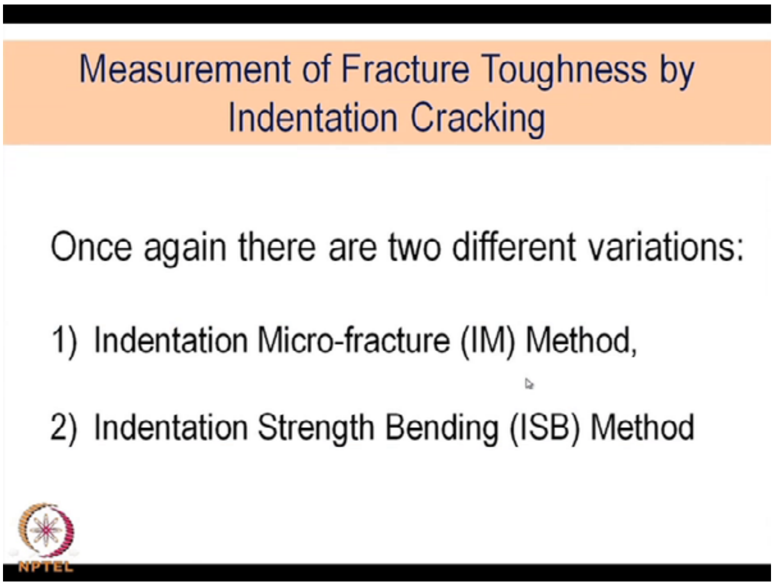
Advanced Ceramics for Strategic Applications
Prof. H. S. Maiti
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 44
Mechanical Properties of Ceramic Materials (Contd.)

(Refer Slide Time: 00:32)



Measurement of Fracture Toughness by Indentation Cracking

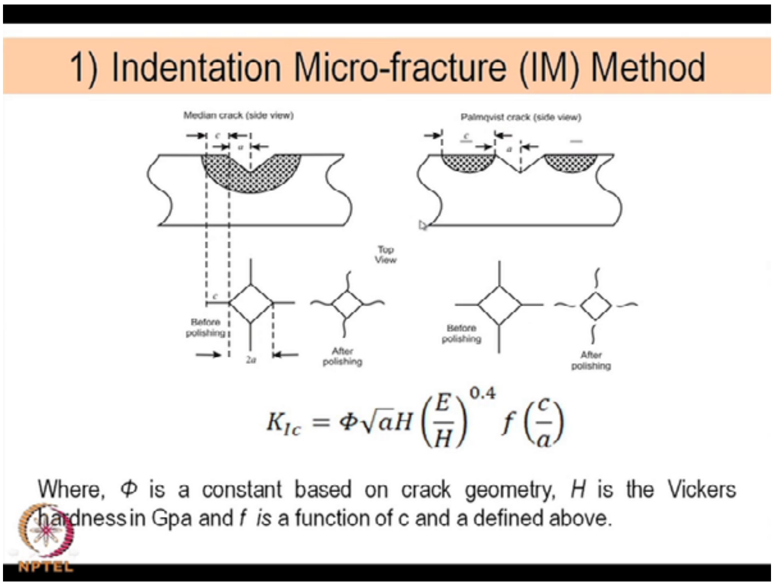
Once again there are two different variations:

1) Indentation Micro-fracture (IM) Method,

2) Indentation Strength Bending (ISB) Method

Welcome, this is also continuation of our earlier discussion that is the mechanical properties of ceramic materials. We have earlier discuss different concepts of our different techniques some measuring different properties of ceramic mechanical properties of ceramic materials. Also, we have started discussing how to measure the fracture toughness. The fracture toughness of ceramic material that is one of the most important mechanical property of ceramic or particularly to understand the fracture mechanics or fracture of ceramic materials. We have just introduced in an in the earlier lecture these 2 techniques, the indentation techniques, the indentation micro fracture method or IM method and then indentation strength bending method, ISB method. So, in the first case, we have just indent it generate indent with a diamond indenter.

(Refer Slide Time: 01:33)



1) Indentation Micro-fracture (IM) Method

$$K_{Ic} = \Phi\sqrt{a}H\left(\frac{E}{H}\right)^{0.4} f\left(\frac{c}{a}\right)$$

Where, Φ is a constant based on crack geometry, H is the Vickers hardness in Gpa and f *is* a function of c and a defined above.

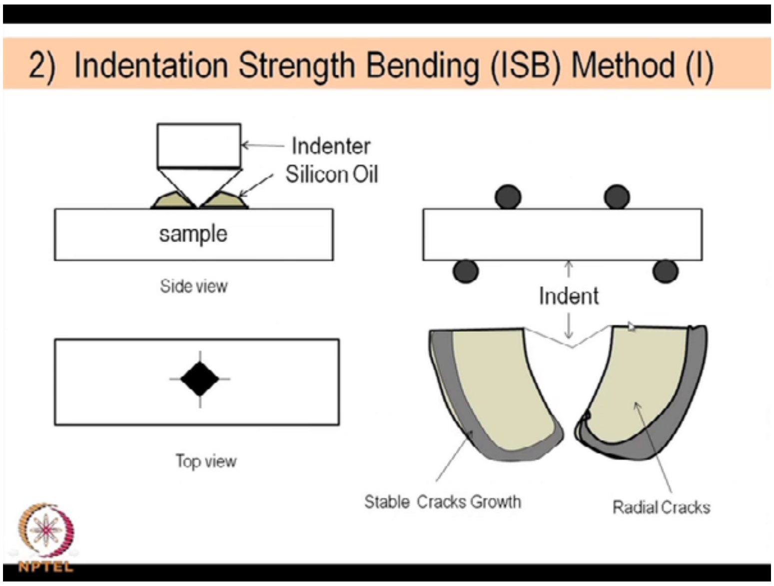
And then apply the load in such a way that not only it creates an indent of a permanent deformation, but also create a crack, because the load is enhanced so that a crack is created. Now there are 2 situations here, this is the side view, and this is the indent; this indent diamond, indent which we have generated this was at low load. Initially this was at low load, when only the crack has been generated here on 2 surfaces. Whereas, higher load this crack as propagated, this crack as propagated, in this manner. So, here you can see this is the crack length C, C is the crack length, this is smaller crack length; this is larger crack length.

Now, we have already said that, making for making a indenter you have to polish the surface, of course, initially the surface was polished, but the crack was internal from the top surface. You may not see the crack properly, and that is why you to, once again polish that surface to see the exact nature of the crack, exact where the crack as propagated. So, as you can see this appears to be straight initially, but inside, inside you will see a bend cross section of the crack. So, after polishing, which you will be evident here and this is at a lower load, is not a higher load and that is why you can see this distance is, this size is slightly larger, and this side is also slightly larger, and you have to measure, you have to measure this crack lengths. You have to this is your c, and once you measure the c, and then you measure the also, a is this distance, the actually the dimension of the indent, here also it is a and this is c.

So, the crack as propagated not only in this direction, but it has being joined together, because these are the 4 cross stress intensifying centers the stress are these are corners are very high. So, the cracks will generate here and then finally, in the bottom at the below the indenter they will join. So, the crack will join like this and that is what you can see here. Before that, before that this is the cross section; this is the formula, which we have to use the curve by measuring the value of c. And then find the value of H, H is the Vickers hardness, and a and c you will find phi is a constant, based on the crack geometric, and H is the Vickers hardness in G p a and f is a function of c and a, defined above.

So that way we have find out from the just by the indenting, you do not have to make a fracture complete fracture of the sample, what we have do in the notch tests? In the notch test the sample is fully fracture here it is not fully fracture just by making a indent you can make that you can have a measure of the fracture toughness. Of course, there will be lot of difference there will be some difference between the fracture toughness obtained by the other technique and these techniques. In fact, all the techniques, will give you slightly different values of the factor toughness. that also you have to remember.

(Refer Slide Time: 06:03)



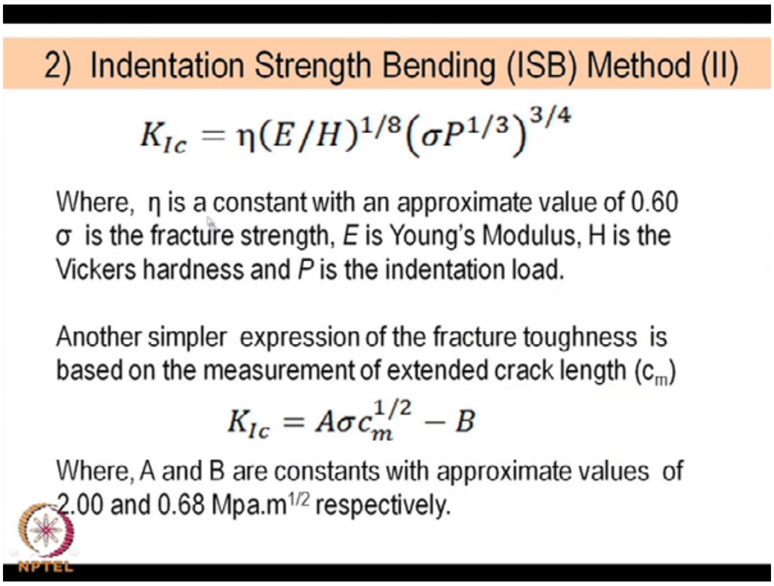
2) Indentation Strength Bending (ISB) Method (I)

There is a another combination of, combination of indentation and fracture that is also possible. And this is what it is done first of all the sample there is a indent is made on the surface and then you put the surface upside down and they then do a 4 point bend test.

So, the indent is here, indent has been created by this indenter silicon oil is placed primarily, to protect the indent, indenting surface from the atmosphere atmospheric contamination and atmosphere effects so so after the indent is form.

So, it is a combination of both fractures. So, if we are making a notch by identity. So, this notch has been created by indenting, and then this notch kept upside down and do the 4 point bend test. Now, this is the crack propagation area below the below the indent, there are 2 different areas of cracks, or the stress concentrations, the stable crack growth. This region is the stable crack growth and this is the radial crack growth, these 2 regions can be separated or their different, type of stress concentrations are there.

(Refer Slide Time: 07:45)



2) Indentation Strength Bending (ISB) Method (II)

$$K_{Ic} = \eta(E/H)^{1/8}\left(\sigma P^{1/3}\right)^{3/4}$$

Where, η is a constant with an approximate value of 0.60 σ is the fracture strength, E is Young's Modulus, H is the Vickers hardness and P is the indentation load.

Another simpler expression of the fracture toughness is based on the measurement of extended crack length (c_m)

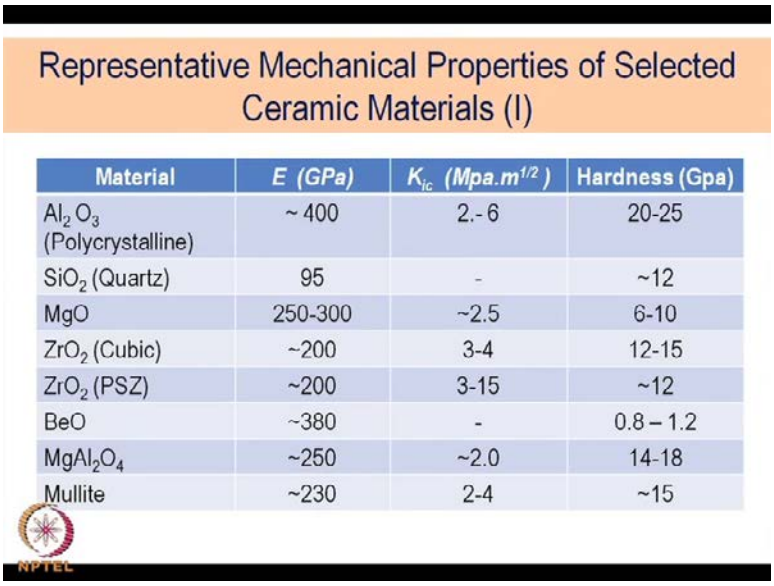
$$K_{Ic} = A\sigma c_m^{1/2} - B$$

Where, A and B are constants with approximate values of 2.00 and 0.68 Mpa.m$^{1/2}$ respectively.

And therefore, one can have once again an expression indentation strength bending by this method K i c is this expression. So, where eta is a constant with an approximate value of 0.6, sigma is the fracture strength, E is the young's modulus, H is the Vickers hardness and P is the indentation load, which we have, which we have been added, which have been used or applied.

So, by that method also, one can find the, fracture toughness. Another simple expression for the fracture toughness is based on the again measurement of extended crack length c m. And where this is again and expression using instead of c is use A c m, which is an extended crack length, where a and b are constants with approximate values of 2 and 0.68 M p a permits a M p a meter square or meter 2 the power half not meter square meter 2 the power half respectively. So, basically what we are saying, there are different techniques of measuring the indentation hardness, fracture toughness. So, either by making a notch or making an indent and or the third one is making a indent followed by fracture a sample.

(Refer Slide Time: 09:15)



Representative Mechanical Properties of Selected Ceramic Materials (I)

Material	E (GPa)	K_{ic} (Mpa.$m^{1/2}$)	Hardness (Gpa)
Al_2O_3 (Polycrystalline)	~ 400	2.- 6	20-25
SiO_2 (Quartz)	95	-	~12
MgO	250-300	~2.5	6-10
ZrO_2 (Cubic)	~200	3-4	12-15
ZrO_2 (PSZ)	~200	3-15	~12
BeO	~380	-	0.8 – 1.2
$MgAl_2O_4$	~250	~2.0	14-18
Mullite	~230	2-4	~15

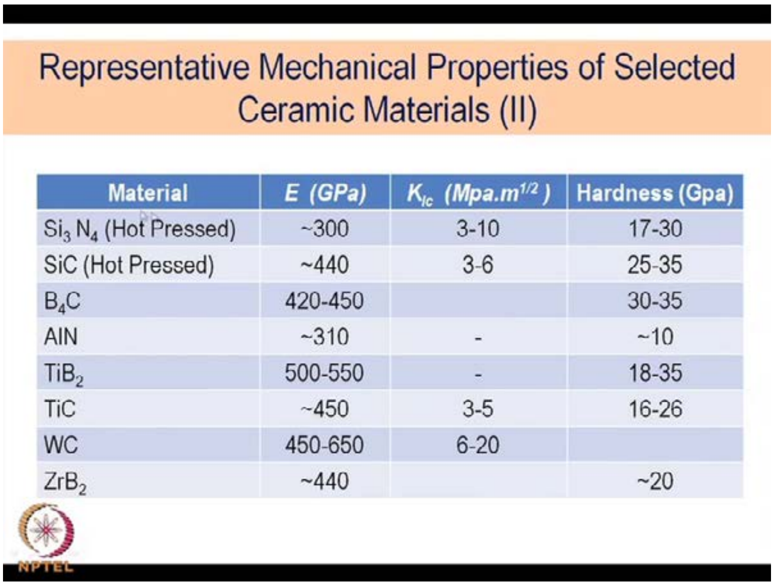
Well with these different backgrounds, we can have one can look at some of the common material, common ceramic materials having different properties and what is the just range of properties? This is gives you some range of different properties, of ceramic materials, so far as the mechanical properties are concerned. A l 2 O 3; that is the polycrystalline A l 2 O 3, this is the value of young’s modulus, in G p a about 400 K i c; this should be not small; this should be capital I, 1 minute I will just correct it here.

So, this is, the K i c value of about 2 to 6 normal A l 2 O 3, hardness is about 20 to 25 G p a, silica or the quartz single crystal quartz, we have 95, the K i c value is not here and this is about approximately 12. Magnesium oxide; the young’s modulus is much larger not much larger, it varies depending on the previous condition, but lower than that of A l 2 O 3, K i c value is almost same, may be in the slightly lower side, and then hardness is also low. Zirconia; you have 2 different forms of zirconia, one is stabilize zirconia or cubic zirconia, that as the young’s modulus of 200, and there is partially stabilize zirconia also, not fully cubic zirconia partially, that is a mixture of 2 partly cubic zirconia and in which you have a tetragonal or mono cubic zirconia.

So that is also young’s modulus in more or less same 200, but one can see that the partially stabilized zirconia as a much higher K i c value it. Of course, the ranges also large it is only 3 to 4 whereas, whereas its can go up to 15, which is a very high value. But it can be as low as depending on how what is kind of microstructure, how it has been to prepare, and what is the size of the second phase and so on. So, it varies, but it is possible to make a very high very PSZ or partially stabilized zirconia, at very high fracture toughness. And in fact, we will come back to this material later that sometime people say it is, the ceramic steel where having the highest fracture toughness.

The hardness is more or less in the same range. Beryllium oxide; the effect of toughness is not there, but it is very hardness is low, soft material, but young’s modulus is fairly high. Magnesium aluminate spinel, which is also being use as a very important refractive these days, and there many other application engineering applications, and these is 250 the K i c value that is the fracture toughness is not so high, the hardness is more or moderate. Mullite 230, 2 to 4 again and a moderate hardness, but most of them are in this range 15 to 20, 25 maximum you can get here. Silicon nitride, hot press silicon nitride is one of the almost important structural ceramics, for engineering application particularly high temperature engineering application. I change this also.

(Refer Slide Time: 13:58)



Representative Mechanical Properties of Selected Ceramic Materials (II)

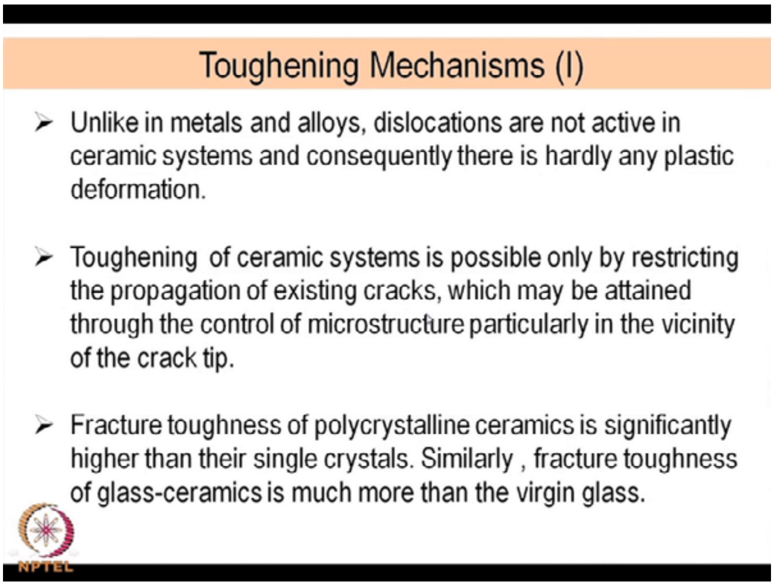
Material	E (GPa)	K_{Ic} (Mpa.m$^{1/2}$)	Hardness (Gpa)
Si_3N_4 (Hot Pressed)	~300	3-10	17-30
SiC (Hot Pressed)	~440	3-6	25-35
B_4C	420-450		30-35
AlN	~310	-	~10
TiB_2	500-550	-	18-35
TiC	~450	3-5	16-26
WC	450-650	6-20	
ZrB_2	~440		~20

Both silicon nitride and silicon carbide they are known for their high strength, that high temperature particularly, silicon carbide. And as you can see there is young modulus also fairly large, the way fracture toughness, which is on the higher side. And silicon nitride in particular can be, made much tougher material or K i c value can be improved by control of the microstructure and preparation condition, and these are the hardness values.

B 4 C that is boron carbide, is supposed to be very strong material and you can see it is young's modulus is also fairly high, unfortunately the K i c value is now available here and 30 to 35 is the hardness. Similarly, another non oxide ceramics aluminum nitride as the young's modulus of this, and hardness of this K i c value is not there. Titanium dibarite a very high young's modulus, one of the hard materials also and it is used for many high temperature applications with the time permits will discuss some of them.

Titanium carbide, once again a high young's modulus value, and then K i c value is moderate and hardness is also the same range. Tungsten carbide is a widely used ceramic material, on per various different applications and you have high young's modulus. This has a fairly high fracture toughness, fairly high fracture toughness of 6 to 20, one of the highest one can say. Ziriconiam diboriate is also of the order same order of the young's modulus as the others and hardness is also in the same range, fracture toughness value unfortunately is not available. So, this is just to give you an example, of different mechanical behavior or mechanical properties of some of the important ceramic compounds. Many of them are used industrially and or many different engineering components or many engineering purposes, including of course, refectories.

(Refer Slide Time: 16:40)



Toughening Mechanisms (I)

- Unlike in metals and alloys, dislocations are not active in ceramic systems and consequently there is hardly any plastic deformation.
- Toughening of ceramic systems is possible only by restricting the propagation of existing cracks, which may be attained through the control of microstructure particularly in the vicinity of the crack tip.
- Fracture toughness of polycrystalline ceramics is significantly higher than their single crystals. Similarly , fracture toughness of glass-ceramics is much more than the virgin glass.

Now, this is we have discussed the properties, we have discussed what is the property means like what is properties fracture toughness, how to measure it and so on. As you have seen in the list, just presented that fracture toughness some most of the ceramic materials are not very large or very high, compare to metal and alloys. They have a very high fracture toughness, and that is one of the weaknesses, of ceramic material right they fracture quite well a fracture very easily, and not only that when the fracture, there is a catastrophic failure.

So, we have to whether it is possible to make this ceramic material little more tougher. So, we let us consider is there any toughening, toughening mechanisms, by which some of the ceramic materials can be more made more tougher and more suitable for engineering applications. Unlike in metals and alloys, dislocations are not active in ceramics systems, and consequently there is a hard there is hardly any plastic deformation. That we have discussed time and again that the role of dislocation in ceramic materials very negligible, even if it there they are the not that operative. And it is the existing cracks, finer cracks, which actually is the weakest link and they are the primarily responsible for the facture.

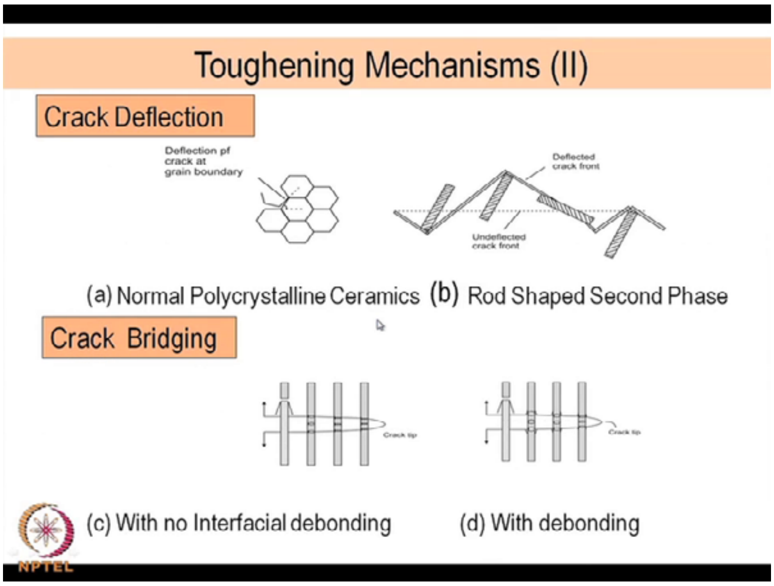
Toughening of ceramic system is possible only by restricting the propagation of the existing cracks, which may be attend through the controller of microstructure, particularly in the vicinity of the crack tip. So, in metals and alloys, when you try to toughen or strengthening, strengthening a ceramic material primarily do we restrict the moment of the dislocations. We put some obstacles on the part of the dislocation moment, and thereby one can restrict the deformation, and also strengthening the material, that is that basic principle on which the strengthening is done in metals or alloys.

However, as just mention the dislocation do not take a very important role or dislocation moments are not of that important, importance in fracture of ceramics. It is actually beyond the dislocation, moment it is a certain fracture or the cracks already gets generated in the material. And it is the propagation of the crack which has to be restricted if the materials or this ceramics have to be strengthen further. So, the fracture toughness of polycrystal and ceramics is significantly higher than that of single crystals.

Similarly, factor toughness of glass ceramics is much more than that of virgin glass. So, this is what, it walls down, or what it is a consequence of how to restrict the movement of the cracks or propagation of the cracks. If you have a polycrystalline material, there are grain boundaries, and these grain boundaries impact impedance the propagation of the cracks. So, if it is a single crystal, then there is no such grain boundary, and once a crack is generated, because of some reason either by thermal stress or by application external, externally applied mechanical stress, that crack propagates very fast. So, it does not get impeded, the motion does not get impeded. Whereas, if you have single crystal, there are grain boundaries and that, acts as an arresting point, grain boundaries act or restricts, the moment of this crack. And therefore, polycrystal material has a higher strength, than poly crystal ceramics is a higher strength than, single crystal.

And similar thing also happens in case of glass ceramics, glass is a basically a, a uniform or homogenous, material in which once a crack is generated, it goes through very easily. Whereas, if you have a glass ceramics that is fine dispersion of second phase crystalline material that is the definition of glass ceramics. So, you have a matrix, in a matrix of glass there is a second phase precipitates which are supposed to be hard. And those hard precipitates, actually restricts the moment of the cracks through the glass ceramics and therefore, the glass ceramics becomes tougher than the virgin glass. So, these are the some of the basic principles one which, one can, look at how to strengthen the ceramic materials.

(Refer Slide Time: 22:33)


Toughening Mechanisms (II)

Crack Deflection

(a) Normal Polycrystalline Ceramics (b) Rod Shaped Second Phase

Crack Bridging

(c) With no Interfacial debonding (d) With debonding

These are 2 basic principles, 2 techniques by which the moment of the crack can be restricted. Here it is crack deflection, here is a crack deflection, in these 2 examples and here is a crack bridging that means some kind of anchoring, anchoring the crack is taking place. So, in this case, if you have a polycrystal material, large grain polycrystal material, then there is a crack has been generated between the grain, it is a kind of grain boundary crack. And this grain boundary crack cannot move across the other material, a others grain, it has to follow because assuming that the grain boundary region is a weaker than the, that the internal grains. So, the crack can grow along the grain boundaries, and because it cannot cross through this grain it has to deflect.

So, this is the deflection of crack at the grain boundaries. So, this is one way of strengthening, the ceramics, that is what has been explained that a single crystal material will have a lower strength than a polycrystal material, because of this crack deflection or restrict the moment of the crack, through and through. Instead of grain boundary these are grains like this you can have; you can have a different, a rod shaped second phase. If you have dual phase material, then also, you will get what happens in case of glass ceramics, we have just discussed that, we have glass ceramics you have a presence of a second phase, either in the form of a rod or a kind of fiber or it can be in the form of a particulates that means, a more circular or regular are particulates.

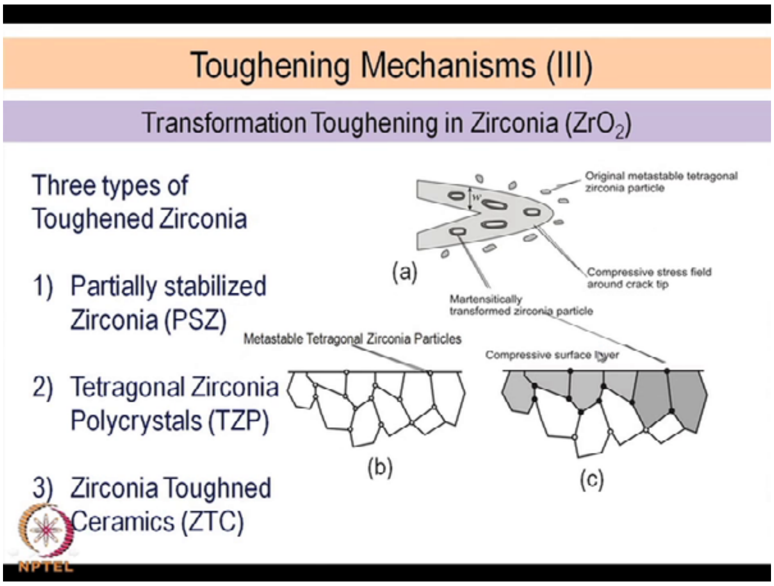
So, in both the cases, the crack has to go through a circuitous route, because it cannot go through directly or on a straight line. Therefore, this is a moment; this is a restriction in the on the path of the crack growth. And therefore, you can also have a strength higher strength, compared to a material which does not have this kind of a second phase dispersion. So, this is the crack reflection method, and then you can also have a crack bridging method, crack bridging technique. In fact, so you can see there is again a second phase, there is a second material coming, this is the matrix is the first page in with the crack is trying to grow.

So, in which there is a application of load obviously. But then we have some anchoring, may be a some kind of fibers, some kind of fibers, have been put together or it has been dispersed in a matrix of the first phase. And therefore, this is which is restricting the moment of these crack to propagate. And therefore, once one again, once again you have a strengthening of the matrix phase. Here also is the same thing you have fibers, some kind of a fibers, which has been which is restricting the moment of the crack, to grow because of the presence of this. The only difference here between these 2 situations is with no interfacial debonding and with debonding. Debonding means, the crack there is an interface there is a interface between the matrix.

And this second phase, second phase, the elongated phases and because of the application of the, of the mechanical stress there may be a possibility of debonding at the surface, at the, at the interface, between the second phase and the matrix. So, there is a as you can see here is small opening up taken place. So that means the cohesive force, the cohesive force between this matrix and the second phase is lower than the local stress, which is getting generated, because of the application of the external force external stress. So, here it has not taken place, such debonding interfacial debonding has not taken place, but with this the debonding as taking place.

So, debonding sometimes is good, because some of the energy, some of the energy gets released there. So, for the propagation of the tip, less energy is available. So, by that debonding also, one can restrict the propagation of the, of the crack. So, there be more deformation, more deformation more plastic deformation can take place with this kind of situation. And here the plastic deformation will be restricted, but it is young’s modulus may be enhanced. So, both these things can be used in a controlled manner to get advantage of the 2 types of mechanisms.

(Refer Slide Time: 28:48)



Toughening Mechanisms (III)

Transformation Toughening in Zirconia (ZrO_2)

Three types of Toughened Zirconia

1) Partially stabilized Zirconia (PSZ)
2) Tetragonal Zirconia Polycrystals (TZP)
3) Zirconia Toughned Ceramics (ZTC)

Now, there is another transform toughening mechanism which is quite different from what we have discussed so far. This is what we called transformation toughening and particularly in a material like zirconia ZrO2. You may be aware may be in some other context, we have discussed that ZrO2 has 3 different polymorphic forms. At room temperature, it is monoclinic slightly above room not slightly above fairly about room temperature is about 1100, 1200 centigrade it transforms to tetragonal phase and then at a much higher temperature about 2500 or so and 2200, so it actually transforms to cubic. So, the cubic phase is normally not stable at room temperature.

However, if you add some calcium oxide or yttrium oxide or magnesium oxide the room temperature at room temperature, the cubic zirconia phase is becoming stable and that is what we call the stabilized zirconia. So, sufficient amount of either calcium oxide, magnesium oxide or yttrium oxide as to be added. So, that the high temperature cubic phase gets stabilized at room temperature and that is one of the materials used for as an ionic conductor on different contexts. But this material also has a very interesting properties so far as the mechanical property is concerned. Now, the transformation, the transformation of monoclinic zirconia or tetragonal to monoclinic, tetragonal to monoclinic phase is supposed to have a martensitic transformation characteristic.

Now, what is martensitic transformation? Martensitic transformation is actually a diffusion less transformation and it is also called a thermal transformation. Now, so this diffusion less transformation does not really is not a isothermal transformation. So, with time, we maintain at a particular temperature it does not the volume fraction does not change only it is called a thermal transformation that by changing the temperature one can have the transformation. So, these are the some of the specific characteristics of this particular tetragonal to the monoclinic transformation.

In addition, it also had a very interesting characteristics that the material can be transformed providing a through a mechanical stress. So, it is a martensitic transformation or a tetragonal to monoclinic transformation can take place by induction or stress induced transformation. One can realize a stress when a mechanically stress induced transformation that means, apply a stress it gets transformed. Now, it is also associated this particular transformation is also associated with a fair amount of volume change, there is fair amount of volume change at this transformation just like alpha beta course transportation.

So, impact that volume change is responsible, why a lot of crack develops if you try to heat or cool zirconia through this temperature, pure zirconia through this temperature range. But stabilize zirconia do not have that, because it is more stabilized there is no tetragonal phase transformation. It is stable, the cubic phase is stable throughout the temperature range. And therefore, that kind of crack generation is restricted or can be avoided. Now, zirconia can be toughened; zirconia not the pure zirconia or the fully stabilized zirconia, it is basically, partially stabilized Ziricona. Partially stabilized zirconia, what is called PSZ general can be toughened, can be toughened by a this kind of a phase transformation. What happens in a partially stabilized zirconia is not the complete cubic phase, but it is a mixture of cubic and tetragonal phase. The fine dispersion, fine structures or the fine dispersions are actually a tetragonal phase.

So, that tetragonal phase is again unstable, thermodynamically unstable. And the tetragonal phase can be transformed to a monoclinic phase, more stabled form by through what we call the stress induced. So, transformation here is a stress induced transformation. So, it is not the temperature on alone, but the mechanical stress also can induce this transformation and that is a peculiar characteristics are very important characteristics of this transformation. So, you have, you can see the crack is trying to propagate here, you have the matrix phase here, which is basically cubic zirconia and these are the, these are the dispersion phase or the metastable tetragonal zirconia particles. So, the metastable tetragonal zirconia particles are dispersed in a matrix of stabilized zirconia or cubic zirconium.

When crack is trying to propagate it generates a stress field as we have seen earlier, that it generates a stress field ahead of it. So, this is the stress field and within that stress field a martensitically transformed zirconia particles has been formed. That means, which was metastable tetragonal phase. Now, it is transformed to monoclinic phase because of this stress here. So, as the cracked rise to expand or crack try to move forward ahead of it, there is a strain field or stress field, there is a stress field. Because of this stress field the tetragonal zirconia which is metastable in nature goes to back to the monoclinic phase with a volume change, that also generates lot of stress and sometimes micro cracks are also get developed. So, because of this phase transformation, a compressive stress field around crack tip generates.

So, normally the crack will try to open up with an tensile load. However, because of this transformation and the volume change and that transformation is also induced by the stress field in ahead of the crack, crack t. So, everything is quiet as I mean coordinated or it is a kind of related to each other. So, you have a metastable phase and when the crack is trying to propagate you generate a stress, that stress transforms a phase transformation takes place of the metastable tetragonal to the stable monoclinic. That transformation also induces some stress, compressive stress, because of the volume change. And as a result everything together, this there is a compressive stress created ahead of the grow of the crack tip.

So, it is a very interesting phenomena, which happens in a partially stabilized zirconia phase. And is happens primarily, because there is a metastable phase, which the transformation, in which the transformation is induced by a mechanical stress not by temperature alone. So, this is what we called the toughening or stress induced transformation, stress induced transformation or transformation induced transformer or transformation toughening. So, it is the phase transformation, which increases the toughness and that is why transformation is toughening in zirconia, particularly in zirconia this kind of thing happens. There are 3 different forms of zirconia in which this kind of or mechanisms are operative. One is I have discussed already, the partially stabilized zirconia PSZ.

Then there is a another material specially prepared material, which is called tetragonal zirconia polycrystalls, which is a pure tetragonal phase that means, there is no cubic phase. This is partially stabilized, because you have a mixture of cubic phase as well as tetragonal phase that is why it is called partially stabilized. Here it is stabilized again a metastable phase, the metastable because it is fully tetragonal phase, there is no sign of cubic phase. So, that can also be prepared by very fine particle size, if the nanometric particle size of zirconia is prepared, it is automatically a tetragonal phase get stabilized. In fact, it is a metastable phase of course, but room temperature it remains almost indefinitely until and unless you stress it. So, this tetragonal polycrystal or the polycrystal of tetragonal also undergoes a similar phase transformation or stress induced transformation. When a crack is trying to propagate through this matrix and that also gets toughened.

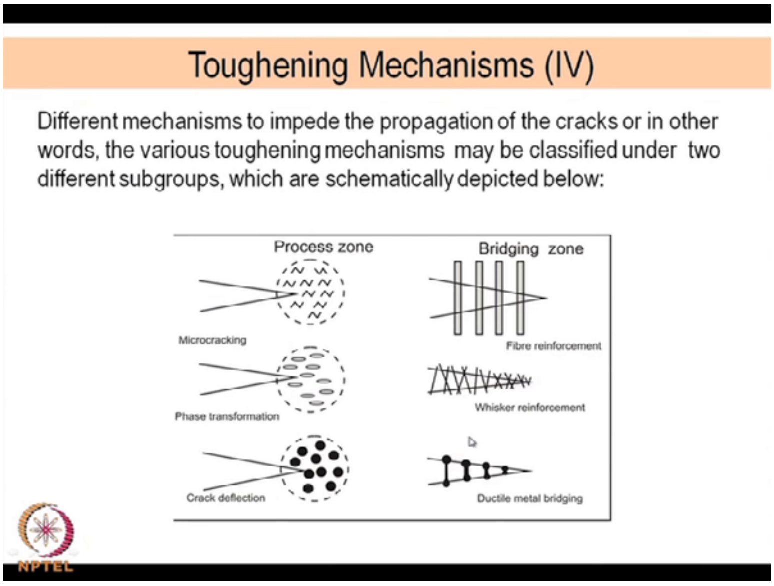
So, a transformation toughening or stress induced toughening can happen, not only in partially stabilized zirconia, but also tetragonal zirconia polycrystals. So, these are the two different materials both based on zirconia, but with different kind of structures. So, that is also tough material, both of them are tough materials and there is another group of zirconia related ceramics, which is zirconia toughen ceramics. Here it is not the matrix of zirconia, zirconia has been added to other ceramics may be alumina, maybe mulillite, may be magnesium oxide.

So, the basic matrix is of that of magnesium oxide or aluminum, a alumina, aluminum oxide in which some fraction of zirconia is added, either in the tetragonal form or maybe in the monoclinic form. So, there available there or this second phase in that alumina matrix of magnesia matrix is basically a metastable, metastable tetragonal phase. And whenever a crack is trying to propagate to that phase, again that transformation toughening can take place. In this case, transformation toughening takes place the matrix is not zirconia, but some of the ceramics, where zirconia is used as a toughening phase. So, that is called the zirconia toughened ceramics. So, all these things are available and they are used in many different applications, particularly zirconia toughened or transformation toughened. Zirconia is used for many different purposes including the dice for wet drawing even knifes one can make almost like a steel knifes made of a toughen zirconia.

Paper cutting knifes, paper searing knifes, knifes, scissors many things are available with what happens zirconia. Of course, toughen zirconia, grinding balls, grindingly media are also there. So, their quite tough at some time hard. So, that is transformation toughening, this is metastable tetragonal zirconia particles, that is what is called the zirconia toughen ceramics. I forgot to mention about these two picture, we have spend a lot of time on this. But this actually represent the zirconia toughened ceramics, where these grains are of different ceramics, but at the grain boundaries you have tetragonal zirconia metastable, tetragonal zirconia particles are dispersed and once they transform, they generate a compressive stress on the surface.

So, this shaded region is actually, because of the transformation these had been transform to this part has not been transform open circles means the untransformed. And the close circles or the solid circles means they have already been transformed, because of the stress applied. Once the stress applied from outside their get there is a phase transformation and that generate a compressive stress on the surface. So, these are the compressive stress area and these are the normally area. So, because the compressive stress area on the surface, you have difficulty in propagating a crack. So, that is very important group of material based on zirconia transformation and that is why they are called transformation toughening zirconia materials.

(Refer Slide Time: 44:27)



Toughening Mechanisms (IV)

Different mechanisms to impede the propagation of the cracks or in other words, the various toughening mechanisms may be classified under two different subgroups, which are schematically depicted below:

Well, this a summary of whatever little already been discuss the toughening, again the toughening mechanisms. They can be grouped under 2 groups; one you call the process zone, the other is called the bridging zone. The different mechanisms to impede the propagation of the cracks or in other words the various toughening mechanisms may be classified under 2 different subgroups, which are schematically depicted here. One is as I said it is the process zone, toughening and it is called bridging zone toughening.

What is happening here? There are 3 different concepts or 3 different principals, you can have micro cracking, phase transformation and crack deflection. This we have not discussed, but if ahead of the crack zone or ahead of the cracker tip, you have very fine, very fine micro cracks. Somehow you have, because of the stress concentration there, because of the material characteristics. In this crack, is much larger crack compare to this crack? So, there are very fine cracks ahead of the crack tip. So, that is what we called micro cracking and that presence of micro crack also impedes the motion of the main crack or the larger crack. And that is how, because our basic purpose, basic purpose is to impede the motion of the crack or which is actually giving rise to the failure.

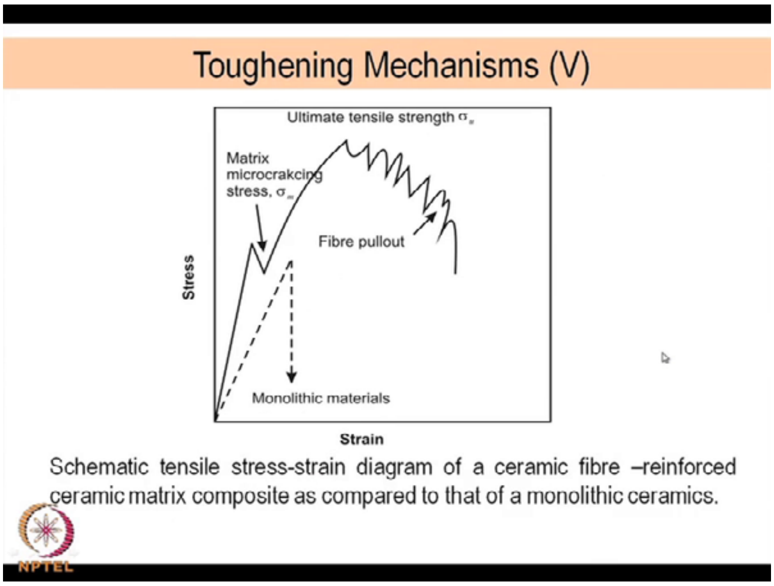
So, it is not only the other second phase material, but this micro cracks also generate some compressive stress here. And that compressive stress is not allowing this main crack to propagate. So, this is a micro cracking mechanism, which is happening in the process zone in the matrix, in the matrix ahead of the crack. Same thing happens here is a phase transformation, which we have already discuss in details in a with reference to zirconia. So, we have metastable phases, they are getting transformed and that is how you have a compressive zone which is created here .Crack deflection; that also have been discussed earlier, either by the presence of some second phase material or just by grain boundary which we have discussed earlier.

These is crack deflection either by grain boundaries itself of the same page or a second phase either it may be a elongated or a rod like second phase or even fine particles can also do the same thing. So, these are process zone that is been the in the material itself, but the crack is propagating ahead of the crack zone, that is why it is called process zone at. And these are bridging zones this is the bridging zones mechanism, there is a fiber reinforcement that means, as you know ceramics can be enforced with different other phases it can be fiber; it can be whisker; it can be a even a ductile metal, bridging metals can be used as a reinforcement. So, these are all reinforced materials.

A reinforcement materials of primarily fiber, fiber like reinforcement there can be particle reinforcement here, but here it is the fiber reinforcement. So, this fibrous are actually bridging the crack, it is anchoring the crack not to. So, that it cannot propagate now, you know it is not the monolithic ceramics, but ceramic matrix composite's are also quite important and there has been extensive or development. So, far as the ceramic matrix composition are concerned. One can use different kind of fibers, you been ceramic fibers can be used silicon carbide fibers or silicon carbides whiskers can be used, even alumina fibers can be used as reinforcement within another ceramics matrix. So, that is called ceramic matrix composites or C M C’s unlike M M C’s or metal matrix composites.

Ceramics can be used in metals for reinforcement, but ceramics can also be used in ceramics matrix t p prepare or to form so so called C M C’s. One of the major examples of C M C is your carbon, carbon composite in which the graphite is reinforced with carbon 5. So, similarly, there are many different fibers which can be used for reinforcement. And if you have use reinforcement that is what happens either use fiber reinforcement, the cracks will be bridged. And we have discussed that earlier, this kind of cracking bridging takes place, there can be debonding also. Here is a Vickers and is you in you were aware, that these are fibrous, which are large size fibers diameters is larger and whiskers as much smaller fibrous materials, the diameter as well as like that small. These are ductile metal, bridging metals can also be used in some of the ceramic composites well particularly in extensive use of metal has been in refractory. In refractory metal fibers has been use extensively for reinforcement. So, these are the major mechanisms of toughening.

(Refer Slide Time: 50:58)



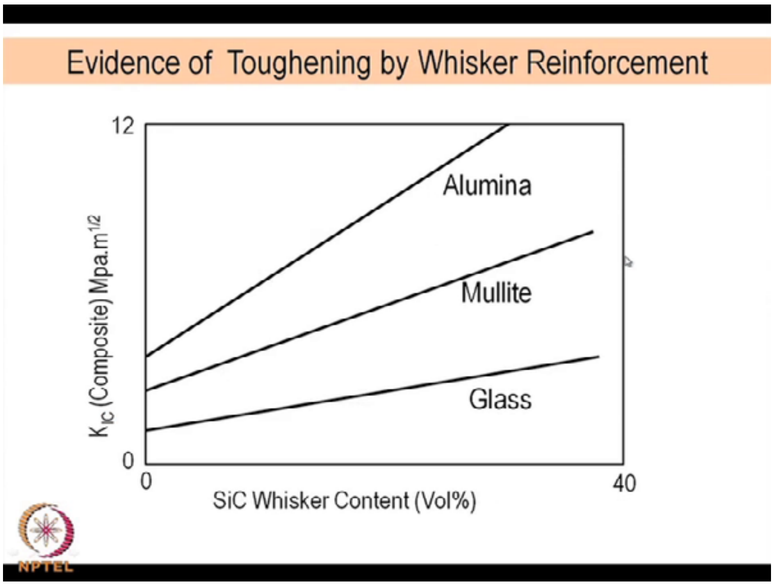
Toughening Mechanisms (V)

Schematic tensile stress-strain diagram of a ceramic fibre –reinforced ceramic matrix composite as compared to that of a monolithic ceramics.

Once we have toughening by some reinforcement, particularly fiber reinforcement, the stress and curve also gets modify compared to original stressed and curve of a monolithically material. This stressed and curve is quite different, because of the, we are basically delaying or slowing down, slowing down the crack propagation and therefore, it behaves little closer to a ductile material. So, this is a the comparison of stressed diagram, stressed and diagram of a composite material, metal matrix composite y a metal matrix composite compared to the monolithic a ceramics. This we have seen earlier a monolithic ceramics if you do tensile load a it goes up to a point and then suddenly breaks.

So, there is no permanent deformation or ductility is almost nil, whereas, if you have a C M C; that means, ceramics matrix composite or reinforcement with some fibers, the stressed and diagram is quite different, these more like a ductile material. In fact, you do not get any ceramic material like this, what is called the yield point, a kind of yield point phenomena takes place here a matrix micro cracking stress. That means, the micro cracking starts here, it is the some something like a yield point phenomena as we get in ductile material. There are once again it goes and finally, which some serrations and it takes place fiber pull out that is debonding actually takes place more, and more debonding takes place here and therefore, all these serious and comes. And the total amount of permanent deformation before fracture is fairly larger compared to almost negligible in case of monolithic ceramics. So, these are a schematic tensile stress and diagram for as ceramic fiber reinforced matrix composite as compared to that of a monolithic ceramics so that is the comparison has been.

(Refer Slide Time: 53:29)

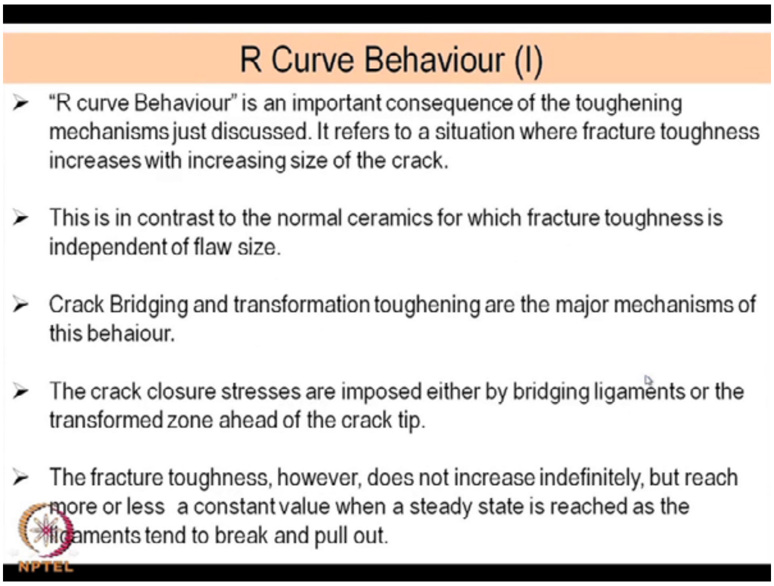


Evidence of Toughening by Whisker Reinforcement

Well, this is that actual evidence of some toughening, what we have discussed? The basic principles we have discuss and these are the some of the basic schematic diagram of some actual materials. For example, if you add silicon carbide Vickers in different volume percentages, two different either ceramics like alumina or mullite or some glass. How the K I c value increases and you can see the K I c value with the addition, addition of whiskers, the K I c, the toughness or the fracture toughness increases quite extensively. Here with 0 percent whisker, you can see the glass has a factor toughness of this value, these are our course schematic diagrams not exact values this 0 to 12 scale.

So, alumina has higher fracture toughness than mullite and then that of glass, but if you add some percentage of whiskers in it alumina, the fracture toughness of alumina can be as high as 12 which is very, very high is almost impossible without a addition of any reinforcing agent. Even glass increases not as much as alumina, but it also improves mullite is in between. So, these are the some of the real examples is of how the toughness can be increased by the enforcement.

(Refer Slide Time: 55:21)



R Curve Behaviour (I)

- "R curve Behaviour" is an important consequence of the toughening mechanisms just discussed. It refers to a situation where fracture toughness increases with increasing size of the crack.
- This is in contrast to the normal ceramics for which fracture toughness is independent of flaw size.
- Crack Bridging and transformation toughening are the major mechanisms of this behaiour.
- The crack closure stresses are imposed either by bridging ligaments or the transformed zone ahead of the crack tip.
- The fracture toughness, however, does not increase indefinitely, but reach more or less a constant value when a steady state is reached as the ligaments tend to break and pull out.

Well, there may not be much time. So, I do not want to discuss stop this discussion of R curve behavior that is also another very important phenomena in a brittle solids, particularly in ceramics and maybe will discuss that in the next class. So, there are few other points so far as the mechanical behavior is concerned will come to that, one is the R curve behavior, the other will be vibel modulus. But since the time is not much there, let me finish for that for this lecture. So, we will continue this lecture next time.

Thank you, thank you for your attention.