tensile direction what happens they can coalesce each other.

And then forma a larger crack the size of which can be more than the critical size so that will lead to fracture right. So the tensile mode is considered to be the most dangerous among the 3 modes and most failures of brittle solid are largely due to the mode 1 failure. So most of the studies are done in a tensile mode crack opening mode and then the stress intensity factor is called K1c c is for the critical this is 1 is mode 1 crack opening K for the stress intensity factor.

So the critical stress intensity factor in mode 1 crack opening=Y* sigma c under root of pi c*. So c* is the critical size right of the crack and sigma c is the critical stress. Then this K1c can be described as a fracture toughness. We will see what is fracture toughness how to measure it in another class, but the fracture toughness the stress intensity factor is a parameter which is generally noted as a fracture toughness parameter.

That is fracture toughness can be defined as resistance against propagation of already existing crack that means crack has a certain length right. So in tribological application the external force induced the K1 value should not exceed this critical value of the K1 that we call K1c of that material. So every material has its own specific K1c that means the K1c which is fracture toughness is a material parameter.

So we must also understand that the K1c value for a ceramic material is much lesser than the K1c value for a ductile metallic material. This unit for this K1c is MPa root meter. So for a plane carbon steel the K1c value is found to be 100 MPa root meter whereas the ceramic material the K1c value is always< 10 MPa root meter that means the K1c value, the fracture toughness is almost one order< than the fracture toughness of a ductile material. So again the K1c is depended on the size of this crack as well as this critical stress right.

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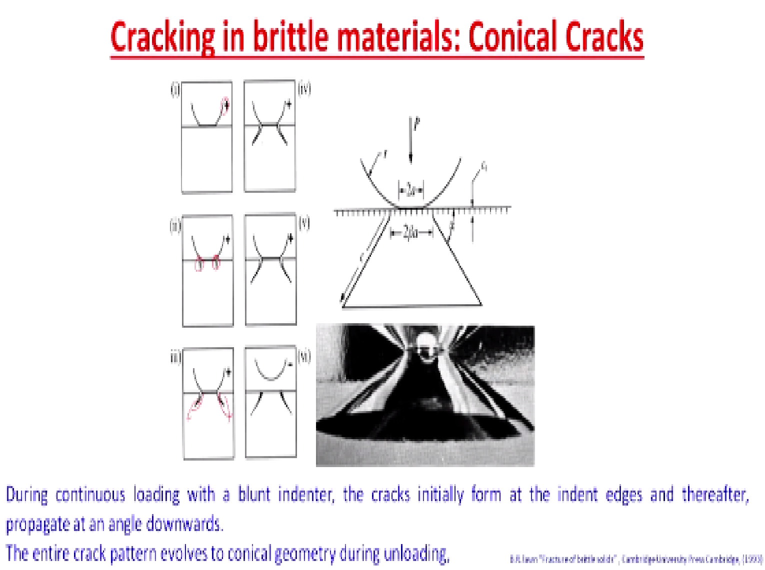

So let us understand more with the cracking characteristics in a brittle material. So cracking can be a conical cracking or a radial median or lateral cracking. Let us understand this in brittle materials. So if you have a material which is indenting on the surface or I must say the loading is a continuous distributive loading right. This can be possible with a spherical indent or a spherical shaped body which is being loaded on the surface of this brittle material right.

So what happens during this continuous loading with a blunt indenter. So you can see the blunt indenter here when it is touching and then you are applying load it is you are increasing load what happens this material will crack at the indent edges and thereafter it propagates, but propagates at an angle downwards right. So as you are increasing the load this crack will be propagating at an angle downwards.

So the entire crack pattern evolves to the conical geometry when you are unloading it right. It increases again it increases in length and then when you are unloading so it becomes more conical and then you will see this conical crack right.

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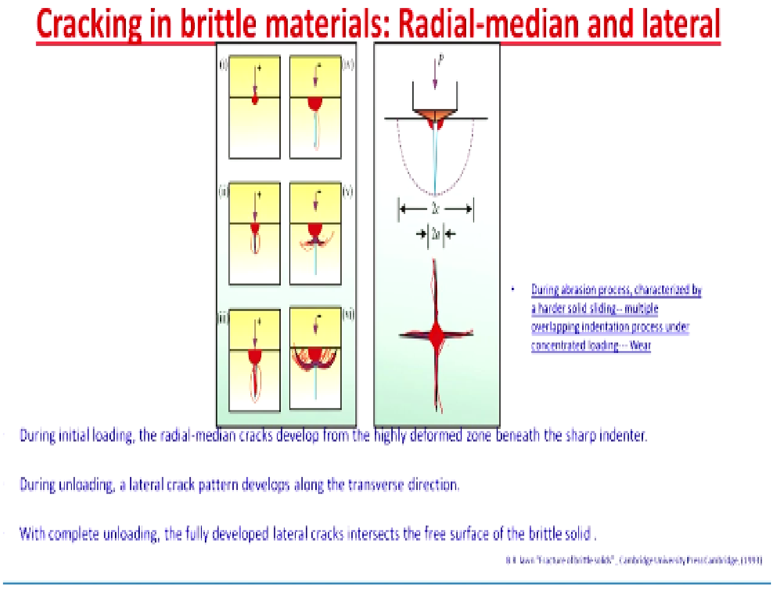

There can be cracks radial median and lateral cracks in a brittle material. So this can be possible with a sharp indenter right with a sharp indenter during initial loading the radial median cracks. You see this radial median cracks developed from the highly deformed zone just beneath the sharp indenter. So when you are unloading it when you are loading taking above this indenter the lateral crack pattern develops along the transverse direction.

So while unloading these crack will be propagating further and with complete unloading the fully developed lateral cracks will intersect at the surface free surface and this material is removed right this material is removed. So you can see after the indentation the surface you will have the impression of the indenter. Generally, if it is a Vickers indenter you get a perfect square at the edges of this square you will see all this cracks right.

So this is very much significant in tribological conditions right. For example, during abrasion process harder solid which is sliding right. So that creates a multiple overlapping such lateral cracks. This lateral crack induced fracture is much more found in brittle materials and such a fracture leads to the material removal called wear. So this kind of cracking is more relevant in wear right.

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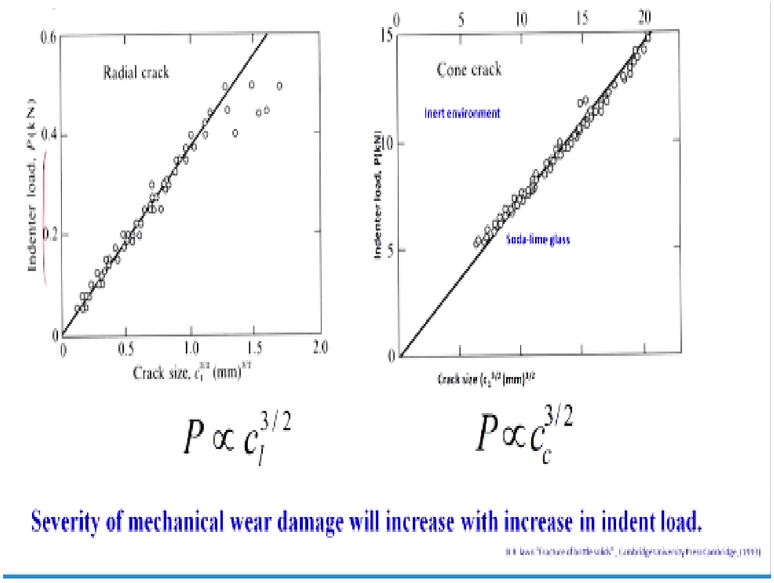

So if you look at this study of this indentation load versus the size of the crack either it is the radial crack or the conical crack or the conical crack. You see the severity of the mechanical wear damage with increase in the load right. Severity of mechanical wear damage will increase with the increase in the load. So there is a crack propagation that leads to failure that we call brittle fracture right.

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Toughening mechanisms

From fundamental aspect, if the interaction between a growing crack and the microstructure car absorb a fraction of the energy available at the crack tip stress field, then the driving force for cracl propagation will be lowered.

In other words, the crack opening displacement will be consequently reduced and as a result, the crack tip will be blunted.

Such mechanisms to improve crack growth resistance that is, toughening mechanism

Toughening mechanisms:

- Processing zone mechanisms
- Bridging zone mechanisms

So if from the fundamental aspect if the interaction between a growing crack and the microstructure can absorb certain amount of the energy available at the crack tip stress field then the driving force for the crack will be crack propagation will be lowered. So what happens this becomes more blunted when it becomes blunted so you will have lesser chance for the propagation of such a crack.

That means in other words the crack opening displacement will be consequently reduced as a result the crack tip will be blunted. Once the crack tip is blunted it is very difficult to move right. The propagation is restricted so you get a fracture toughness improvement. So if you can find out a microstructure or if you can generate a microstructure if you can develop a microstructure such mechanism will be possible to improve the resistance against the crack growth right.

Such mechanisms to improve crack growth resistance are called toughening mechanism that means the brittle materials are made toughen by this micro structural engineering. So the toughening mechanisms in a brittle materials are mainly 2 types right. One is the processing zone mechanism another one is the bridging zone mechanism.

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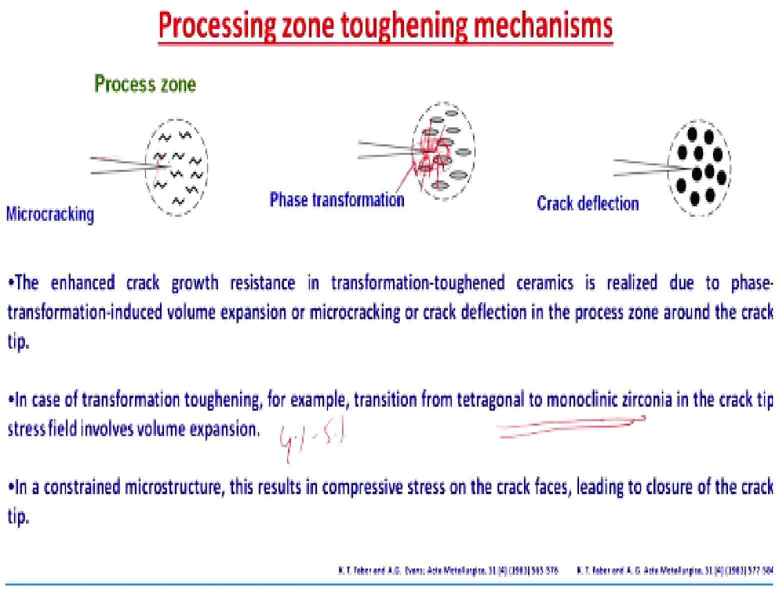

So let us see the processing zone mechanism. For example, micro crack, phase transformation or crack deflection are the major toughening mechanism in processing zone. So enhanced crack growth resistance in transformation toughen ceramics is realized due to phase transformation induced volume expansion or microcracking or crack deflection in the process zone around the crack tip.

So in case of transformation toughening for example a transition from a tetragonal zirconia to monoclinic zirconia. So this tetragonal to monoclinic zirconia in the crack tip stress field involves volume expansion. Generally, this volume expansion is around 4% to 5% volume expansion. So because of the volume expansion the material the material adjacent to this crack tip will be monoclinic right.

There is a transformation so there is a material which is transformed monoclinic, but in the vicinity of the crack tip whereas the other material is still in tetragonal zone. So this is a tetragonal one there is a monoclinic one right. So the tetragonal zirconia will be transformed monoclinic zirconia under the applied stresses right. So the stress inducted transformation will lead to monoclinic zirconia around the crack tip.

So this leads to volume expansion. So when the monoclinic zirconia is formed with a volume expansion this material will be compressed at the crack tip right. So this material compressed as the crack tip. So the transformation compresses that crack tip. So the crack will not be propagated easily so you get a toughening right. So in a constrained microstructure this results in a compressive stresses on the crack faces that leads to closure of the crack tip.

So you get a toughening right or the induced will be used to create more micro cracks than this major cracks. So what happens the energy will be used in creating such a micro cracks. So micro cracks that means the lesser sized cracks right and the major crack here. So material will be safe even if you have a micro crack because the size of the crack is less than the critical size of the crack for the brittle fracture.

So what is happening the energy consumed energy is consumed in creating such a micro crack. So micro crack will also compress this one as well as energy required to move this major crack will be reduced so you get a toughening. Certain materials you have crack deflection because of the second phases or any other reinforcement right. So you get a processing zone toughening mechanisms micro cracking, phase transformation and crack deflection are the major toughening mechanism in processing zone.

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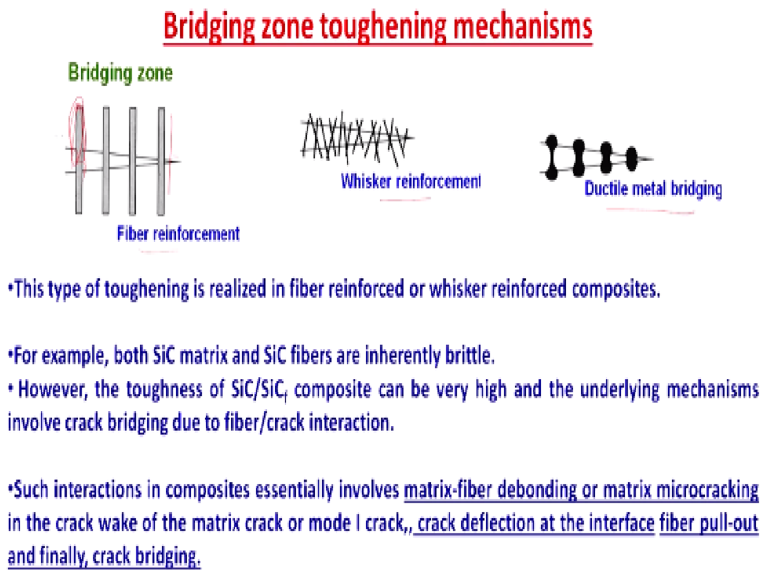

In bridging zone mechanism this type of toughening is generally realized in a composites reinforced the material reinforced the fibers or a whisker right. So the whisker reinforced or fiber reinforced composites you get a toughening mainly because of this bridging zone toughening mechanism namely fiber reinforcement or whisker reinforcement or ductile metal bridging.

For example, silicon carbide matrix and silicon carbide fibers both are inherently brittle, but you get a toughness by making this a composite a silicon carbide reinforced with a silicon carbide fiber because of the underlying mechanism that involve crack bridging due to this fiber and crack interaction. So you got this fiber so the crack will be propagated either by breaking this fiber or by travelling along the fiber length right.

So in either case the energy required to propagate further will be reduced right so you get a toughening. So the toughness of this fiber reinforced ceramics composites can be very high and the underlying mechanism involves crack bridging due to this fiber crack interaction right. Such interaction in composites essentially involves the matrix fiber debonding. So either the debonding or matrix microcracking in the crack wake of the matrix.

The crack deflection at the interface fiber pull out and finally crack bridging. So you get a toughening right.

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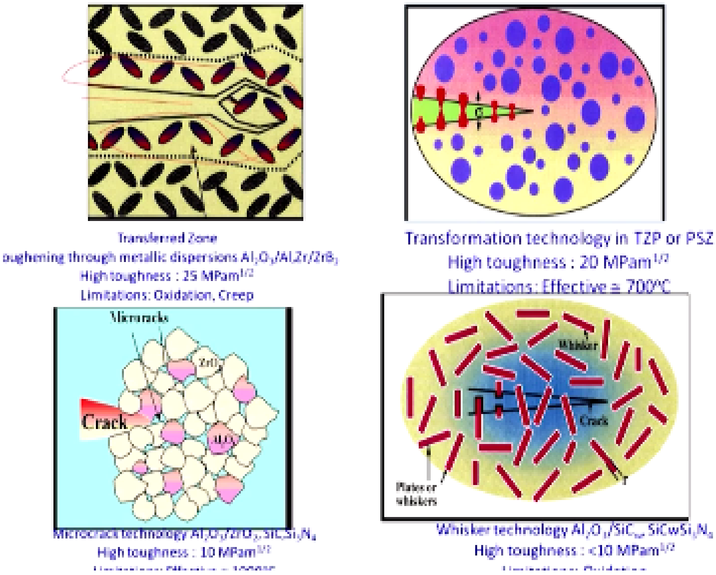

So you can see several examples are schematically shown here. So that is a transferred zone it is a transferred zone here you can see this zone is a transferred zone this is a major crack. So the aluminum oxide particle reinforced aluminum or zirconium reinforced by zirconium diboride.

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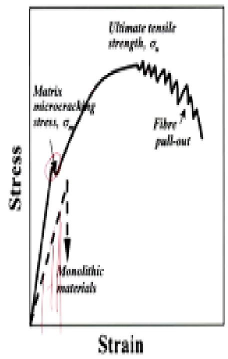
Damage tolerant behavior in composites



The extent of fiber pull-out as well as properties of matrix-fiber interface strongly determines the toughness increment.

The fiber toughening is also accompanied by the modulus enhancement and this is governed by the rule of mixtures.

The fiber reinforced composites however have their own limitation, which includes expensive production cycle, anisotropic properties with higher property along the fiber direction.

So in a composite material the extent of fiber pull out as well as the properties of the matrix fiber interface strongly determines the toughness improvement right. You can see this monolithic materials stress versus strain response for a monolithic material and this is a fiber reinforced composite material and this is a fiber reinforced composite material. So we can see the first the matrix is cracked right. So you can see there is a decrease in the stress and then there is a ultimate tensile strength right it reaches and fiber is pulled out.

So there is a serration so large number of serrations here. So you can see the toughness actually is improved, the area under the curve is improved which is a measure for the toughness as compared to monolithic material right this is the area. So you get a maximum improvement in the toughness if you use the fiber as a reinforcement in a composite. Fiber toughening is also accompanied by the modulus enhancement you can see this slope is increased here and this is governed by the rule of mixture.

The fiber reinforced composites however have their own limitation which includes expensive production cycle anisotropic properties with higher property along fiber direction right.

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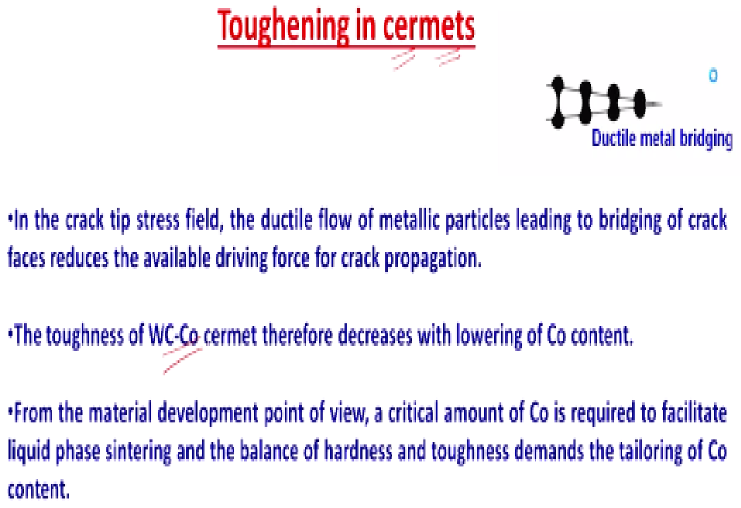

So finally there is one material called cermets in which the ceramic grain are bonded by a metallic binder. So in that material we call that material a cermets because ceramic under metallic both faces are present. So in the crack tip stress field the ductile flow of the metallic materials metallic particles leading to bridging of the cracks faces reduces the available driving force for the crack propagation.

For example, Tungsten carbide cobalt ceramic material decreases with lowering of cobalt content. So the amount of cobalt content is also important factor in getting a proper improvement in the toughness. From the material development point of view, the critical amount of cobalt is required to facilitate the liquid phase sintering and the balance of the hardness and toughness demand the tailoring of cobalt content right.

The toughness is improved either of these toughening mechanisms. So these toughening mechanism can be more than one. They may act simultaneously, but in certain cases we see the domination of one toughening mechanism than the other. So we say certain mechanism is mainly responsible for the toughness. So if you have a toughness improvement in combination with the hardness and elastic modulus improvement you get a better wear resistance.

So in coming classes we will also see certain examples where the toughness can be improved by micro structural engineering that means by incorporating such mechanisms of toughening. So by toughening by improving the toughness we will see the resistance against the wear will also be improved right. Thank you.