Friction and Wear of Materials: Principles and Case Studies
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Lecture – 17
Mechanical Properties of Ceramics

Hello welcome back. Today in this lecture we will learn about the mechanical properties of ceramics mainly the experimental methodology to determine the mechanical properties of ceramics. For the tribological applications mechanical properties such as hardness, elastic modulus, strength and fracture toughness are very important properties. So the influence of this properties will be reflected on the tribological performance of these materials.

So it is very much important to learn about the methodology to determine the properties of these ceramics. So mechanical properties of metals and polymers are measured in a different way than what we measure for the ceramic materials.

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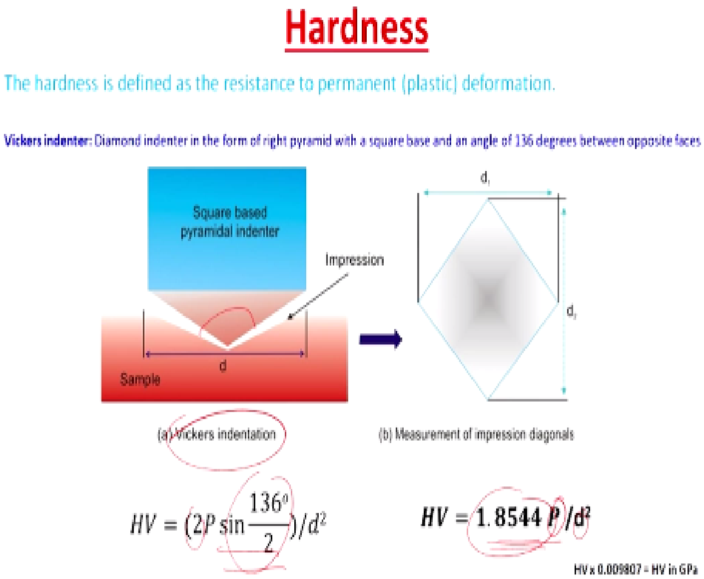

So first hardness, hardness as per the definition is the resistance against the permanent deformation. If one material is trying to deform the other material the other material is relatively softer than the material, then you have a response. Response is nothing but deformation. So if any harder material is trying to penetrate into the softer material then after this penetration there is response.

If the response if permanent deformation, then we say the material this material is less in the hardness right or the material is softer. So the resistance against the permanent deformation is hardness. So this hardness of ceramic materials are generally measured by Vickers indentation. In the Vickers indentation a indenter which is of diamond is used. This diamond indenter having a square based pyramidal indenter it is a diamond square based pyramidal indenter.

So the opposite faces of which has around 136 degrees angle. So such an indenter is pressed on the surface of your sample. So once you release the loading then you get an impression. The impression is a perfect square impression so that square impression is measured for its diagonals right. So the diagonals are measured average of the diagonals is measured then you will know the hardness of this material= 1.854* the load applied/ d square.

D is the average diagonal length of the square impression. So this number actually came from this sign of 136/2 *2 right. So this will give rise to this 1.8544 right. So hardness is expressed in pascal if the load applied is taken in Newton right so or you can say if load applied is in kilograms then you multiply the hardness number * 0.009807 then you get a hardness is gigapascal right.

So generally ceramic materials have higher hardness more than 10 gigapascal right. So certain ceramic materials like Boron carbide, Silicon carbide, Titanium Diboride these materials have extremely high hardness of around 25 to 30 gigapascal. So the Vickers indentation is to be done very carefully to obtain the hardness of the ceramic material.

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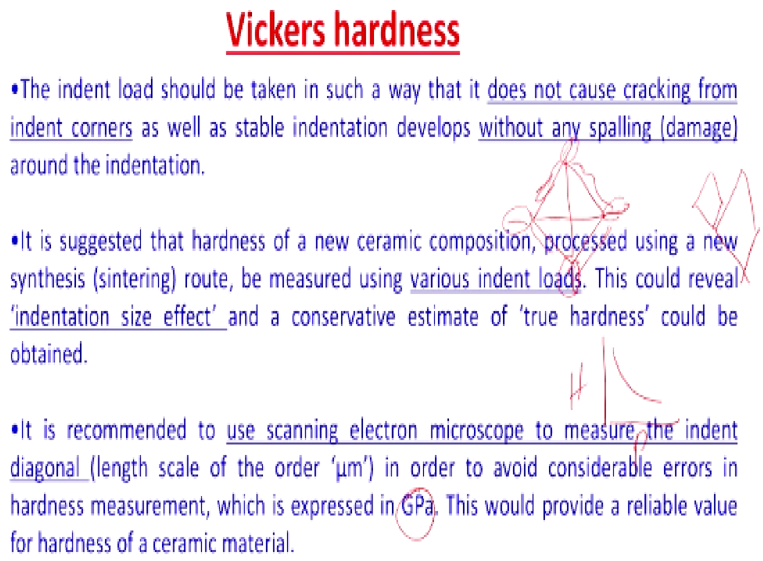

So the indent load should be taken in such a way that it does not crack from the indent corner. It does not give any cracking from the corners of this indent right. We will select a load where there are no cracks generated from the corners of this indent such a load is taken. In addition to that the indentation developed shall be without any spalling or damage around indentation. Generally, we will have some damage around the indentation.

So we will select the load such that the damage is not there around indentation right and it is also suggested that the hardness of a new ceramic composition processed using a new synthesis or the sintering route that we will see later. So such a hardness be measured using various indent loads right. So if you see here the hardness is proportional to the load here right and then inversely proportional to the square of the impression.

So if there is a load applied and then hardness is measured with respect to the load as the load is increased you will have bigger impression right smaller load a smaller impression a larger load a bigger impression. So you will have certain indentation effect that means hardness decreases with the load. So this could reveal the indentation size effect and the conservative estimate of the true hardness could be obtained.

So it is suggested that hardness of a new ceramic composition processed using a new synthesis route be measured using various indent load. It is also recommended to measure the indentation length right. The diagonals of this square impression using scanning electron microscope rather than using the optical microscope so that the length are measured very carefully. So generally the impression is in micron meter order.

So if there is a error in measuring this micron meter order length there will be a large difference in the hardness we are obtaining. So there will be error in hardness measurement which is generally expressed in gigapascal. So this would provide a reliable value for hardness of a ceramic material. So better we use more sophisticated techniques to precisely measure the diagonal lengths.

For example, the scanning electron microscope to be used to measure the indent diagonals precisely. So Vickers indentation shall be done at load where it does not cause cracking from the indent corners and it shall not have any result of the spalling around the indentation or you must take at various indent loads so that it could reveal the indentation size effect. It is better if you use the scanning electron microscope than the optical microscope to measure precisely the diagonal length which is generally in the order of micron meter right.

So the other method where the ceramics are measured for their hardness property is a Knoop indentation. So Knoop indentation is also similar to Vickers indentation.

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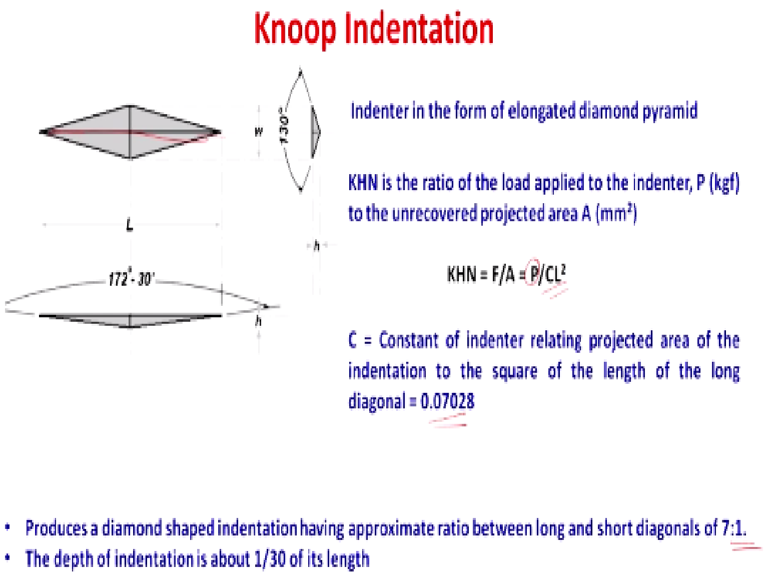

Only difference is the indenter in the form of elongated diagonal pyramid. So in the Vickers indentation is the squared based pyramidal indenter whereas here you have one along one line along one direction there is a longer diagonal than the other directions that means indenter in the form of elongated diamond pyramid. So the hardness is measured again load applied the area.

So you take the ratio of the load applied to the indenter to the uncovered projected area generally taken P/CL square A is the length of the longer diagonal of the impression and C is a constant that relates the projected area of the indentation to the square of the length of the long diagonal. So generally it comes about 0.07. So you get a hardness in gigapascal, but this Knoop indentation produces a diamond shaped indentation having an approximate ratio between the long and short diagonals as 7:1.

The depth of the indentation is about 1/30 of its length. Knoop indentation is also used in for determining the hardness of Ceramic material right.

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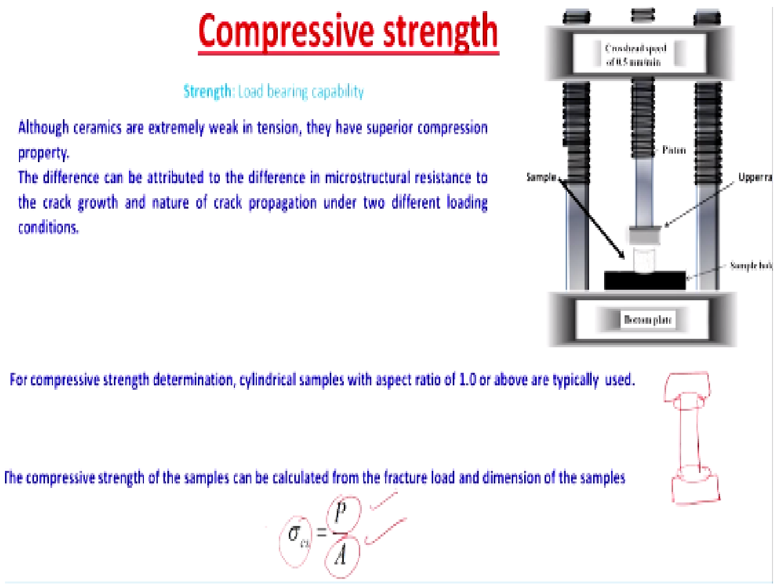

So let us go to the other mechanical property that is strength. Strength is nothing, but the load bearing capability of a material right. So but ceramic if you measure the strength in a tensile loading condition it is very difficult to have a reliable data right because first of all it is very difficult to have a dog bone shape specimen because the machining of a ceramic material is itself a difficult task right. The moment you start machining to that shape that will fail that will fracture.

If you have somehow some non conventional machining type of things are used to somehow make such dog bone structure for the tensile testing, but you have to grip it at the edges right. So while griping itself the material may crack, but even though if you could able to manage to measure the tensile strength. So the fracture will occur at a very less strains of 0.01%. So it is not reliable to have certain strength in a tensile loading condition.

The strength is always measured in a compressive loading condition for ceramic. So although ceramics are extremely weak in tension as I told very smaller strains at very less strains the failure will be occurring. So although ceramics are extremely weak in tension they have superior compression property. So the difference can be attributed to the difference in micro structural resistance to the growth of the crack.

A nature of crack propagation under two different loading condition of tensile and compression. So you get a difference in the response of this material so the load bearing capacity in compression loading condition is much more than the tensile loading condition for ceramic material right. So we better go determine the strength in a compressive loading condition.

So for the compressive strength determination generally a cylindrical sample with aspect ration or 1 or above or typically used. So the compressive strength can be calculated from the fracture load and the dimension of the sample using the simple formula that compression strength is= P/A where P is the load at which the fracture is occurring A is the area of the sample.

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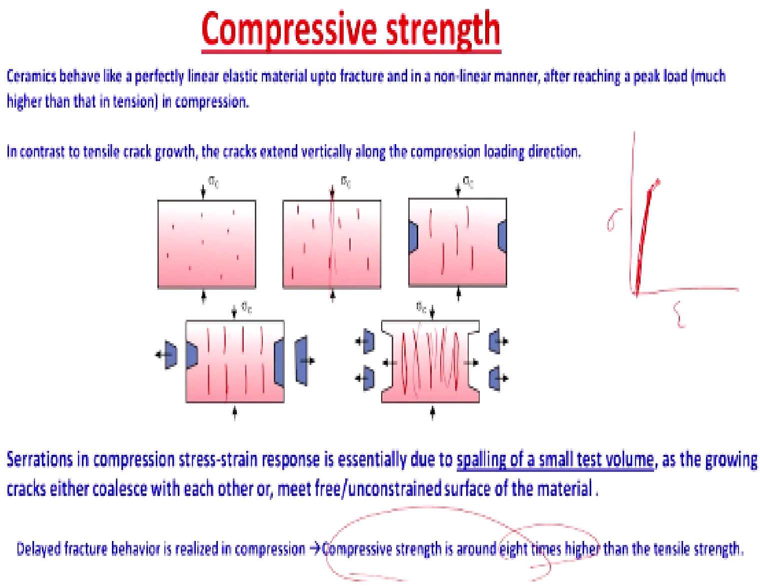

So ceramics behave like perfectly linear elastic material up to fracture right. If you see the stress and strain even in the compressive loading condition. So we have almost linear relation between stress and strain up to this elastic limit and after that the material yields and then immediately after yielding start there is a fracture. There is a very small amount of (()) (12:10) deformation before fracture.

So ceramics behave like a perfectly linear elastic material up to fracture and in a non-linear manner after reaching a load much higher than what was in the tension right. So in tensile in contrast to tensile crack growth the cracks generally extend vertically along this compression loading direction. So if you have a material and compression loading condition is applied all this cracks inside this material will be aligned themselves to along this direction of this compression.

So you see so they align and they coalesce each other and then from a bigger, bigger crack front that leads to the fracture. So because of this serrations are observed. So serrations are essentially due to spalling of the small test volume as the growing cracks either coalesce with each other or meet the unconstrained surface of the material. So you get generally the serrations.

So because of this delayed fracture the compression strength is much more than the tensile strength. It is generally found 8 to 10 times more strength in compressive loading conditions than in tensile loading condition for the ceramic material. So we will also see that in the other class that there are certain secondary cracks growing because of this reorientation with respect to the compressive loading conditions right.

So the secondary cracks will also consume certain amount of energy. So the major crack will not be propagated easily. So that means there is a difficult in the crack propagation that means the fracture is delayed. So the delayed fracture behavior is realized in compression so the resultant of which we see the compression strength is around 8 times higher than the tensile strength right.

I must tell you for ceramic materials for example aluminum oxide the compressive strength is around 1000 MPa is 800 to 1000 MPa. In tensile loading conditions the strength is around 300 MPa right whereas in steel materials plain carbon steel material either in compressive loading conditions or tensile loading condition the strength is around 250 MPa. So there is a large difference in strength in compressive loading conditions to tensile loading conditions for ceramic material.

So 300 to 350 MPa in a tensile loading condition that strength and 800 to 1000 MPa in compressive loading conditions are typically observed for aluminum oxide ceramic materials. So the other way to measure the strength is by bending right.

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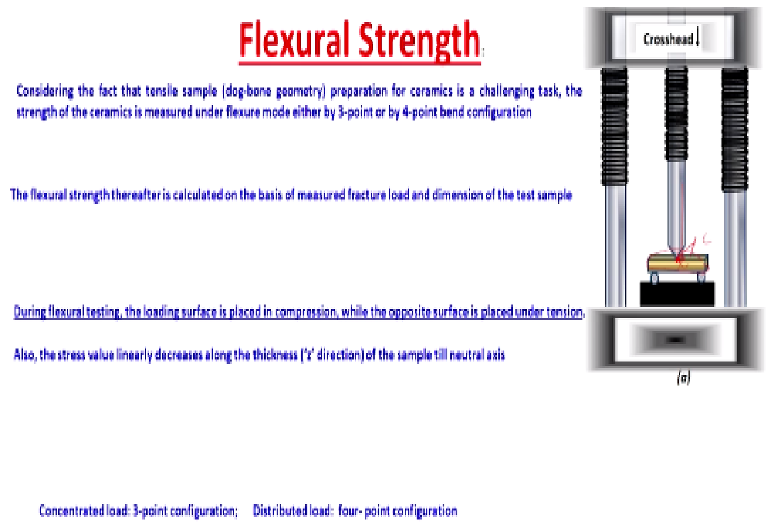

So again considering the fact that tensile sample preparation for ceramic such a challenging task, the strength of the ceramics is measured in a compressive loading condition or in other way by flexural mode right. What we do we take a specimen and try to bend it by application of a load. So we may have a 3 point bending or 4 point bending method for determining the flexural strength.

The flexural strength is calculated on the basis of the load at which the fracture occurs and the dimension of the test sample. So during this flexural testing the loading surface is in compression so this is in compression and the opposite surface is in under tension. So the stress value linearly decreases along the thickness direction of the sample till the neutral axis. So as I told it can be measured the flexural strength can be measured by 3 point bending or 4 point bending configuration.

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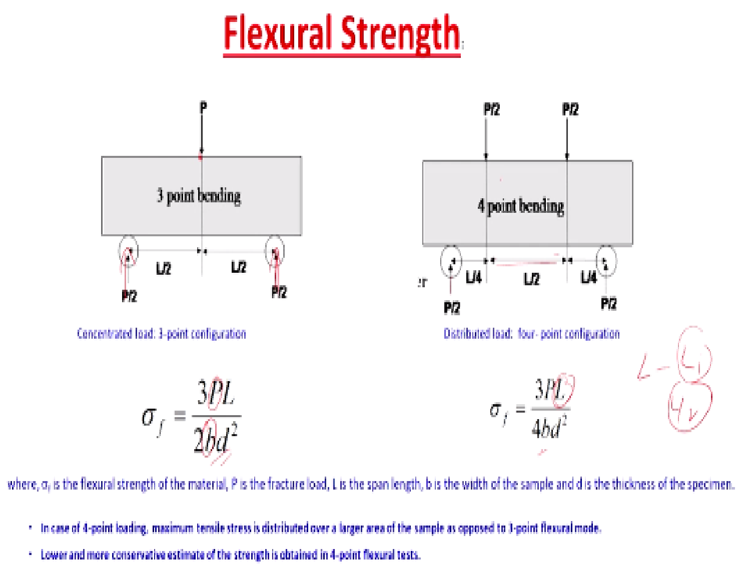

So what is 3 point bending the load is given at the one surface top surface of this material. For example, a rectangular block right having certain dimensions b and d. So this load which is applied under top surface is supported from 2 different locations from the bottom surface. So as I told the top surface is under compression right the loading surface is under the compression.

So you increase the load right at certain load the fracture will happen. So you note down the load at which the fracture happens that is the P and L is the span length and b is the width of this sample and d is the thickness of the sample right. So for a rectangular specimen the flexural strength in 3 point bending configuration becomes 3 PL/bd square right. In a 4 point bending configuration the load is more distributed the 3 point bending concentration the load is concentrated.

In a distributed loading conditions like a 4 point bending configuration the load is applied at 2 different locations on the top surface half of the load is applied at each location on the top surface and it is again supported from 2 location from the bottom surface. The flexural strength is= 3 PL/4 bd square actually this L=L-Li Li is the internal span length from here to here.

So generally it is L/2 so it becomes L/2 so L3 PL the L becomes L/2 so it becomes 3 PL 4 bd square right. So for a rectangular block specimen the 4 point bending strength=3 PL/4 bd square were P is the load at which the fracture happens that we called fracture load. So comparing these 2 in case of 4 point bending maximum tensile stress is distributed over a larger area right.

Larger area of the sample as opposite to the 3 point bending flexural mode. So we will get a lower and more conservative estimate of the strength in 4 point bending test right.

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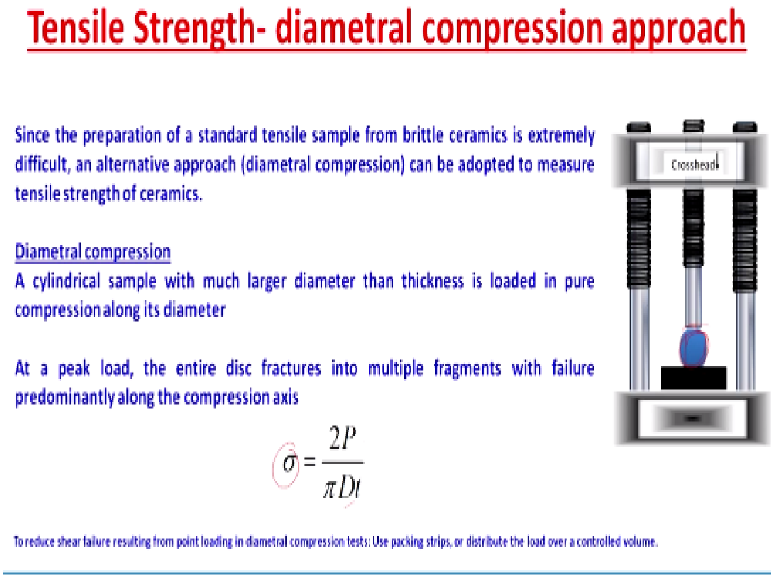

And the strength can be measured in a diametral compression approach as well. So actually in a diametral compression approach we can determine the tensile strength. Again since the preparation of a standard tensile sample from brittle ceramics is extremely difficult and alternative approach which is diametral compression can be adopted to measure the tensile strength of the ceramics.

You see we do diametral compression, but we get the result as a tensile strength. So a cylindrical sample is taken right a cylindrical is taken which has much larger diameter than the thickness. So such a cylindrical sample is loaded in pure compression loading conditions right. So you increase the load so at peak load the entire disc fracture into multiple fragments with failure predominantly along the compression axis.

The tensile strength measured in a diametrical approach sigma= 2 P/pi Dt right t is the thickness of the sample D is the diameter of the cylindrical sample. So generally while measuring such a tensile strength from the diametral compression approach to reduce the shear failure which can occur from point loading in diametral compression test generally we use certain cotton strips or we generally go for distributing the load over a controlled volume right.

So to reduce the shear failure resulting from point loading in diametral compression test we usually go using the packing strips generally copper or we usually go for distributing the load over a controlled volume. So strength can be measured in a diametral compression way also. This strength is a tensile strength actually right.

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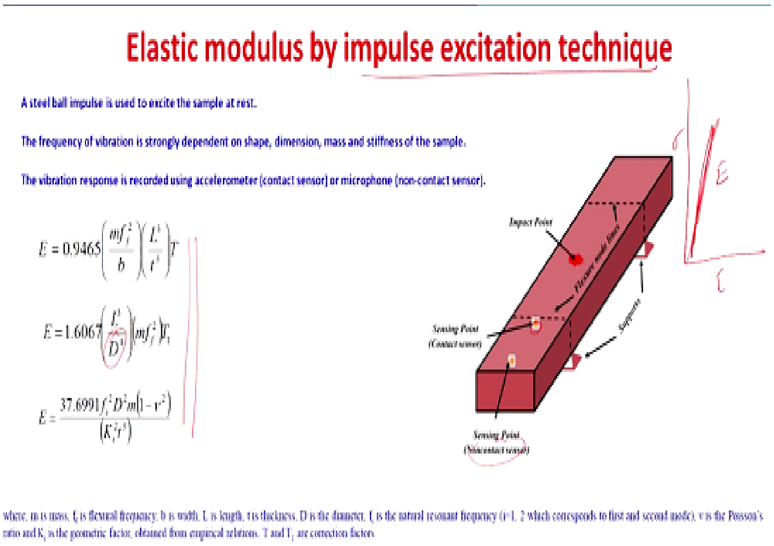

The other mechanical property is elastic modulus. Again elastic modulus can be measured if you have a tensile stress sample or in a compression loading condition or a tensile loading condition so you see the sigma versus the epsilon the stress versus strain response. So the slope in this linear region of this stress strain response for a material can be taken as a elastic modulus right. So the slope is nothing but elastic modulus.

But brittle material after this elastic deformation the fracture occurs. So but it is a destructive test right, but we can actually measure the elastic modulus by non destructive test as well. So generally this is done by impulse excitation technique. So you take the steel ball and you use this steel ball impulse to excite the sample right the response is the vibration. The frequency of vibration is strongly depended on the shape, dimension, mass and stiffness of the sample.

The vibration response is recorded using accelerometer or microphone. Accelerometer for the contact sensors or you can use the microphone that is a non-contract sensor. So the frequency of such vibration is strongly depended on shape of the sample, dimension or the mass of the sample and stiffness of the sample right. So you can see certain sensing point like a non-contact sensor whereas impact is done with a contact one contact sensor.

So there are certain formulae to determine the elastic modulus. So either of this formulae can be used to determine the elastic modulus. So where m is the mass and ff flexural frequency b is the width of the sample, L is the length of the sample, t is the thickness of the sample, D is the diameter if the sample is of cylindrical. So ff cylindrical right so fi is the natural frequency natural resonant frequency.

Generally, I want to corresponds to first and second mode etcetera. So nu is the Poisson's ratio K1 is the geometric factor and obtained from the empirical relations and T1 and T2 are correction factor again they are factors based on the dimension of this sample. So we do not need to go details about this formulae, but it is better to note down that there are certain non destructive test non destructive way to determine the elastic modulus of such material.

Particularly this is very much significant because ceramics are brittle to prepare a specimen for the tensile testing it is very difficult task. So this kind of techniques are generally used and impulse excitation technique is generally used for metals, glasses as well in addition to the ceramic materials.

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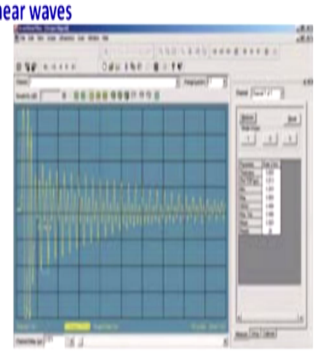
Elastic modulus by ultrasonic method

The thickness of the specimens and travel time of the waves across the thickness/height of specimens can be used to estimate the velocities of the longitudinal and shear waves

$$E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)}(\rho C_L^2)$$

$$\nu = \frac{1/2(C_L/C_S)^2 - 1}{(C_L/C_S)^2 - 1}$$



where, ρ is the density of specimen (g/cc), C_L is the velocity of longitudinal wave (m/s) and C_S is the velocity of shear (transverse) wave (m/s).

There is one more method where the elastic modulus is generally reported for ceramic materials is by ultrasonic method right. So what we do we take a specimen and then send a ultrasonic waves from one side of the specimen to the other side of the specimen. You know the specimen thickness right so thickness so you note down the time required for this wave to go and touch and other end of the specimen and come back.

So by using an oscilloscope you can determine what is the time. So you know the thickness and what is the thickness you know the time so you get the velocity right. So the distance upon the time velocity. So you measure certain velocity of this waves in a longitudinal or shear waves right. The thickness of the samples and the travel time of the waves across the thickness of the samples can be used to estimate velocity of the longitudinal or shear waves.

You get these longitudinal and shear waves and then you get a elastic modulus if you know the Poisson's ratio. So longitudinal velocity and shear velocity of this ultrasonic waves are estimated and these are used to determine the Poisson's ratio. This Poisson's ratio is used to determine the elastic modulus. So where rho is the density of the sample and CL is the velocity of the longitudinal wave.

And Cs is the velocity of the shear wave both are in meters per second. So but you must note down that the elastic modulus data obtained by ultrasonic method is not much reliable because the material is not perfect right. The material has lot of defects for example cracks or pores or any other defects right. So the ultrasonic waves may also come back after hitting these cracks right.

So if there is a crack in between so the ultrasonic waves my come back. So you get a error in the time estimate for the longitudinal or shear waves. So you get an error in the Poisson's ratio or elastic modulus data. It is not much reliable data.

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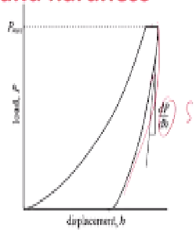
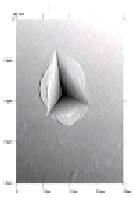
Instrumented indentation for elastic modulus and hardness

- Vickers or Berkovich (three-sided pyramid geometry) indenters
- Small loads and tip sizes
- Displacement and load are recorded simultaneously during load application or removal.

$$E = (1-\nu^2)\left[\frac{1}{E_r} - \frac{1-\nu_i^2}{E_i}\right]^{-1} \qquad E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}} \qquad A = 24.56h_c^2$$

$$H = \frac{P_{max}}{A}$$





While the initial slope of the unloading response (P-h plot) in case of instrumented hardness measurement provides an estimate of elastic modulus, the slope of the initial linear loading response under uniaxial compression/flexure/diametral compression can be used to determine the elastic modulus under respective loading condition.

So the other way to measure the elastic modulus is by instrumented indentation. So instrumented indentation is also used for hardness measurement. In this instrumented indentation for the elastic modulus and hardness generally done by Vickers indentation or Berkovich indentation. Vickers indentation we have seen that Vickers indentation is a diamond pyramid indenter is used which is a square based indenter square based pyramidal indenter.

Whereas Berkovich we have a 3 sided pyramidal geometry. So both are made by diamond right. So those small loads are applied on the tip sizes are also small. The displacement and load are recorded simultaneously during loading and then unloading. So you can see the loading it goes to the maximum and then comes back unloading.

So the elastic modulus can be determined by this recording of this load and the displacement right. The (()) (27:35) modulus can be determined by the reduced elastic modulus the (()) (27:32) modulus can be determined the E can be determined by this reduced modules Er and Ei is the modulus of the indenter. So we know it is a diamond so we know the so the nu is the Poisson's ratio of this material.

And nu I is a Poisson's ratio of the diamond indenter Berkovich indenter. So we know this Er Er is again calculated by S and A right. S is the stiffness parameter and stiffness is usually obtained while unloading the slope the slope while unloading. The slope of this load and displacement while unloading is taken as the S. So A is the area of the impression right. So the area can be determined as a function of this displacement.

So A is determined by certain functions for a perfect Berkovich indenter it is A=24.56*hc square hc is the displacement one and you know the maximum load applied/by this area you get hardness also. By instrumented indentation elastic modulus and hardness both can be measured, but we must note down while initial slope of the unloading response right in case of the instrumented hardness measurement provide an estimate of the elastic modulus.

The slope of initial linear loading response under uniaxial, compression, flexural or diametral compression can be used to determine the elastic modulus under respective loading conditions whereas the first one both are used for measuring the elastic modulus right. So after this elastic modulus let us go to the other property which fracture toughness.

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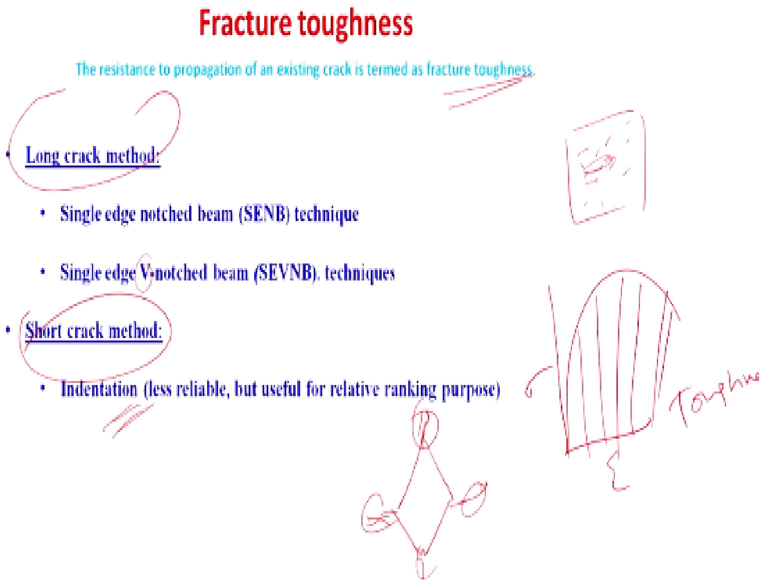

Fracture toughness by definition it is the resistance to propagation of an existing crack. So you have a ceramic material right. So there are certain cracks oriented in different directions and having different sizes right. So the resistance to propagation of this crack is nothing but the fracture toughness. So for metallic materials you have a toughness parameter which is more relevant right.

The toughness is nothing, but if you know the stress and strain the area under the curve is the toughness or you must say you can also say the energy required to break a unit volume of a material is toughness right, but in ceramic materials because of the sensitivity towards the cracks so because of the strong influence of the crack propagation in fracturing the material so the resistance against the propagation of existing crack is taken as a parameter to understand such toughness so it is named as fracture toughness.

The fracture toughness is the resistance to propagation of an existing crack. So existing crack means there is certain physical dimension of the crack. So the fracture toughness can be measured by different techniques. The fracture toughness if they are measured by different techniques generally we get a different value of fracture toughness. So there are 2 methods for measuring the fracture toughness of a brittle material.

A long crack method and a short crack method. In a long crack method generally single edge notched beam technique are a modified single notched beam technique called single edge V-notched beam technique are used whereas short crack method it is indentation Vickers indentation is used to generate cracks and then these short cracks right after this indentation the cracks generated at the corners of this Vickers indentation impression.

These cracks are measured and the crack length is taken for determining the fracture toughness by indentation method.

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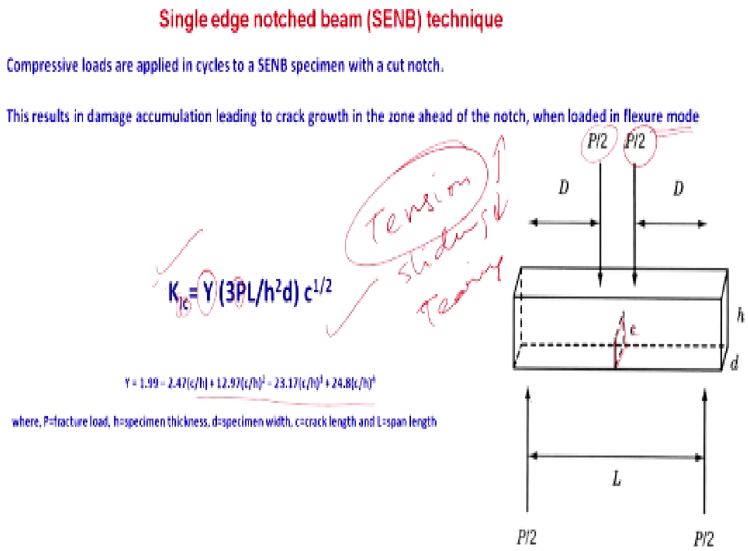

So let us see these the single edge notched beam technique. So compressive loads are applied in cycles to a specimen with a cut notch. So you take a specimen right. So there are certain (()) (32:09) stream standards for preparing this specimen for the single edge notch beam technique to determine the fracture toughness of a ceramic material. So what do you do you cut a notch right a notch having certain length certain dimension C.

So you know what is the initial dimension of this crack. So the compressive loads are applied in cycles to a specimen having such a notch of certain dimension. So this results in damage accumulation so that leads to crack growth in the zone ahead of the notch when loaded in this flexural mode. So as I told you the flexural mode can be 3 point bending configuration or the 4 point bending configuration.

So this illustration is given for the 4 point bending configuration. So either way you can apply this load and then see at what load the fracture happens right. This is the fracture load that means the load at which the fracture occurs L is the length of the span h and d are the dimensions of the specimen. C is the notch length and Y is the parameter again dependent on the length of the crack and the height of the specimen right.

So we can determine what is the K1C value. The KIc value is actually c indicates the critical K indicates the stress intensity factor. So 1 indicates the mode ones. There are actually 3 modes for crack opening. So mode 1 is the tension and mode 2 is sliding and mode 3 is tearing. So crack can be opened up in a tensile mode when it is opened up in a tensile mode easy to coalesce such a crack and then that leads to longer size of the crack.

So when the size reaches the critical value there is a spontaneous propagation of a crack and that will lead to fracture. So sliding mode is another mode of crack opening where the crack is generally opened in a sliding mode whereas the tearing mode is another mode of opening a crack out of these opening in a tensile mode is much dangerous. So much of the studies are done to determine the fracture toughness or this stress intensity factor of a brittle material in a mode one crack opening.

Though the stress intensity factor is a fracture toughness. So the fracture toughness parameter the stress intensity factor K. So K1c means critical stress intensity factor in mode one crack opening. So K1c= Y* 3 PL/ h square d* c power 1/2. So Y is again determined with the help of the specimen thickness and the crack length. So you can have the K1c value for a brittle material and this is the most precise measurement for the K1c that is fracture toughness measurement.

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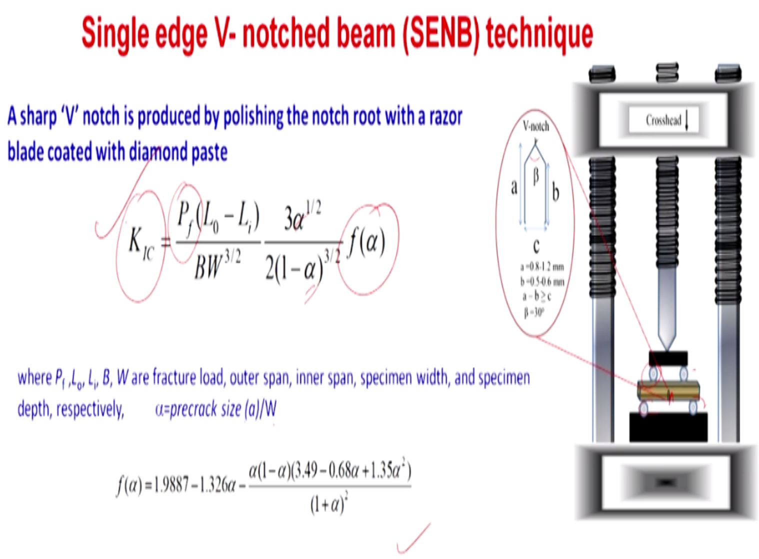

There is a slight modification for the SENB technique. So here the notch is given as a V shape right. So it is actually zoomed here you see there a V notch. So a sharp V notch is produced by polishing the notch root with a razor blade coated with diamond paste. It is actually a difficult task right. So again after this notch you apply the loading condition so that there is a flexural loading and then fracture occurs.

Again you determine the K1c so where P f is the load at which the fracture happens and L0 is the outer span and Li is the inner span in this 4 point bending mode right and B is the specimen width and W is a specimen depth. So alpha this is alpha is actually the precrack size/W right. So precrack size is actually taken as a. So again there is a function of this alpha which again can be determined with respect to the geometry of this testing condition.

So we do not need to go into details of this one, but we must note down there is one more method which can precisely give the fracture toughness value. This is single edge V notched beam technique which is slight modification with for the single edge notched beam technique.

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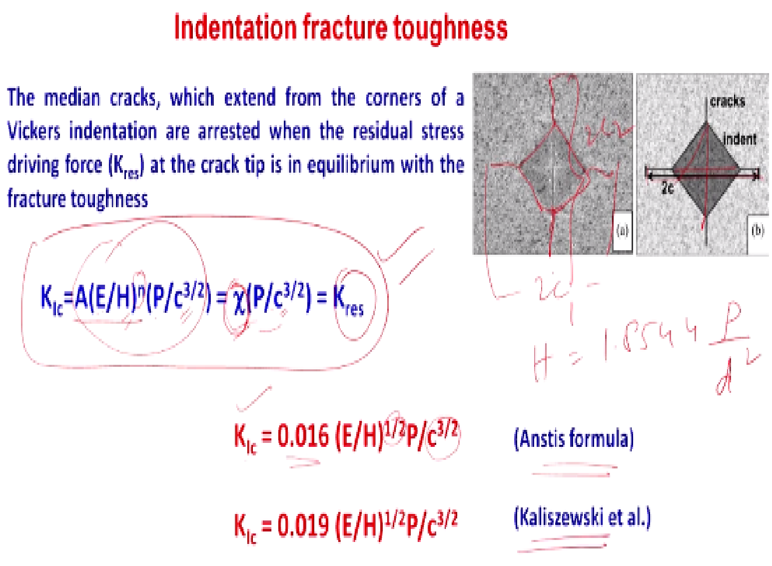

The last one is the indentation fracture toughness method. The toughness the fracture toughness measured by indentation method. So generally as we understand after this Vickers indentation there is a square impression and from the square impression there is certain crack right. So in 4 corners we have certain cracks developed. So these cracks are median cracks which extend from the corners of this Vickers indentation.

These median cracks which extent from the corners of a Vickers indentation are arrested when the residual stress driving force that we call K residual at the crack tip is in equilibrium with the fracture toughness. So if you can say the residual stress factor here and then P is the load at which the indentation is done. C is the crack length so from here to here this is the 2c right. This is 2c this is also 2c right.

So 2c1 2c2 so you get a average of 2c. So from here you get a c value. The P is the load at which the indentation is done H is the hardness from the Vickers indentation again we know H-1.8544* load applied/square of the average diagonal length right this average diagonal length. So you get the H value E is elastic modulus of the specimen so elastic modulus hardness the load applied for the Vickers indentation and the crack length.

So these is the fracture toughness value. It is in equilibrium with the residual driving force at the crack tip. So you know the residual stress factor and then again. So this is a fundamental relation for the fracture toughness in equilibrium with the residual stress driving at the crack tip. Based on this concept there are several formulae developed for the several ceramic material.

Based on this formula based on this concept there are several formulae developed for different ceramic material. The very important of which is Anstis one. Anstis formula says that the a here you can see the A is 0.016 and N here is 1/2 and here c. So the K1c=0.016* under root of E/H* P/ c power 1.5. So that means for smaller crack length K will be higher right.

So recently the other group of researchers provided a modification for this Anstis formula just a change in the constant 0.019 instead of 0.16. These are semi empirical formulae developed based on the data obtained for ceramic materials.

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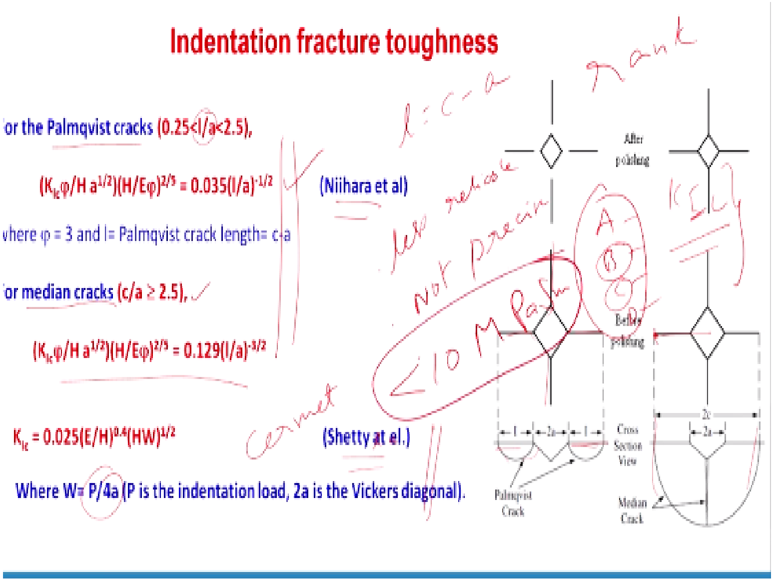

So now we know the indentation gives the cracks at the corner of this Vickers impression right, but these cracks can be mainly of 2 types a Palmqvist cracks or a median crack. Generally, these are the median cracks right. So if you see before polishing that means after indentation is done without doing polishing you can see the impression and then the cracks generated at the diagonals in both cases it is same.

But if you polish it and remove all the strains there and then after polishing you see a different characteristics and this is Palmqvist crack right this is a median crack radial median crack and radial median crack and the Palmqvist cracks are related with l=c-a right l is the Palmqvist crack length c is the half of the total crack generated from one side to another side or c is the length of the crack measured from center of the impression to at the edge of the crack right.

So l and c are related that l I is the Palmqvist crack and c is the median crack and both are related with relation l=c-a right. So Palmqvist cracks are generally generated in a low load conditions right and when the l/a this one the l/a 0.25 is< l/a< 2.5 then Niihara proposed a formula right whereas the c/a if it is more than 2.5 the formula is different. As I told these are based mainly on the experimental data obtained from the different ceramic classes.

So recently the Shetty at el also modified the Niihara formula where K1c=0.025 E/H whole power 0.4* HW whole power 0.5 where W=P/4a where P is indentation load 2a is the Vickers diagonal average of the Vickers diagonal. So we will see several case studies these formulae are used to determine the fracture toughness easily by this indentation method right. So this

Shetty formula is generally applied for the ceramics materials right where these are generally used for different ceramic and ceramic composite materials.

So we must note down this indentation fracture toughness are the fracture toughness measured by the indentation method are less reliable right they are less reliable first of all they are less reliable. The fracture toughness data is less reliable, but it is generally used frequently the fracture toughness is determined generally by the indentation method because there is hardly any preparation required for the testing right.

So whereas in other methods you have to prepare a sample of this geometry right. So preparing such a sample of this geometry is itself difficult task for a brittle material right and in addition to that you have to give a notch of a particular dimension. So giving this notch is itself a difficult right. So it is very difficult task, but once you get this the data obtained by these technique is much reliable.

That means the fracture toughness obtained by this long crack method is much reliable and precise right. It can be reproducible as well whereas the fracture determined by indentation method is less reliable and it is not precise and reproducibility is also very less, but it is still used as I told because of the simplicity of the procedure. There is no preparation of the material only the surface has to be flat and (()) (44:33) right.

And then the indentation is done after the indentation impression is measured for its diagonal and the crack length the length of the cracks from the corners of this indentation impression are measured to determine the fracture toughness. So this type of indentation fracture toughness is generally used when you want to rank a material right. So you have several ceramic composites.

So generally for the study purpose we take a material A, material B, material C, material D and these are differing only in the composition right or certain material parameter is only differing. So we know only difference is because of certain material parameter. So the response is the result we get in the difference in the K1c value. So K1c value of A, K1c value of B, K1c value of C, D.

So we do not say this K1c value of this certain class of material is exactly the what you are getting, but we can actually rank them. So that means the fracture toughness value of B is higher than the fracture toughness of C or lesser than the fracture toughness of D. This kind of analysis or this kind of understanding is obtained by this fracture toughness by indentation method.

We do not use the data obtained by indentation method for precisely mentioning the fracture toughness of that material, but we use this data to relatively rank the material. So only for that purpose this indentation fracture toughness is still valid so people are still doing. Otherwise for the precision point of view the other method which is a long crack method is much more reliable right.

So the fracture toughness values for the ceramic materials are generally < 10 MPa root meter. So if you see this units it comes as MPa root meter right. Just for comparison other materials like metals right. They have very higher fracture toughness. For example, plain carbon steel have a fracture toughness of around 80 to 100 MPa root meter that means the metals have higher fracture toughness at least one order of magnitude higher fracture toughness.

Ceramics are inferior with the fracture toughness point of view that means they are inherently brittle; the propagation is much spontaneous. So that means the resistance to such propagation of a crack is very less for the ceramic material that means the fracture toughness value K1c is very, very less compared to the metallic material of fracture toughness right or the polymeric material fracture toughness.

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So summarizing today's class experimental methodology to conduct mechanical property evaluation of ceramics is mainly discussed in this lecture and mainly we focused on very important properties, mechanical properties hardness strength, elastic modulus and fracture toughness. The influence of which will be observed in different case studies done for different material of ceramics or ceramics composite materials.

The hardness by definition is the resistance against permanent deformation, strength is the load bearing capability, elastic modulus is the ratio of stress to strain in the elastic regime of stress strain curve whereas fracture toughness is resistant against crack growth right. So thank you.