Introduction to Biomaterials
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Lecture No. # 22

Fracture and toughening of ceramic composites

In the last lecture I finished at the point, that you know, that critically mentioning, that why porosity needs to be reduced in order to get better ceramics with higher flexural strength and modulus of elasticity. So, just to refresh your memory, that if you, if you have a very dense ceramic like, which has more than ninety-nine percent density, then you can get much higher flexural strength.

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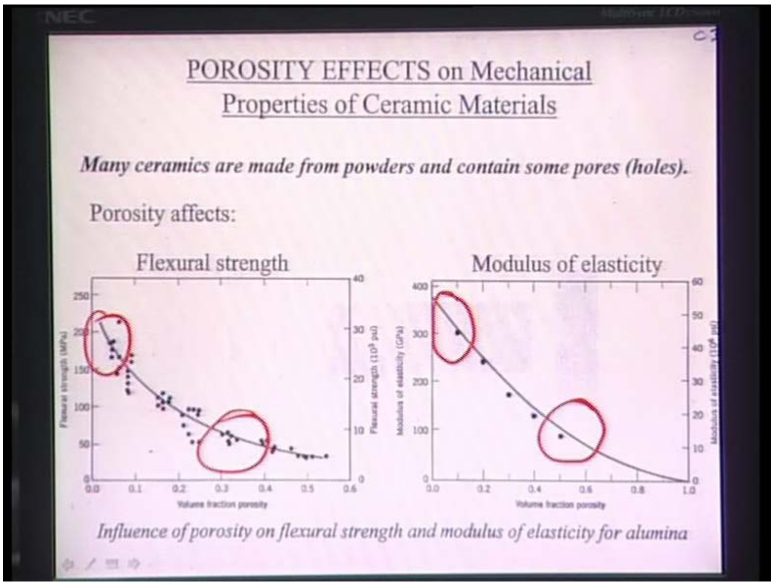

Now, this example has been given for alumina. At the same time, if you have more than ninety-nine percent theoretical density, then you also can get larger elastic modulus. Now, this is the trick to play, that you can play while developing bioceramic materials for bond replacement applications. If the material has very high elastic modulus and then you want to match the elastic modulus of that of the bone, then what you can do? You can get porous ceramic, so that you know, that with increase in porosity the elastic modulus will be lower.

Now, you have to do experiments just to find out, that at what porosity level the mixture will have, what elastic modulus? So, if you want to do get down to, from 200 giga Pascal to 70, 80 or 100 giga Pascal, then you roughly know, that around forty percent or fifty percent, forty percent porosity, that you should have in the material, so that this material has the required porosity level. But remember, when the material is highly porous, then it has also, consequently, very low flexural strength, so it cannot be used for highly load bearing implant applications, or in other words, it cannot be used in biomedical applications, which require large load bearing capability.

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Now, this essentially tells you, that that like the way that you know strength, that elastic modulus largely depends on the pore size. Similarly, K 1c, you, I repeat, K 1c stands for critical stress intensity factor under mode one loading. So, critical stress intensity factor means, in last lecture I have mentioned, that K 1c, you can define as Y sigma f root over pi a. What are the different terms here?

Y is actually a parameter, which depends on the orientation, the crack, with respect to the loading axis, as well as, the nature of the loading, whether it is uniaxial loading or biaxial loading. In many cases it was, the value of Y is not given, the value of Y is taken as 1 or 1.1. Now, sigma f is a fracture strength, that means, the stress value acts, which this, that particular ceramic fractures, a is the half, half crack length. If this crack is in the volume crack, that means, this crack is well within the ceramic body or if the crack exists on the ceramic surface, then the pool crack length is taken as a. Now, from this it is very clear to you, that critical stress intensity factor under mode one loading, does not depend, depends, sorry, depends not only on the stress value at all.

So, the crack length value and that has been mentioned here, that let us say, for good steel, like you know, the steel, which has very good mechanical properties. Now, if K 1c is, let us say, 100, now K1c is a fixed value, so what it shows, that I think I will spend some time on this slide, that you know what, what it tells, that if it is a, if the steel has very good mechanical properties, then the K 1c is 100 MPa square root meter. Then, the value of a, a, is that crack length, that it can be tolerated for the same steel, which has a fracture strength of 100 MPa is 320 millimeter. 320 millimeter, it means, is very large crack length and typically, if the material has any size, which is less than 320 mm, that means, that material is safe.

Now, if you go to cast iron, which has a 20 MPa square root meter fracture toughness and the same strength value if the cast iron has a strength value of 100 MPa 100 mega Pascal, then the crack length is 13 millimeter and 13 millimeter means, that means, that if any cast iron sample, which has a length or which has a size more than 13 millimeter, then it can be and if it contains the crack length of 13 millimeters, then it is dangerous.

Now, typical ceramic, now ceramic is less than alumina, which is a bioceramic and in case of alumina, if K1c values 4 MPa square root meter and for sigma f is 100 MPa, then it can only tolerate 510 micrometer. So, 510 micrometer means, it is much less than a millimeter. So, if your sample size is of 3 millimeter or 4 millimeter or 10 millimeter size and if the same sample has a K1c value 4 and the fracture strength of 100 MPa, then you can very well see from this table, that only 510 micrometer crack length can be tolerated, anything larger than 510, it will lead to on stable fracture propagation.

Now, extremely brittle ceramic, for example glass, now very or many examples, many applications bioglasses are used and the glasses, that are extremely brittle, they have a fracture toughness of 1 MPa square root meter and then, you can only tolerate up to 32 micrometer.

So, what you can see, that there is an order of magnitude difference, you go from 320 millimeter to go to 32 micrometer. So, 32 microns means 32 10 to the power minus 6, 320 micrometer means, millimeter means, 320 10 to the power minus 3. So, in other words, 332 into 10 to the power minus 2 and then it go to here, 32 into 10 to the power minus 6. So, what is the order of magnitude difference? Order of magnitude difference is four orders of magnitude difference. If you go from good steel, which is a 100 MPa, 100, which is a fracture toughness of 100 MPa square root meter and if you go to very brittle ceramic, which has fracture toughness of only 1 MPa square root meter, so by decreasing the fracture toughness value by two orders of magnitude the maximum crack length, that can be tolerated in these materials, that can be reduced by four orders of magnitude.

So, I, I, I again emphasize this point. So, 320 millimeter means, 32 into 10 to the power minus 2 meter. 32 micrometer means, 32 into10 to the power minus 6 meter. So, when you are decreasing the fracture toughness from 100 MPa square root meter to 1MPa square meter, that means, you are decreasing by two orders of magnitude, by decreasing in the two orders of magnitude fracture toughness. The maximum crack length, that can be tolerated in the material, that decreases from 32 into10 to the minus 2 to 32 into 10 to the minus 6, that means, four orders of magnitude difference. So, that be, that comes because, that the square root dependence of the crack length. So, this, that means, that you know, you have this crack length is, crack length has much more significant influence on the fracture toughness value of the materials.

Now, if you, if you go to the next row, if you increase the fracture strength from 100 MPa to 500 MPa, now what you notice here, that your tough metal, like wood, steel, you have the, the, the maximum crack length, that can be tolerated in 13 millimeter. And if you go to that brittle ceramic there the maximum crack length, that can be tolerate is 1.2 micrometer, again 13 into 10 to the power minus 3 and there you can get 1.2. That means, it, you know, it is 12 into 10 to the power, so1.2 to the minus 7. So, this is 12 into 10 to the power minus 7, that is the crack length in very brittle glass and 13 10 to the minus 3, that is in very tough metal.

So, again, there is a roughly like four orders of magnitude decreased in the maximum tolerable crack length. And only thing is, that other thing, that you notice, that if the fracture strength of the material can be increased to higher value, then maximum tolerable crack length for any given material is subsequently or systematically reduces form 320 millimeter to 13 millimeter.

So, the thing, that I am trying to mention here, that pi micro structural design you can always increase the fracture strength, but for brittle ceramic you can immediately see by increasing the fracture strength, you have a opposing directions. That means, you increase in the crack strength will be accompanied by a decrease in the decrease in the length of the maximum tolerable crack length. So, that means, you can always increase in the strength of the materials, but then it should be accompanied by, that the critical crack length that you can tolerate in this microstructure.

So, in that high strength material, that maximum tolerable crack length is very fine crack. So, very fine crack, if it is present it can lead to fracture. So, therefore, you can see 500 MPa, when it is crack to fracture strength, then this critical crack length is 1.2 micron.1.2 micron is extremely small crack length. So, any crack length which is greater than 1.2 can easily lead to the fracture of the entire ceramic. Is it clear?

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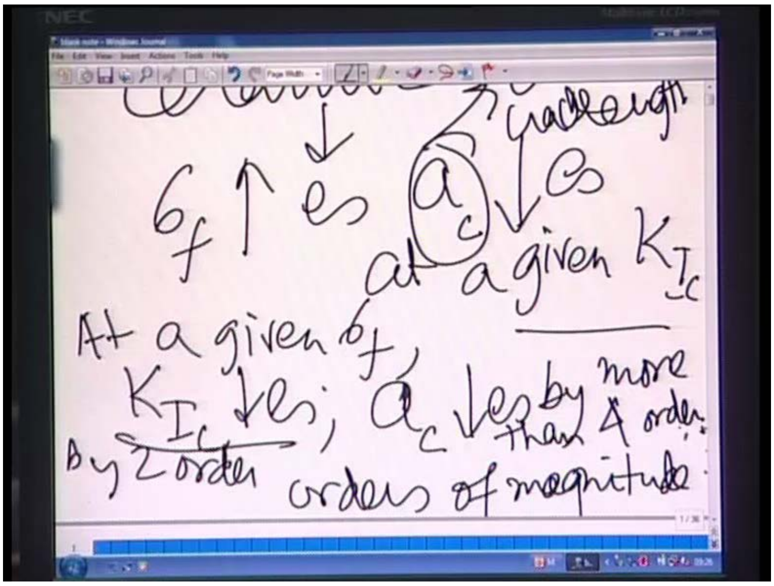

Then, so for, basically for ceramic materials you, now there is fracture strength, so if sigma f that increases your critical crack length, let us say a c, that decreases systematically at a given K 1c value. So, when K 1c is constant, that if sigma f increases, your a c, that is the critical crack length, that significantly decreases and this decrease is quite significant, as you have seen in the table.

Other thing is, that at a, at a given sigma f value, at a given sigma f value, that when fracture strength is constant, that if your K 1c decreases, then your a c, that is, the critical crack length actually, sorry, if K1 c is in, if K1 c increases 100 MPa square meter to 1 MPa square meter, so you are actually decreasing the fracture toughness. Now, if K1c decreases, then your a c value decreases by around, by more than two orders of magnitude.

So, what it means, that you know, if K 1c decreases by two orders of magnitude, then, then a c will decrease by four orders of magnitude. So, basically, whatever order of magnitude decrease in the K 1c, your critical crack length value will decrease more than two times the same order of magnitude. So, if the K 1c decreases by three orders of magnitude, then that a c value will decrease by six orders of magnitude. So, that is what, so that is what we are trying to mention here.

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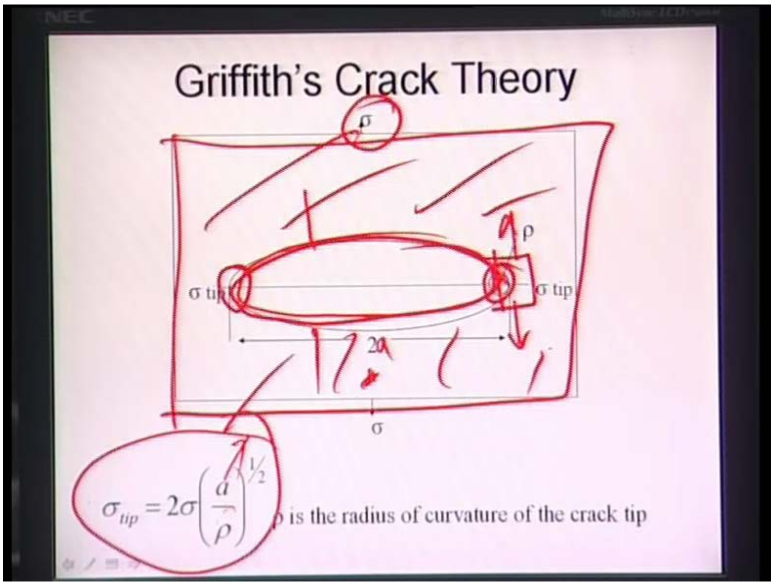

And then, if you go back to the, if you go to the next slide now, what you see here, that there is a Griffith's crack theory. This is a famous crack theory of, proposed by Griffith. Now, what is in this Griffith crack theory? If you have a, sorry, you have a rectangular plate and this rectangular plate has a central crack and this rectangular crack, rectangular plate has a central crack, crack means, this is a dense solid and this solid, there interatomic bonds are not extended across this crack phase. So, therefore, there is a kind of wide space here. Now, you have that two edge here, one edge is here and one edge is here.

And in the last lecture I have shown you, that at the tip of the crack your stress is, if you consider this volume element and this is sigma, so at the tip of the crack this stress value is much, much higher than that stress value, that you are actually applying, or in other words, there is a stress concentration at the tip of the crack. And this stress concentration value you can find out is by sigma t is equal to 2 sigma a by rho to the power half.

Now, what is the value of a? a is the half crack length because this is your 2a. So, 2a is the total crack length and what is rho? rho is the radius of curvature at the crack tip.

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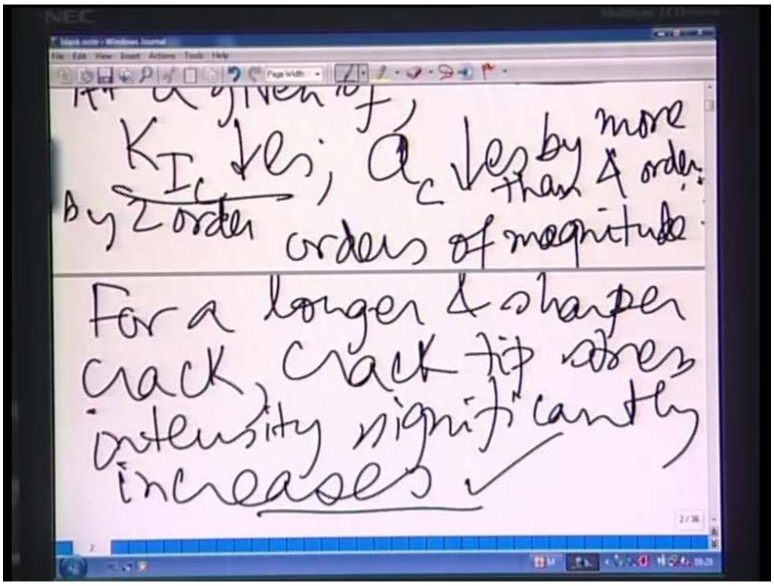

And this radius of curvature at the crack tip is important and that indicates what I have mentioned in the last lecture is, that for a longer and sharper crack the stress intensity factor increases; for longer and sharper crack, crack tip stress intensity significantly increases. So, whenever the cracks are longer and cracks are sharper, that essentially indicates, that your crack tip stress intensity also significantly increases. Now, this is some of the important thing that you have to remember all the time as far as you are dealing with ceramic base materials.

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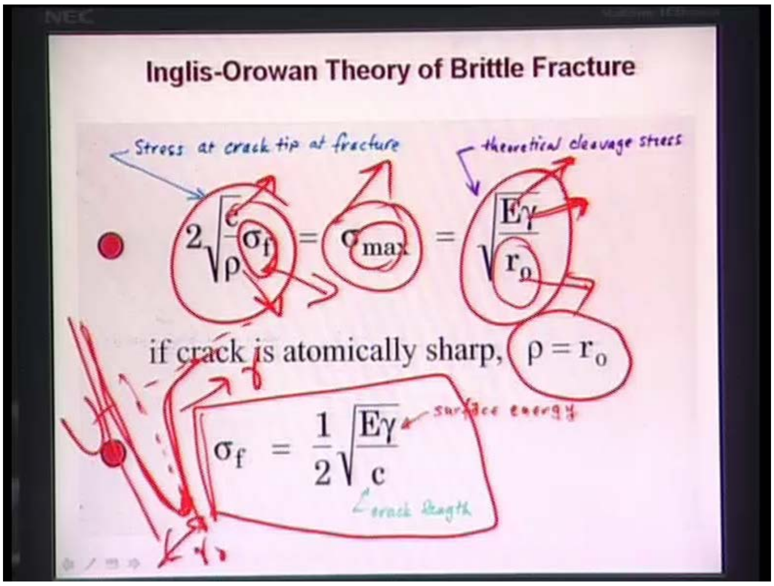

Now, other thing is that there is another theory called English r 1 theory of brittle fracture. What it says is that if 2 c by rho into sigma f, that is the stress at the crack-tip at fracture, if it is equal to E gamma by r naught that is the theoretical cleavage stress. Now, what it means by theoretical cleavage stress means?

Now, remember from the basic physics of this fracture of this brittle solid, from the basic physics of the fracture of brittle solids. Now, if this sigma tip is greater than interatomic bond strength, that means, at this crack tip region if this sigma t values are greater than interatomic bond strength, interatomic bond means this, there is ionic bond or covalent bond in the material. Now, if this sigma tip is greater, the interatomic bonds strength, then this crack will slowly propagate leading to the fracture of the material. So, that is the point I want to mention here.

So, therefore, the same criteria has been used by English and r1 and what it says, that sigma max at the crack tip at the point of fracture. So, this fracture strength means this when sigma becomes sigma f. So, when sigma becomes sigma f or in other words, you are applying the external stress, which has the value of the point of fracture at that point, 2c by rho into sigma f would be equal to sigma max, that is the maximum stress at the crack tip and if that is equal to square root of E gamma by rho.

What is E? E is the elastic modulus of the material. What is gamma? Gamma is the surface energy of the material and r naught is, r naught will come from your very fundamental interatomic energy potential well.

So, interatomic energy potential well means, that is, the interatomic force between two atoms and as a function of the interatomic distance if you plot, then it shows a kind of potential well like this and the potential energy minimum. This value is known as the r naught.

So, I repeat what are the different terms? c is the crack length at the point of fracture of sigma, sigma f; rho is the crack tip radius of curvature at that criticality condition; sigma f is the externally applied stress; sigma is equal to sigma f; sigma max, it is the crack tip stress intensity or the stress, which is realized stress at the crack tip; E is the elastic modulus of the material; gamma is the surface energy of the material and r naught comes from the interatomic energy potential, that is, the interatomic force, if your interatomic potential energy E u if you plot as the function of r. Now, this r value where it is the minimum of u, that interatomic potential energy, that is the, that is the lowest interatomic potential energy and that corresponding r value is called r naught.

Now, from that, so this is the equilibrium bond distance. So, r naught is nothing, but equilibrium bond distance and if the crack is atomically, atomically sharp, then rho is taken as r naught and from that you can find out, that sigma f is equal to half of E gamma over c and then E is the elastic modulus, again gamma is the surface energy and c is the crack length.

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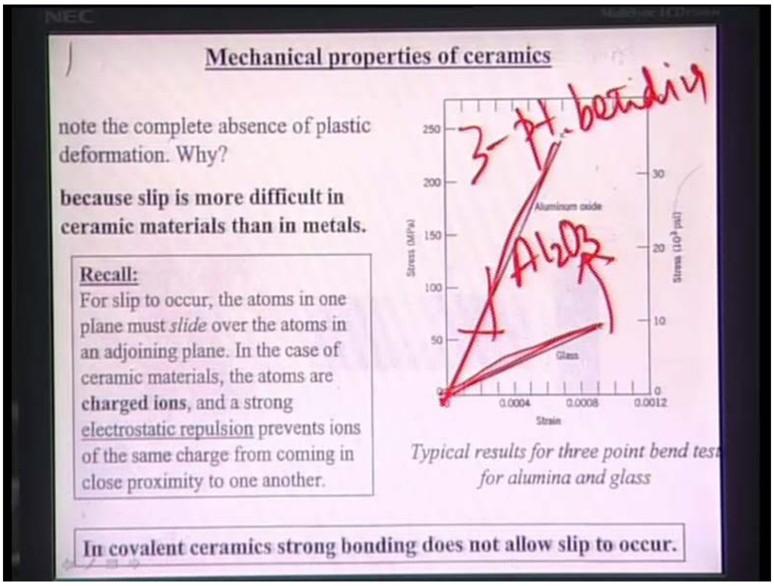

So, this is, so essentially this, this particular plot shows you, that how this stress and strain they are perfectly linearly proportional to each other in case of the ceramic material.

Now, this is for the alumina. In case of alumina it has a large. So, the steeper the line is, the mode is the elastic modulus because elastic modulus comes from your slope of this stress strain curve. And if, in case of your glass material the slope is much less, in case of alumina the slope is much higher, that means, glass has a much lower elastic modulus compared to alumina. The other thing you know, that this stress in plot, this has been recorded during the three point bending configuration. And this will keep on bending configuration if all this ceramic material it shows extensively linearly elastic behavior up to the point of fracture.

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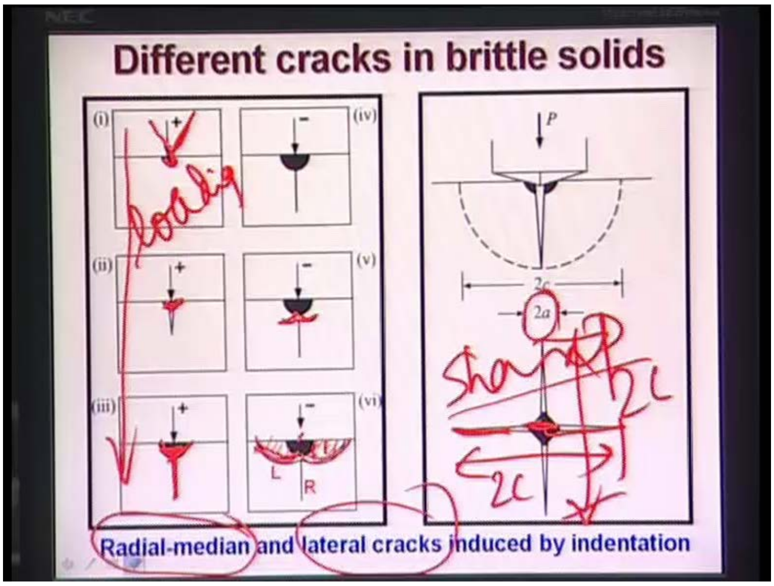

The other thing is that, that has to be mentioned here, that in this ceramic this, as you know, that ceramics of the brittle material. So, therefore, ceramics are very much prone to fracture. Now, the question is what are the two different types of cracks that stems in this brittle solids?

The first one is called radial-median crack. Now, plus sign essentially indicates when you are indenting the ceramic surface. Indenting means, you are placing the indent and let the indent making the pool contact over the flat surface. Minus sign indicates you are actually unloading the surface. That means, you are releasing the load, so that indent comes back to with original position and as you grow from plus to plus, that means, you are actually applying more and more amount of load to the indent, so that it reaches the maximum load. What it means? Suppose you are you are trying to apply 5 Newton loads. So, you start with 0 and slowly increases to 5 Newton and minus sign means, from 5 Newton you just cannot come back to 0 just automatically, it has to be step-wise, it goes to 0.

Now, in during the loading process this side, so during the loading process what you see, that as the indents will come in contact with the material, there is the deformation zone, this black zone is essentially the deformation zone just beneath the indenter and it is the cross sectional surface you take. So, essentially, if you take this as the material surface, you take as an indent. So, you are looking at from these directions. So, you are looking at this direction, that is, the transverse direction. So, you are indenting the material from the top and then, just beneath the indentation you have these kind of plastically, largely plastically deform regions. And then, what you see, that after, at the complete loading, when the loading is complete, then you see very stable radial, radial-median crack.

Now, while unloading, now remember this material, this indent is here, very sharp indent. So, all these things are essentially, are essentially valid for sharp indenter. Sharp indenter means, this is like Vickers indent, Vickers is the pyramid type of shape. So, Vickers is a sharp indent.

Now, when during the unloading, at, at certain point you see, that another type of crack, which will start propagating from the other direction. So, which direction it is? It will be at the 90 degree to that of the radial-median crack. Now, that will be generated and that will go through and when it is completely unloaded, this lateral crack, you will be completely touching the surface.

Now, what happens? If now, if you, if you relate this kind of behavior to, actually, the friction and wear scenario, like tribological scenario, now you can consider, that it is the sharp, sharp indentation and multiple sharp indentation, they are going just like this. So, one is lateral crack form, say, touch the surface, then this is the hatch region, which can be taken off from the surface or which can come out as the, due to the spoiling of the material.

Now, when this indent is coming at this point, indent to go like this and indent goes like this. So, when it goes like this to and fro motion, then what will happen to this? More number of spoiling will occur because this lateral cracks will come in contact with the material much, much extensively and this lateral crack will lead to the fracture of the material.

So, in case of the sharp indent you have the two types of crack, one is the radial median crack and one is the lateral crack. Which crack we use for this fracture toughness measurements, for fracture toughness measurements? You are actually measuring this 2 c values, like in the Vicker’s indent. You may, you were actually measuring the 2 c values in this direction and you are measuring also in those directions. And what is your 2 a values? 2 a value is just what is mentioned here, that is your total Vicker’s diagonal.

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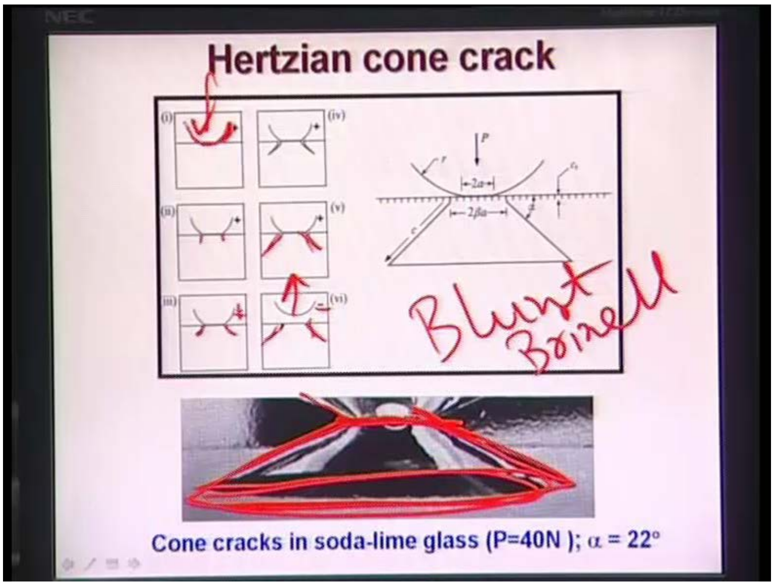

So, however, if you use the very blunt indenter, what is blunt indenter? Blunt indenter means, like you know, you use this Brinell indenter. So, this is the case, that you get for the blunt indenter and the example of the blunt indenter is the, let us say, Brinell indenter.

Now, this Brinell indenter, again this plus sign means, it is a loading and when you keep on loading, then slowly some pre-existing crack will be activated and this pre-existing crack will further propagate this plus means, it is complete. Now, it has completed loading and then you, more and more you load the flat surface with this Brinell indenter or blunt indenter.

So, blunt indenter means, suppose you replace your Vicker's indenter wise spherical steel ball and this spherical steel ball you indent it from the top surface, then what will happen? This cone cracks. Why it is called cone crack? Because it will, when the cracks are fully developed, when it is fully unloaded, this, this indenter will go up and will not any more in contact with the material, then it will actually form a this kind of cone crack.

Now, this cone cracks has been, has been seen or absorbed in the soda lime glass and soda lime glass, why glass material has been used? This glass material is transparent, you can see the cracking behavior in the glass material, your, many of your ceramic materials, they are not transparent. So, you cannot see how the crack acts on the soft surface region. And what you see here? This cone crack actually, essentially, formed here at this region and this region, it extends, it characteristically forms, that geometrical cone and this cone has a typical length as alpha 22 degree.

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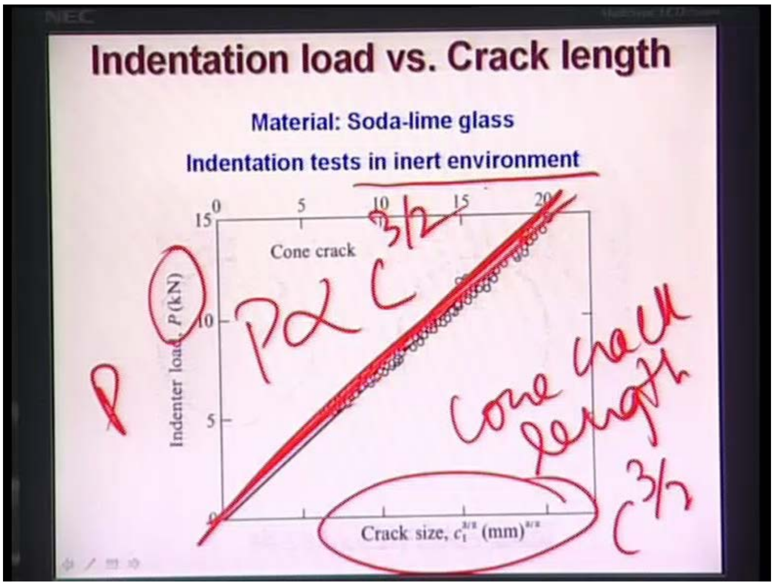

Now, people have done experiments on soda lime glass and this indentation tests were carried out in inert environment. Now, why inert environment? Many times if you do this testing in this aqueous environment or any acid environment, in aqueous and acid, can additionally lead to more attack chemical attack on this glass materials, and inert environment means, for example, this indentation tests were carried out in vacuum. Vacuum means there is no aqueous environment outside, so you can exclude the influence of that any external liquid environment on the glass material.

Now, if you change the load, let us say, you start with the 5 kilo-Newton, 10 kilo-Newton, go to the 15 kilo-Newton and each case you correspondingly measure, that what is the cone crack length. So, this is your cone crack length and if you plot this P, what is this c to the power 3 by 2. Now, it forms more or less like a straight line. So, that means, P is proportional to C to the power 3 by 2. So, this indentation load is proportional to crack length to the power 3 by 2. It does not have a typical linear relationship like P is proportional to C, but P is proportional to C to the power 3 by 2.

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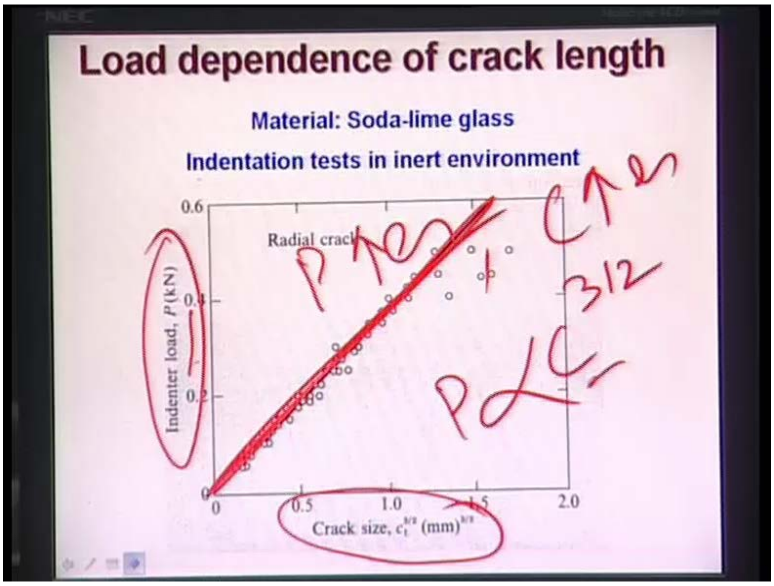

Now, what you see here in case of the radial crack, what you have seen, what is formed in this sharp indenter, like a Vicker's indenter? In case of the radial crack, even, similarly if you increase the load, indenter load and if you increase the crack size, so by increasing in the, so if P increases your crack size also increases. That comes from your basic physics.

Now, if P increases C increases and again, if you plot P versus C to the power 3 by 2, then again, you are going to get a straight line, that means, P is proportional to C to the power 3 by 2. And what is the C value? If you go back to this length, this is your P value; this is your C because this is your total 2C. So, half of the C is this one. So, you measure the crack length and you measure the indent load and systemically if you vary that, then if you plot it, then you get P proportional to C to the power 3 by 2.

So, what is the summary of the thing? in case of the blunt indenter you get gradual median crack, as well as, the lateral crack and in case of the, and sorry, in case of the sharp indenter you get radial median crack and lateral crack, and in case of blunt indenter you get a cone crack. In both the cases, irrespective of the crack geometry, you get P is proportional to C to the power 3 by 2, where P is indentation load and c is the crack length.

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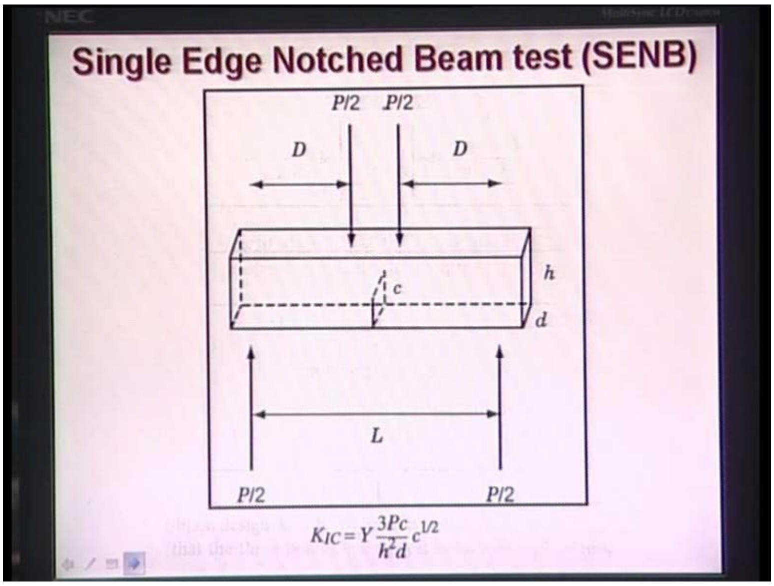

Now, single edge v-notched beam technique that has been also mentioned earlier and then single edge v-notched beam technique now there are two ways you can find out is fracture toughness.

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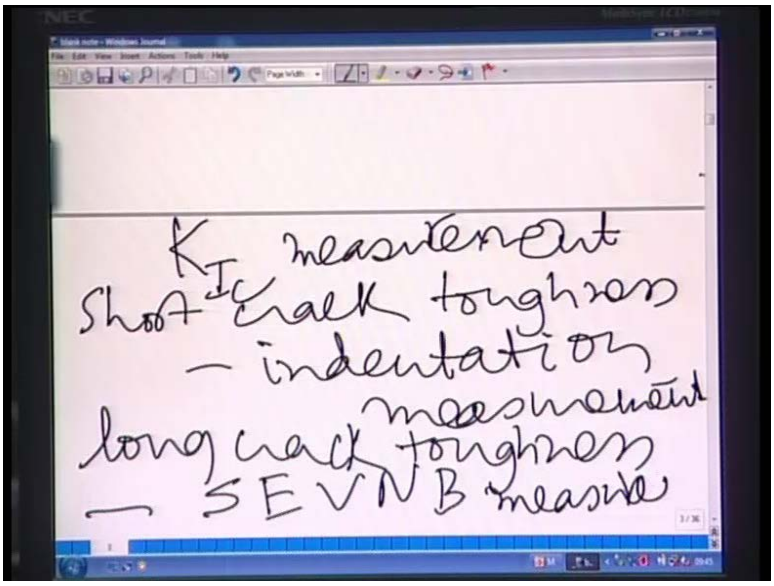

There are two ways you can measure the fracture toughness, one is the short crack toughness measurement and another one is the long crack toughness measurement.

Now, short crack toughness is typically measured by indentation because the crack length is very small with respect to the long crack, that you typically measure and long crack fracture toughness measurement is single edge v-notched beam measurement.

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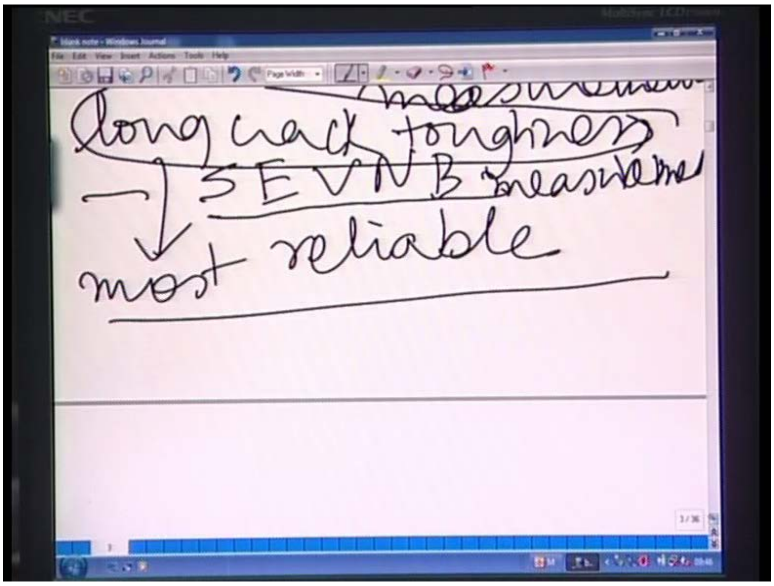

For example, now this is the long crack toughness, which is recognized as most reliable. Now, then the question is, that why short cut toughness is measured? The short cut toughness is measured because it is most easily obtainable and you can get it for, in the laboratory scale experiments within very reasonable time frame. And then, second thing is that when you are trying to develop a series of materials and these materials, they are developed by changing the composition or by changing the processing temperature.

Then, each time you cannot make a SEVNB sample because SEVNB sample making for ceramic material itself is time consuming matter and therefore, in order to avoid very tight rigorous measurements using SEVNB, there short crack toughness measurement is required. However, this indentation toughness you cannot use as a design parameter.

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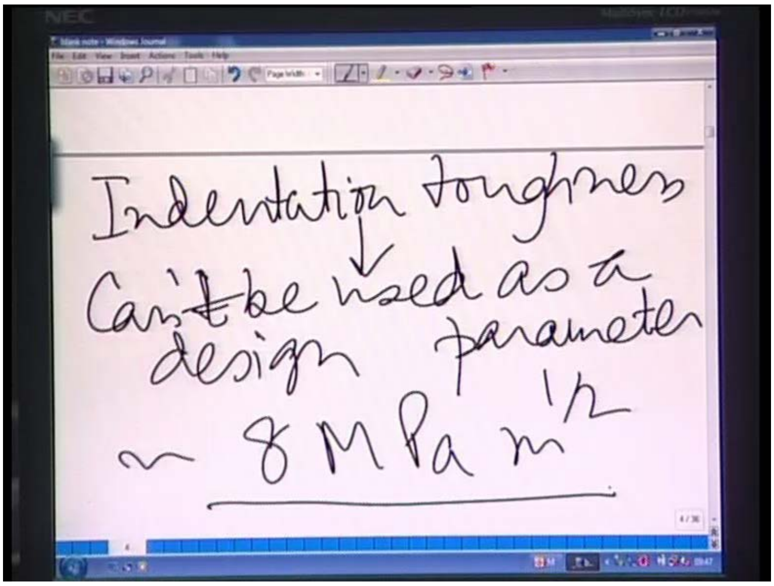

It cannot be used as a design parameter, that what it means, like if you are getting indentation toughness evaluates, for example, 8 MPa square root meter. You cannot say the same material in actual, real practice situations or in reality they will have the same level of toughness because your short crack toughness is typically, overestimates the, overestimates the factor toughness.

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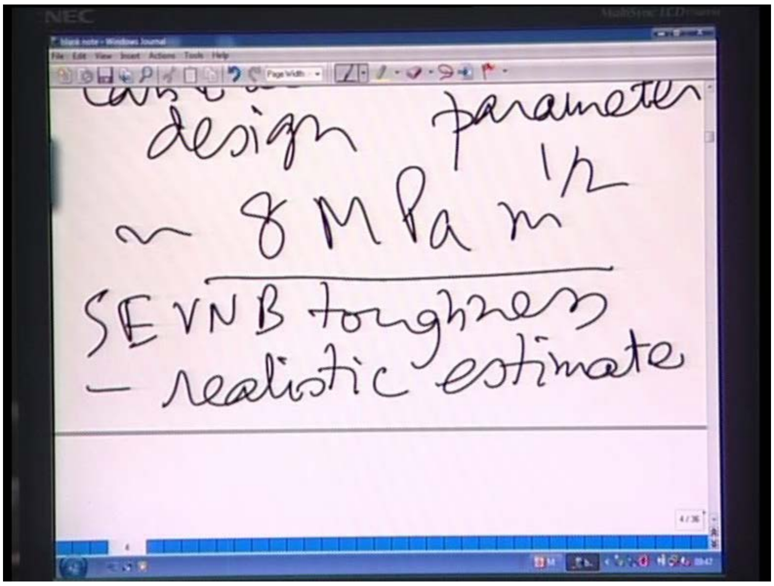

So, therefore, SEVNB toughness value all kind of realistic estimate and all this information is valid only for brittle materials like ceramics. For metals you get a stress-strain curve and from this stress-strain curve you can find out. For metals, it is different issue.

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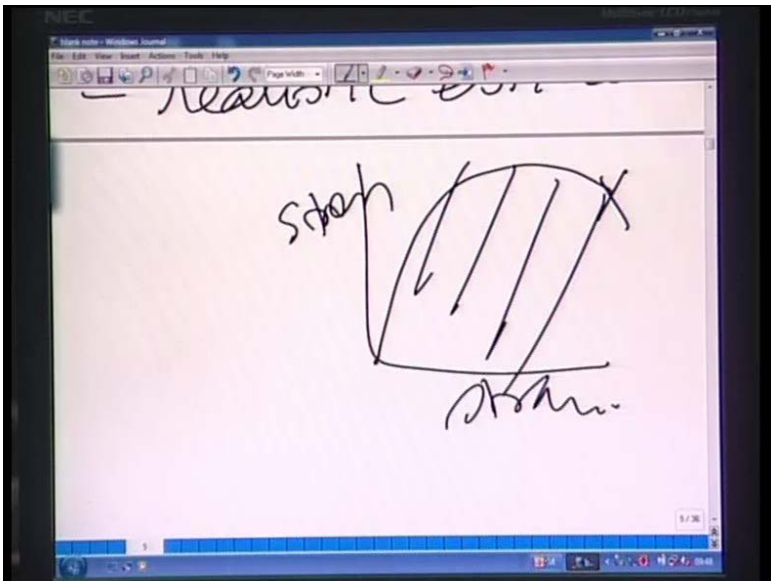

So, you get a stress strain curve like this. So, this is your stress and this is your strain and then, area under the entire curve is the measure of the toughness. But in ceramic you cannot get an elastic, elastic plastic kind of behavior in case of, during this tensile stress and behavior. And then, for ceramics you have to add up an alternative method to obtain the fracture toughness value.

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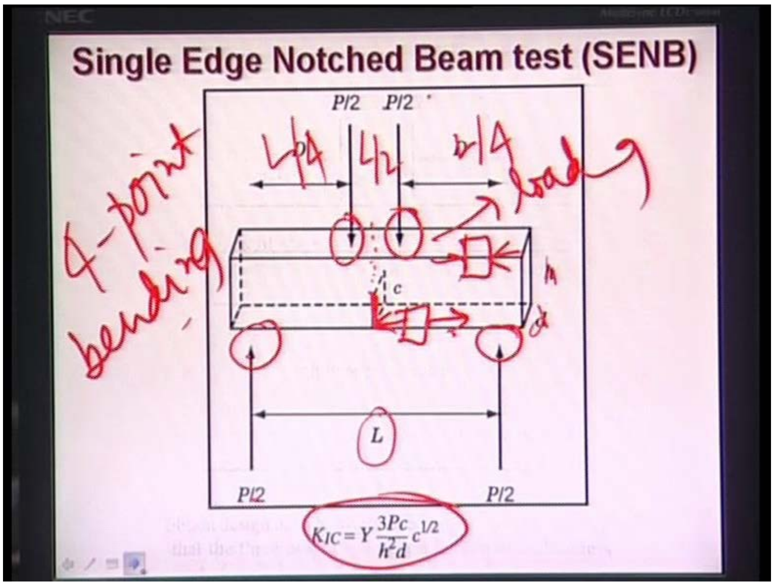

Now, this is that, so in each case, anyway you can keep this, you can see, that in at one edge, at one edge you have this notch and then from the notch tip there is some cracks and this, if crack length, entire crack length is seen here, then what you can do? You can put it under the two support roles here in the 4-point loading configuration. From the two top role you are actually pushing them by P by 2, P by 2 and therefore, this support role will, must exert a load, which is again P by 2, P by 2. So, this is like a, from the equilibrium coming back to the discussion on this long crack fracture toughness.

So, essentially, a single edge notched beam shaped specimen contains a notched, as well as, associated with that of length c and these cracks are faced. Remember, that when you put this in the 4-point loading, 4-point bending configuration and 4-point bending configuration, the loading side will be always under compression. So, any volume element you take here it will be under compression; the tension surface, it will be always under tension. So, this is the opposite to the loading surface is always under tension, the loading surface is always under compression and your, you know, the tensile stress actually influences or tensile stress actually enhances, that crack propagation or cancels themselves, triggers the crack propagation in the material.

So, therefore, if a crack is placed on the tensile surface, then these cracks can lead to the fracture of the material very fast. So, that is the reason in the single edge v-notched beam technique your crack needs to be placed on the tensile surface. And therefore, the crack surface needs to be placed opposite to the loading phase. This is your loading phase, so here you are actually loading it and this is your compression phase and then, sorry, this is your tension phase and being the tension phase you have to put the crack.

Now, depending on the geometry of the specimen, like what is the height, what is this one width and what is this value of? This is the half of the span length in both the sides. So, actually if your span length is L here, so this d is actually L by 4, this d is actually L by 4 and this will be L by 2. So, L by 4 plus L by 4 plus L by 2 would be equal to L and therefore, and then you can calculate the K1c value from this particular expression.

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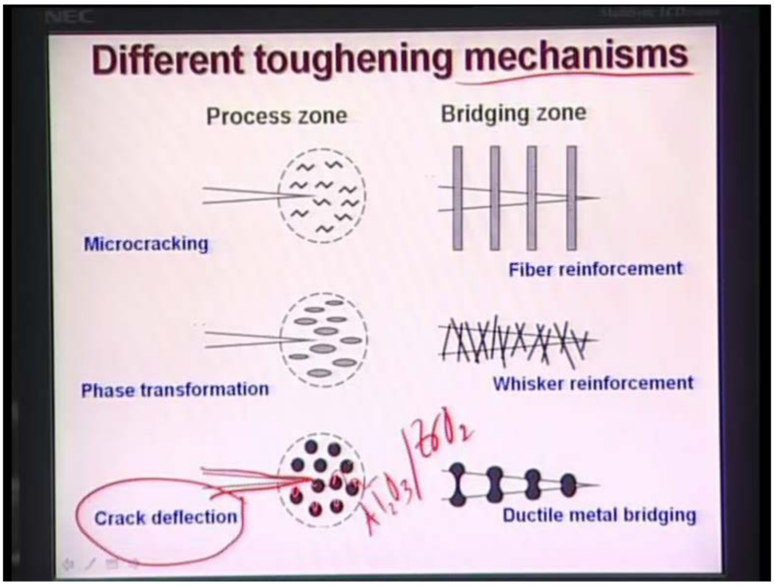

Now, toughening mechanisms, toughening means the ceramic, as I mentioned a number of times, the ceramic suggestion briefly, they lack fracture toughness. So, toughening mechanisms, essentially, indicate the mechanisms by which you can potentially increase the fracture toughness of the material and these mechanisms are only applicable in the ceramic based materials.

And now, let us go one by one, what is, what is the different toughening mechanisms that they are, that they can possibly work in this ceramic based materials? Number one is the crack deflection. Now, in the particular reinforced ceramics for example, this is your one particle, this is your a capital N number of particles, let us say, example is that alumina, zirconia particulate reinforce ceramics composing.

So, here zirconia for example, say second phase and you have a crack here. Now, this crack will tend to propagate, but then, since there are numbers of particles are on its path now, how this crack will propagate? Cracks will go, they will be deflected around the particles and they will go like that. So, these deflection of the cracks, what it will have effect? That will increase the tortuosity.

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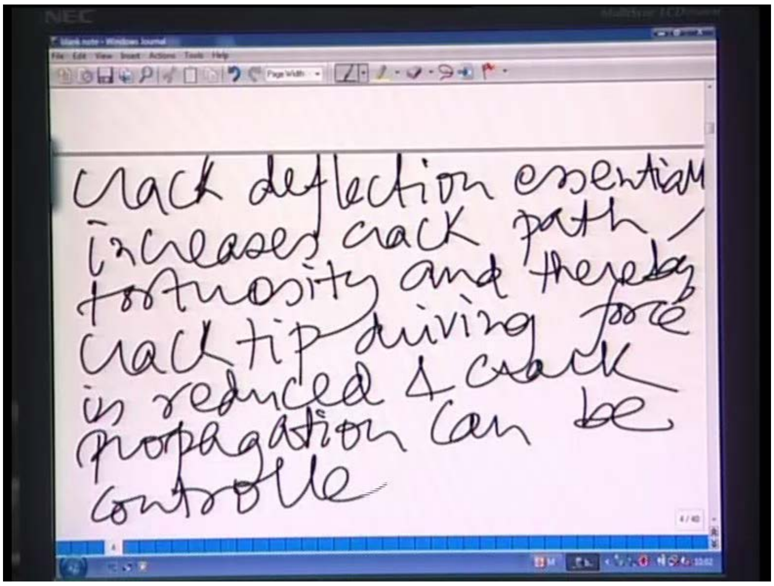

So, if, so crack deflection, essentially, increases crack path tortuosity and thereby, crack tip driving force is reduced and crack propagation can be controlled.

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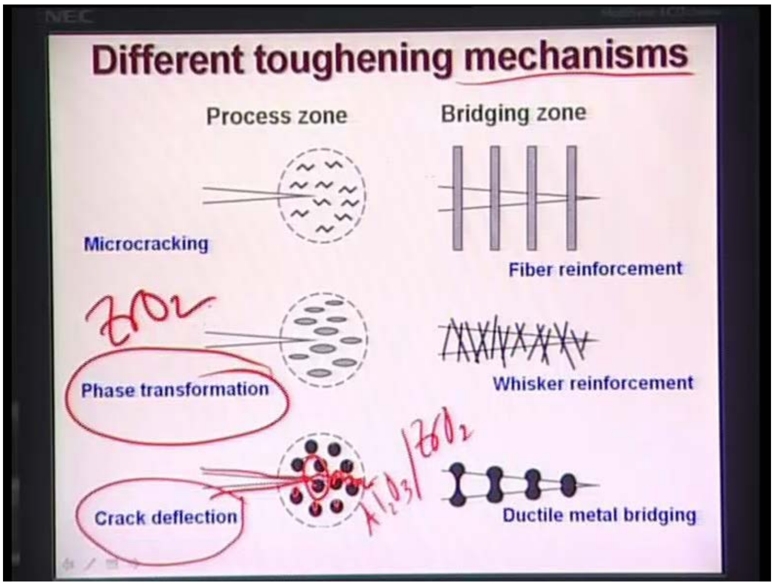

So, if you go back to the slide now here, then you will understand that when there is a particulate reinforce composite, now this crack will always. So, crack tip is always associated with some stress intensity because as you know, that this at the crack tip the total stress that will be experienced is much larger than the externally applied stress. Now, therefore, the cracks will find its easy way if they propagate along this direction.

However, since there is number of particles, which are present on this, now on its crack path, this crack path will tie, will tend to be deflected by the number of particle boundaries and if a crack path will go through this number of particle boundaries, then crack path tortuosity. Tortuosity means, it is the deviation from the straight line propagation. Tortuous, highly tortuous crack path means it will go through like, you know sinusoidal type of things or it will go through like this. So, if the crack per tortuosity increases, then what will happen? The total driving force, that is available for the crack propagation, that is reduced and if that is reduced, then the fracture toughness will increase.

Then, second thing is that phase transformation. Now, this is a unique property of the phase transformation. Now, how this phase transformation can be improved, like you know, in case of the zirconia case?

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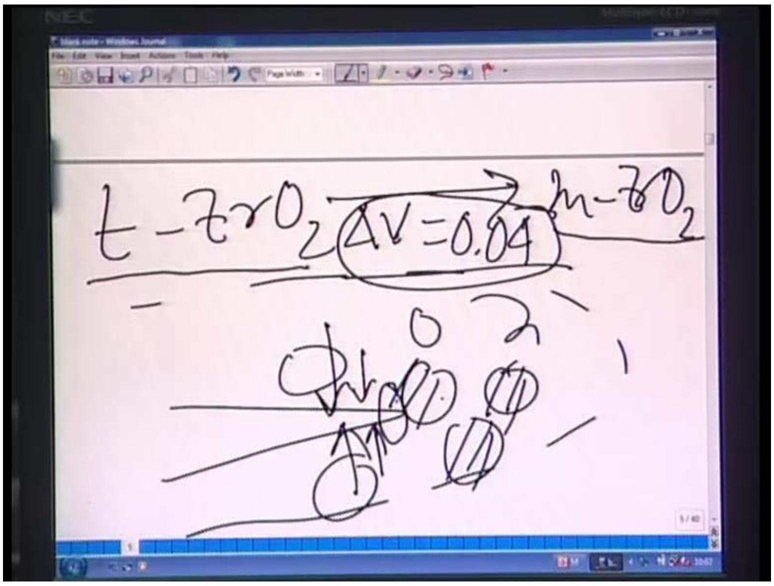

Now, in case of zirconia there are, there is a transformation, which is known as tetravalent zirconia to monoclinic zirconia transformation. Now, if there is a crack tip here, now if there is tetragonal zirconia, which is present in this crack tip and then what will happen? This tetragonal zirconia will be transformed in this crack tip, stress will come tetragonal to monoclinic zirconia and this kind of phase transformation is associated with the volume change of 4 percent.

Now, if there is a volume expansion, then what will happen? This at the crack tip, this hash, hash particles of the monoclinic zirconia. Now, if monoclinic zirconia, because of this phase transformation some volume will expand, but this monoclinic zirconia is also enclosed by its number of tetragonal zirconia. So, the neighboring particles will not like, that monoclinic zirconia will itself try to increase in size. So, there will be some constraint effect and because of this constraint effect there will be some compressive stress, which will be acting on the crack tip.

I will explain it, what I mean by that. This, in the case of zirconia, this tetragonal zirconia can be transformed to monoclinic zirconia in the crack tip stress field. So, this is your crack tip and there is an extensive stress or intense stress, which is surrounded by the crack tip. Now, in this crack tip stress field tetragonal zirconia will be transformed to monoclinic zirconia and which is shown here in the case of, with the case of this hatch circles. Now, once this transformation is completed, now there is a 4 percent volume expansion. So, now you think it physically like this hatch circles are surrounded by all tetragonal zirconia and hatch circles have a larger volume. So, therefore, hatch circles will try to expand because it is the larger volume and if it tries to expand the neighboring particles will not like that hatch circles will try to expand. So, neighboring particles will try to squeeze them and that squeezing action leads to the compressive stress on the crack tip and this compressive stress, if it is acting on the crack tip, then that leads to the closure of the crack tip.

So, if there is any, any crack like this and there is a compressive stress is acting on both the side, then what will happen? This crack tip will be closed. So, this crack tip cannot go further and therefore, fracture toughness is improved. So, fracture toughness means, it is a measure of the crack propagation ability in the material.

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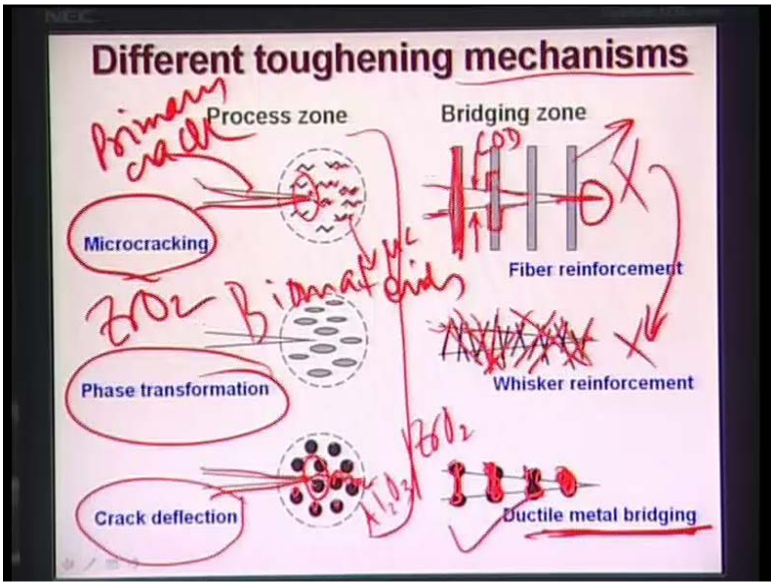

If the crack propagation ability is reduced, then your fracture toughness is increased coming to the third zone, third mechanism, which is known as the microcracking; so, which is known as the microcracking. Now, how this microcracking, they can improve the fracture toughness of this material?

Now, if you come to this place, this is a crack here this is a primary crack or what would we call as a, what we call as a major crack and this is your microcrack, I am writing mu c; mu c stands for microcracks here. Now, what it tells you, that depending on your processing conditions, depending on your machining, that you are taking the material prior to the fracture. Now, as you have seen, that for the strength measurement you need to take a bar specimen and that bar specimen has to be caught from a larger specimen. So, then you are cutting by diamond shaw. So, depending on the severity of your machining processes, all your materials are bound to have some smaller or final size cracks in the material.

Now, this is your primary crack and your primary crack has a much larger length compared to microcrack that you realize first. So, as far as the length scale is concerned, your primary crack has a much larger length compared to your microcrack. Now, you know that your sigma t, that is, the stress that is concentrated at the crack tip, that sigma t is directly proportional to the square root of the crack size. So, therefore at the primary crack your stress concentration will be much more and then, when this primary crack will try to propagate, then your microcrack, what it will do? The stress will be transferred to the microcrack and in this stress field region or in this crack tip stress field, microcracks will also try to propagate. And if microcracks will try to propagate, then what will happen? Lot of energy will be consumed from the crack tip stress field in the propagation of the microcracks and if the microcracks will propagate, then the primary crack growth also will be reduced because there is not much energy that will be available for the propagation of the primary crack tip, I repeat, this microcracking mechanisms.

So, essentially, microcracking mechanisms, based on the hypothesis, that you already have preexisting microcracks in the sample, preexisting microcracks means, as I said, microcracks from the basic nomenclature you can immediately find, you can immediately realize, that microcracks means, it has a length scale of micron size, let us say 2 microns, 3 microns, 5 microns like that length here, whereas primary cracks may have be, may have size of several microns like 40, 50 or 100 micron crack length.

Now, if, if this cracks, primary crack tip stress field, the microcracks are present, then what will happen? Primary crack tip stress field has much larger stress intensity because it has a much larger crack length and if it is a much larger crack length, then this stress field, in this stress field whatever microcracks are present, this microcracks will try to propagate faster because they will consume the energy from this primary crack tips stress field and as a result, if the microcracks will now grow in length.

So, the 2 micron lengths becomes 10 micron, then the total amount of stress field or total amount of energy, that will remain at the primary crack tip stress field will be reduced because some amount of energy is spent in making the microcracks grow in length and as a result what will happen? The total amount of energy will be reduced as the primary crack tip stress field and if the total amount of energy is reduced, then primary cracks cannot propagate the way primary crack should otherwise propagate in the absence of microcracks. So, therefore, microcrack toughening means, that propagation of the microcracks in the crack tip stress field of the primary cracks leads to major toughening, major toughening properties, major toughening of the material ceramics. Now, all this factors actually are much more relevant to your biomaterials also.

Now, coming to the other aspects, that is, the bridging zone, whisker reinforcement and ductile metal bridging. This is somewhat important for your biomaterials, but not this one and not this one, I will explain to you what it is and then subsequently, I will explain to you why it is not relevant for biomaterials. Now, whisker reinforcement, then next is the fiber reinforcement. Fiber means, it is long fibers, which is a larger aspect ratio. Aspect ratio means, here this crack length to diameter ratio is much higher particulate, means it is a smaller aspect ratio, which is smallest. Particulate means, mostly it is, you know, spherical size, means in all the dimensions it is r, r, r. So, particulate, they do not have any aspect ratio.

Now, fibers have a large aspect ratio. Now, if a crack will try to come and try to propagate through this fiber, now what will happen? This cracks cannot propagate to the other side of the fiber unless it breaks the fiber and go to the other side, you understand. So, there is a physical obstacle. Each fiber will provide physical obstacle to the propagating cracks. So, how it happens? So, crack comes, then it breaks, then this interface of the fiber and matrix, they are the cracks, will propagate. Now, suppose a crack is, they are at the fiber and according to this crack it is activated in the crack tip stress field and then cracks can go to the other side. Again, it will be coming naturally to its own way and it will try to propagate.

Then, what I am trying to mention here, each time a primary crack will interact with a fiber, then each time this crack opening displacement, that is called COD, this crack opening displacement is subsequently getting reduced and finally, after interacting with, let us say, small n number of fibers, then crack tip is completely closed. Closed means, it cannot propagate any further. So, that is the way this fibers will lead to the toughening mechanisms. I repeat, when a crack will, when a primary crack will come and interact with the fiber the primary crack will see the fiber as a kind of physical obstacle to its propagation, so the crack will not propagate to the other side of, the crack we cannot propagate through the fiber unless until crack will make the fracture of the fiber.

And how this fracture takes place? Now, at the crack tip fiber matrix interface, that your interfaces brittle and if there are some cracks on the fibers, then cracks will go to the other side of the fibers. And then, they will (( )) the fiber matrix interface and then they will propagate further. In each time crack interacts with the fiber crack opening, displacement significantly reduces and unless until it is completely closed, that means, cracks will not propagate any further and that is the point, that the major toughness, toughening is achieved.

Coming to the whisker reinforcement… Now, you know the fiber, fiber has a very long aspect ratio and this is the case, that we are talking about, unidirectional fibers. Unidirectional fibers means, the fibers is only oriented in one direction, not in multiple directions. Now, coming to the whiskers; whiskers means, when the aspect ratio of fiber is reduced. Now, you can consider whisker has chopped fibers, like you know, if you have fibers here and then you can chop it, that fibers, let us say 2 or 3 whiskers, then this whiskers have a much lower aspect ratio, so, that you can clearly see from the slide. And this whisker, if it is oriented this way, then others are oriented this way, others oriented this way. So, in all these directions of whiskers are oriented and these whisker orientation, like the fibers, that whiskers also, whiskers also lead to the crack bridging.

Bridging means, bridging means what, that two surfaces will try to come together and they will form a bridge. So, similarly, that crack bridging also will be activated in case of the whisker reinforcement. However, from these two process description you can immediately see, that in case of the fibers your toughening will be more compared to your whiskers because in the whiskers case your aspect ratio is reduced and therefore, the obstacles or the hindrance to the crack path propagation, that it provides, that is also much less.

Next one, now the question is that why this fibers and whiskers cannot be used in the biomedical applications? The answer is, now if there is a ceramic matrix and there are fibers or whiskers, then what will happen during in vivo applications? If the whiskers they are released in the, in the, in vivo application because of the wear or fracture or whatever, it is then what will happen, that whiskers, because of the small lengths scale they can be transported in the other part of the material and they can cause a potential, genotoxicity property, they can cause the potential inflammation in the materials and so on. So, whiskers and fibers, they are never used or they are never kind of, what I would say, approved or as such for the different federal agencies for the application in the biomedical application because of the potential risk, that is involved in releasing this whiskers or fibers under the in vivo condition.

The last point is the ductile metal bridging. Now, ductile metal bridging, essentially, tells you, that you have metallic particles. Now, you know, at the crack tip stress field this metallic particles, actually we undergo plastic deformation. Now, this plastic deformation means, they will essentially flow. Flow means, there is a plastic flow of the ductile metals and if there is a plastic flow in this ductile metal, then what will happen with this plastic flow? This crack tip will be subsequently reduced and accordingly, this ductile metal will act more like a bridging; ductile metal acts as more like bridging element. So, more the stress field, more the elongation, more the plastic flow and ultimately, this will be completely closed by a ductile metal.

Examples of this ductile metal is, let us say, hydroxypatite silver. Silver is a metal, hydroxypatite is a ceramic. So, addition of the silver, essentially, is stimulated by the fact, that in the crack tip, in the hydroxypatite silver, particles will undergo plastic deformation, they will flow and they will take part in the ductile metal bridging. Another example is that why hydroxypatite titanium material is developed, because titanium is a metal, hydroxypatite is ceramic. So, what was the postulate? Postulate is, that titanium will undergo deformation and that deformation will act more like a ductile metal bridging and that will decrease the crack tip displacement and as a result, your toughness will increase.

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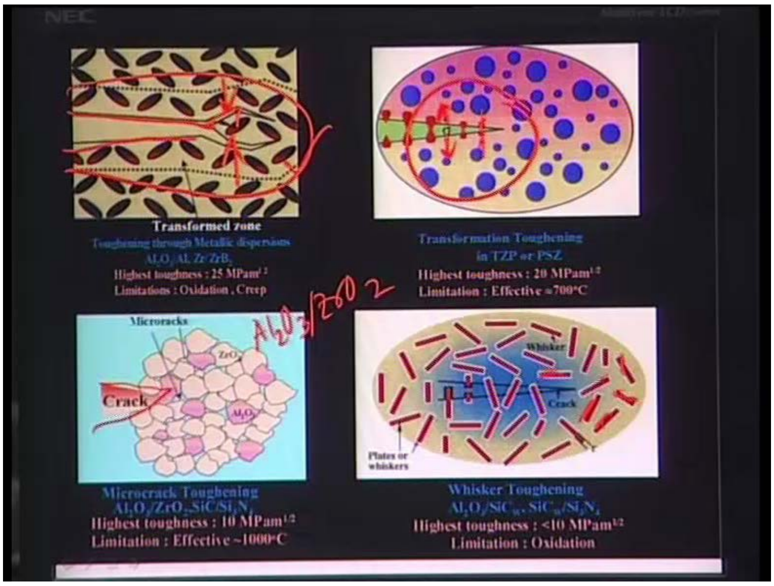

Now, this is like more examples, that you know, that more kind of schematic diagrams as how different mechanisms they operate. Let us start with the transformation zone here. Now, in case of this transformation zone what you see, that your zirconia case, that you are in the process zone here, in the dotted zone, your tetragonal zirconia transforms to monoclinic zirconia, that increases the volume expansion and that is indicated by these and then it experiences the compressive stress field, and that leads to the toughening improvement, toughness of this materials.

Microcrack, I have already told you the classical example is alumina zirconia particulate reinforce composite. You have this alumina matrix or alumina particles, as well as zirconia particles and these microcracks of the particle, particle grain boundary that causes the cracks to be start at certain point. Then, you have the ductile metal bridging, that you know, in the tensile force here this metals will flow. And however, once this metals to start flow, then they will kind of flows the crack tip.

Here, the whiskers, these are the whiskers you can see. Now, this small whisker, if they are released under in vivo conditions, they really have potential health rays. So, that is the reason whisker reinforce composites are not used.

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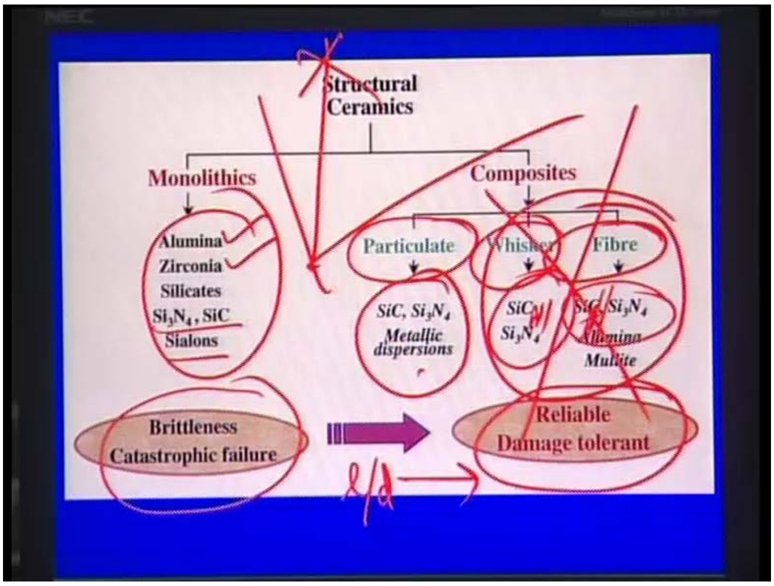

And typically, the ceramics, traditionally ceramics structures, ceramic are also classified as monolithic and composite materials. The monolith means, this is alumina, zirconia, silicates, silicon nitrite, silicon carbide and sialons. And composite means, this is a particulate reinforce composites, whisker reinforce composites and fiber reinforce composites.

Now, monolithic means, that it is simple monolithic ceramic without any second phase reinforcement and monolithic ceramics are essentially, extremely brittle. Catastrophic failure means that stressed in-curve, in-plot it goes and straight to failure, that is, no deformation here particulate.

Whisker fiber composites, the way it is quote, l by d ratio increases this way. Now, if you quote from whiskers to fibers, your aspect ratio increases and you have more and more toughness. And what you see here, that if you go more from the silicon carbide or metallic dispersions particulate reinforce, you can have silicon carbide fiber since silicon nitrate composite. And you can have silicon carbide fiber or silicon fiber whiskers in silicon nitrate composite silver fibers in silicon nitrite composite.

So, these are like examples of the particulate fibers or whiskers reinforce composite. The more you go to the right more toughness you can achieve in the fibers and whiskers, but however, for biomedical application, as I said, this fibers and whiskers are not generally, are to be avoided. Therefore, you are already left with the particulate reinforce composites, that is, that you can have metallic dispersions in a ceramic matrix.

And if your material is more tough or if your material is, has a much higher toughness compared to that of the monolithic ceramics, then what will happen? This material also will have better damage tolerance property or better damage resistance property. So, that is what has been made by brittleness to catastrophic or damage tolerance property.

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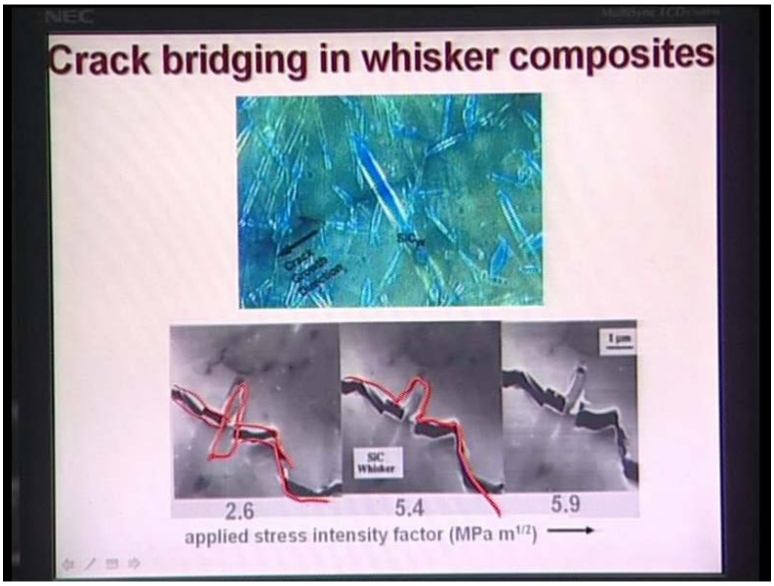

Now, this view graph tells you, that how these whiskers will lead to the crack bridging. Now, this is your whisker if you can see closely. Now, these whiskers, this is your crack, this is your primary crack tip and what you notice here, that in this primary crack tip this whiskers are going and this whiskers are getting pulled out. Pulling means, the whiskers are broken and whiskers are getting pulled in the ceramic matrix and that leads to the toughness of these materials.

So, I think I will stop here and in the next one we will start with the other important topics of biomaterials.