Non - Metallic Materials
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Module - 10
Measurement of the mechanical electrical, thermal, magnetic and optical properties of non - metallic materials
Lecture - 50
Measurement of mechanical properties, fracture toughness, MOR, hardness

Welcome to my course Non-Metallic Materials. And this is module number 10 – Measurement of the mechanical, electrical, thermal, magnetic and optical properties of non-metallic materials. And this is lecture number-50 where I will be describing Measurement of mechanical properties, fracture toughness, MOR, and hardness.

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Already this mechanical property I have described as a part of my earlier lectures. So, this lecture is devoted to look at the measurement of the elastic behavior, particularly elastic modulus measurement of elasticity. Then strength of the brittle materials will be discussing about, then measurement of strength how to do that for the brittle materials. And finally, we will relook once again the measurement of fracture toughness.

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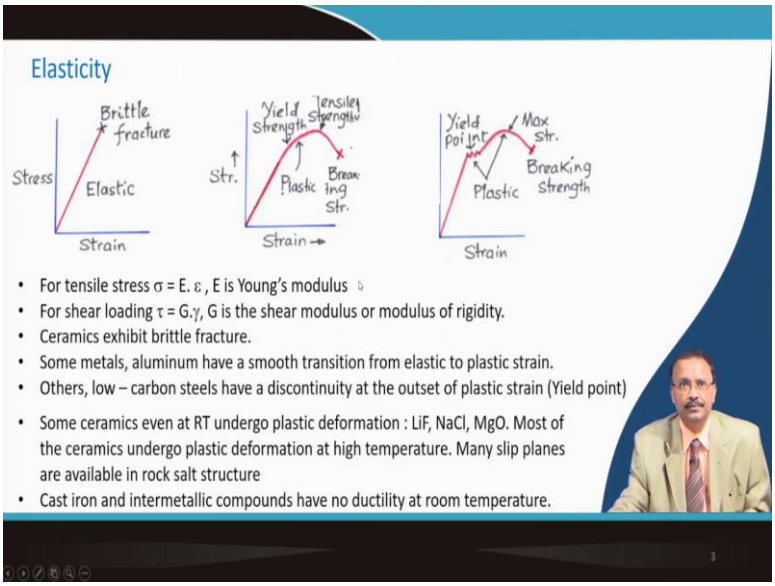

So, this is the curve which I described earlier, this is for the brittle material. And the stress and strain, this curve is linear in nature. So, stress is proportional to strain. And the proportionality constant is the elastic modulus. So, E is defined as the elastic modulus; it is termed as Young's modulus. For shear loading, shear stress is proportional to shear strain.

And in this case this G is the shear modulus, and sometimes it is called modulus of rigidity. So, usually ceramics exhibit this brittle kind of fracture. So, some metals – particularly aluminum, it has a very smooth transition from elastic to plastic region, so that you can see that initially it is elastic. And there is a very smooth transition to the plastic domain plastic region. In case of low carbon steel, they have a discontinuity at the outset of the plastic strain.

There is some kind of ups and downs. And we call this is yield point. It is specific to low carbon steels. And some ceramic even at room temperature, they undergo plastic deformation. The example is ceramics with rock salt type of structure lithium fluoride, sodium chloride, magnesium oxide. So, other than that most of the ceramics at high temperature they undergo plastic deformation.

So, in rock salts type of structure, we have many slip planes, concentration of slip planes are more. So, the dislocation can move along the slip plane, and that exhibits this kind of plastic behavior. On the other hand cast irons and other inter metallic compounds they do

not exhibit any ductility at room temperature. So, depending on the types of the material the characteristics are different.

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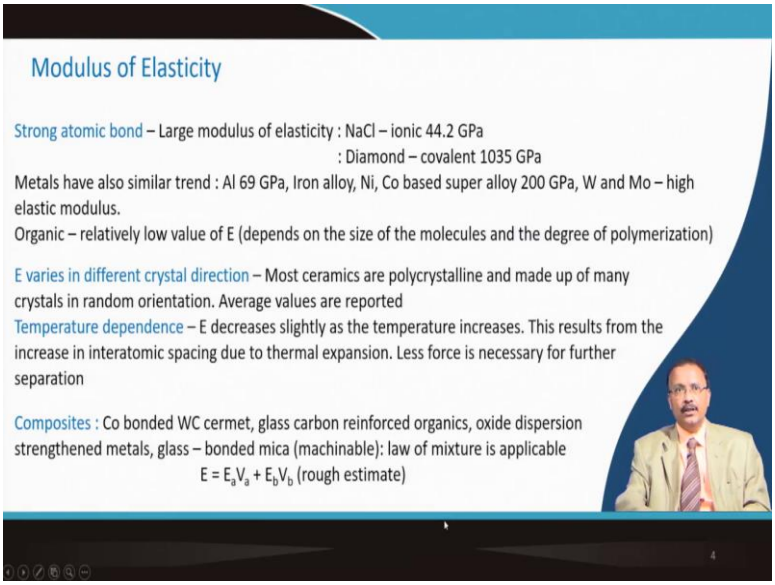

So, if you consider this modulus of elasticity, usually if it is having a strong atomic bond, then usually the modulus of elasticity is large. Sodium chloride, it is having ionic bond. So, it has elastic modulus about 44.2 Giga Pascal. Diamond is a covalent which has exorbitant elastic modulus about 1035 GPa.

So, metal they also having similar trend aluminum, iron alloy, cobalt nickel, cobalt based super alloy, for example, they give elastic modulus about 200 GPa. Tungsten and molybdenum, they have high elastic modulus.

As compared to that organic material, for example, polymers they have relatively low value of elastic modulus. And that basically depends on the size of the molecule as well as degree of polymerization. Now, this elastic modulus it varies with different crystal direction. So, most of the ceramic, they are polycrystalline in nature.

So, they are made of different types of grains of different orientation. So, each orientation E will vary, and ultimately it will average out. So, it depends on temperature. Generally, elastic modulus decreases slightly with temperature. And this is the result of the increase of the inter atomic spacing mostly due to thermal expansion. So, eventually less force is necessary for further separation.

If you consider composites, for example, cobalt bonded tungsten carbide, this is one kind of cermet or if you considered that last carbon reinforced organics or oxide dispersion to strengthen the metals even or glass bonded mica which I talked about it is machinable ceramics, then the law of mixture is applicable.

So, individual component elastic modulus and respective volume fraction if you know, then it is a rough estimate for you to estimate the elastic modulus of the composite using this rule of mixture.

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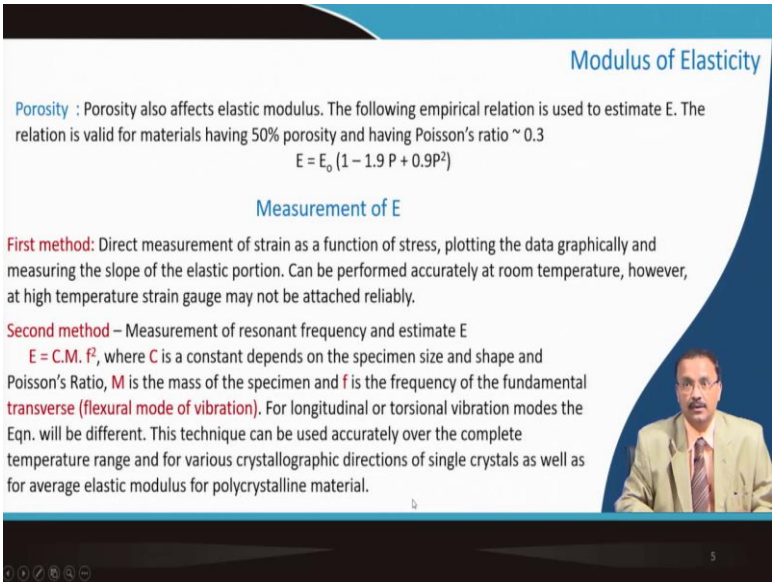

Porosity, it affects elastic modulus. So, there are empirical relation that relates porosity of the elastic modulus. And this kind of relation that is valid up to 50 percent of the porosity. And usually when the Poisson ratio is about 0.3, then this empirical relation is valid, so that you can estimate with porosity what will be the elastic modulus of not so well sintered ceramic material.

So, the elastic modulus can be measured directly as a strain as a function of stress, and then plot the data graphically and measuring the slope of the elastic portion the straight line portion. And this can be performed at room temperature. At high temperature, it is difficult to put the strain gauge reliably. So, at high temperature, this is a bit difficult to measure the elastic modulus.

But there is another method by measuring the resonant frequency and estimate the elastic modulus. And the relation is E is equal to C into mass of the specimen; and f is the fundamental frequency, usually, it is in the transverse mode in flexural mode what is the fundamental frequencies, so square of that. And C is a constant which depends mainly on the specimen size and shape.

If you consider the longitudinal or torsional kind of vibration modes, then this kind of equation will change. But this is a good way to measure accurately the elastic modulus at various temperature ranges and for various crystallographic directions of single crystal, as well as average elastic modulus for polycrystalline material. So, this second method is good for accurate determination of elastic modulus.

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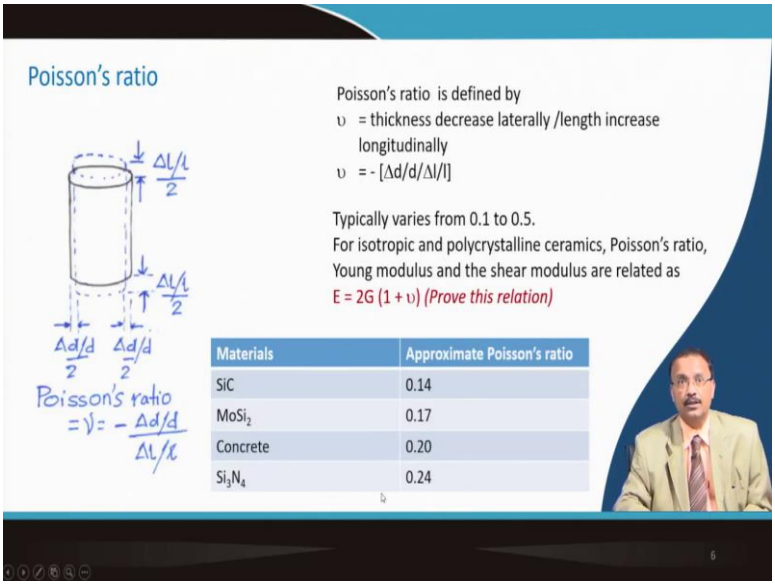

We can define Poisson ratio is basically when the sample is under tension, then it will be elongated in this direction, but it will be contracted in the lateral direction. So, Poisson ratio is the lateral deformation by longitudinal elongation. So, it varies about 0.1 to 0.5. For isotropic and poly crystalline ceramics, Poisson's ratio, Young's modulus and shear modulus they are related.

And this relation is elastic modulus is equal to 2 into G into 1 plus Poisson ratio. And I would like you to try to prove this relation. And usually for various material like silicon carbide, molybdenum disilicite which is a material for heating elements, concrete, silicon nitrite, they are usually in the range of 0.1 to 0.5.

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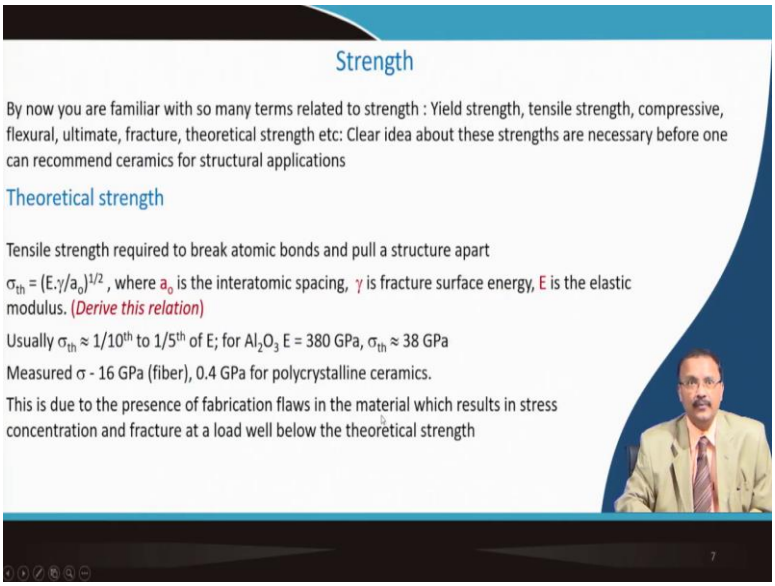

Now, by now you are familiar with so many types of strength. We talked about yield strength, we talked about tensile strength, compressive strength, flexural strength, ultimate strength, fracture strength, theoretical strength, so, so many strength we have described in our previous lecture when I talked about the mechanical properties of the non-metallic materials.

So, it is important for you to have a very clear idea about these strengths before you can recommend one particular brittle material ceramic material for any structural application. So, theoretical strength that is basically the strength required to break the atomic bonds and pull the structure apart. So, theoretical strength is related to elastic modulus. And once two surface will be created, so this surface energy is a part of it is this equation.

And it depends on the inter atomic spacing which is defined as a 0. So, this relation can be derived from the first principle. And try to derive this relation to estimate the theoretical strength of a ceramic material. It is a having a very unusually high value. Usually the theoretical strength is one-tenth to one-fifth of the elastic modulus. And you know that for alumina the elastic modulus is about 380 GPa.

So, in principle, theoretical strength will be if you take one-tenth of it, it will be 38 GPa. But when you measure the strength fracture stress of the alumina or brittle material in case of fiber which is basically a whisker defect free fiber, you get about 16 GPa but actual polycrystalline ceramics, it reduce down to 0.4 GPa. So, there is a tremendous

difference between the calculated theoretical strength and the strength that actually you are getting. So, this is due to the presence of various types of flaws in the material which eventually result the stress concentration. And fracture at a load well below the theoretical strength is usually achieved.

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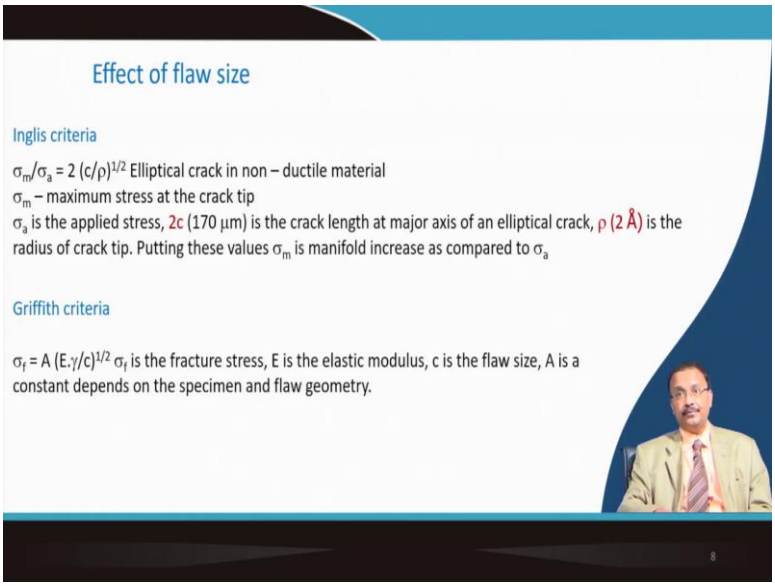

So, there are various theory pertinent to the effect of this flaw. So, Inglis criteria tells that the maximum stress at the crack tip and the applied stress ratio goes with 2 into half crack length by this is the radius of curvature of the crack. So, if it is a very sharp crack, then this value will be very large because it will be very small. So, basically the maximum stress at the crack tip will be multiplied many times even if the applied stress is relatively small.

So, you can calculate it that sigma a is applied stress. If you take the full crack length is about 170 microns, so I half crack length is half of that along the major axis of the elliptical crack. And if you take a sharp crack with the value of rho is about 2 Angstrom, then you can see that this stress concentration is manifold increase as compared to the applied stress and that is one of the reason that if the crack or void is present in the ceramic.

Why, it fells at a stress much lower than the theoretical strength. So, something similar to this is Griffith criteria which already I have described, some similar expression. So, E is

the elastic modulus, c is the flaw size here. So, basically your A 0 inter atomic spacing is being replaced by crack. So, therefore, this stress is much more reduced.

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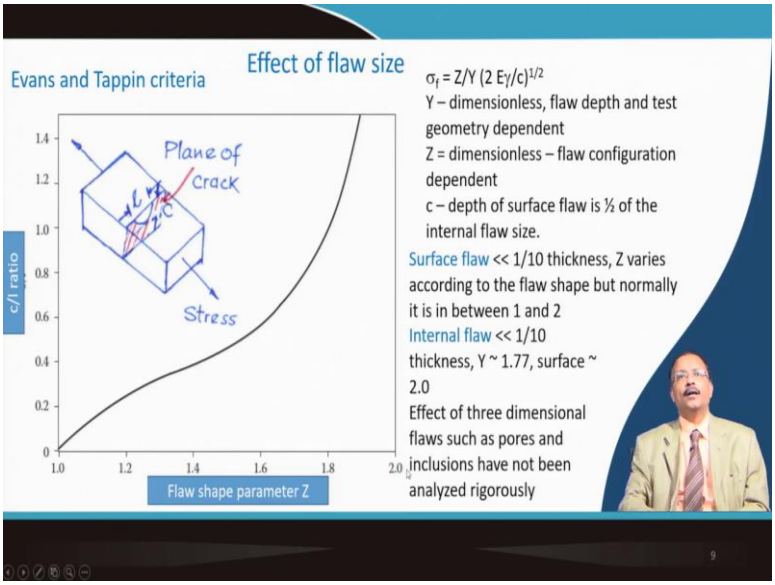

Some little bit complication, but the concept remains same is given in Evans and Tappin criteria. Here the fracture stress is again the same kind of relation 2 E gamma by c to the power half. Now, here you have a dimension, two dimensionless parameters – one is Z, and one is Y. So, this Y is related to the flaw depth and test geometry; and Z is also dimensionless and this is also dependent on the flaw configuration.

So, typically if you see the crack from the surface half crack is c here, and l is the width of the sample. Then the c by l ratio it is dependent on this flaw shape parameter. So, this value of Z is usually in between 1 and about 2. So, if you have a surface flaw which is much less than one-tenth of the thickness of the sample, then the Z varies according to the flaw shape, but normally it is in between 1 and 2.

In case of internal flaw, not the surface flaw, but if the flaw stays somewhere in between and again the sample this floss size is less than one-tenth of the thickness, then usually y is taken as 1.77. And in case of the surface flaw, it is taken as 2. So, these are all empirical relationship.

And with using this, you can estimate the fracture stress of a ceramic sample. Three-dimensional defect like pores and voids or inclusion that have not been rigorously analyzed to see their effect in your the strength of the ceramic material.

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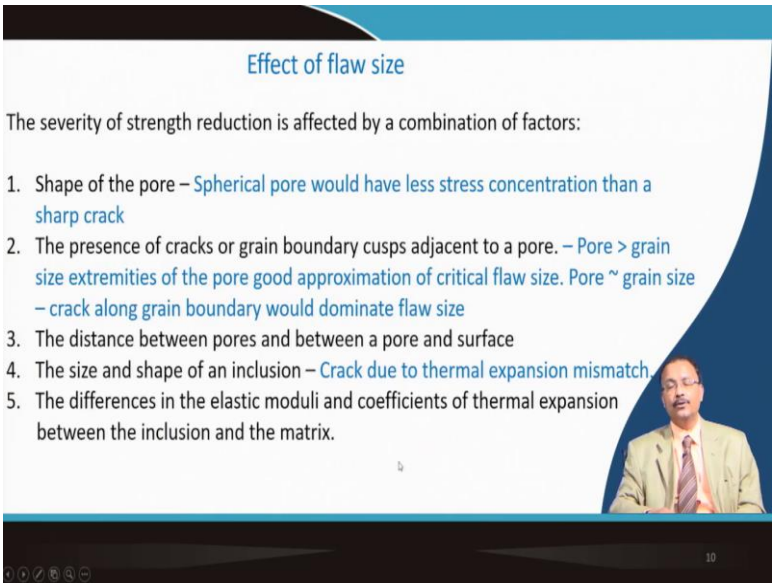

So, the severity of the strength reduction is actually affected by a combination of factor. So, pore is one of them – spherical pores that will have a less stress concentration than a very sharp crack. So, it is better to have spherical pore. The presence of crack or grain boundary adjacent to the pore, so that will affect the strength of the ceramic. The distance of the pore and pores and between the pore and surface that is also important.

The size and shape of the inclusion inside the ceramic that is important, particularly, if the inclusion is having very different thermal expansion coefficient as compared to the original ceramic. So, due to the thermal mismatch, the micro crack will be generated. And the differences in elastic modulus coefficient of thermal expansion between the inclusion and the matrix that also will contribute to the lower strength value.

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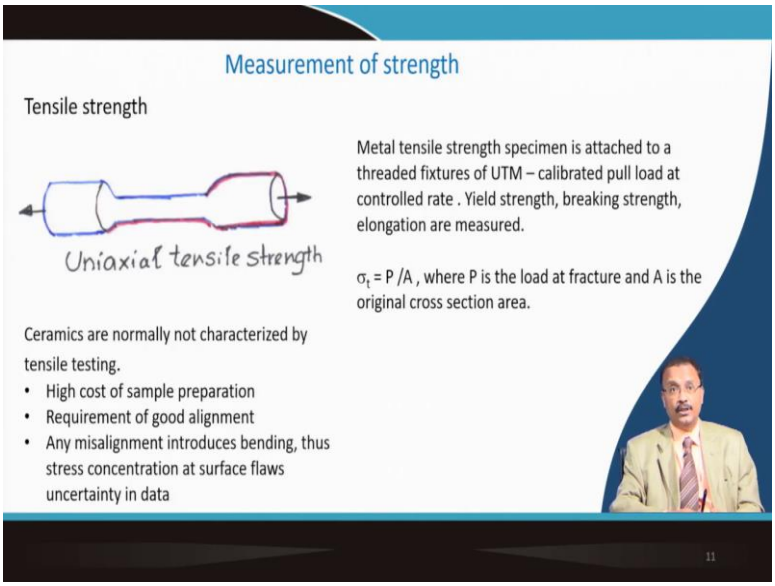

So, usually, in case of the ceramic the tensile strength is measured by making a specimen something like this, but this sample preparation is costly and very good alignment is required to make this kind of samples because any small misalignment will generate the stress concentration. So, usually unlike the metal the ceramic is not measured by this kind of sample.

So, usually this specimen is attached to a threaded fixture in a universal testing machine, and a calibrated pull load at a control rate is applied, and yield strength, breaking strength, elongation, etcetera are measured. And sigma is nothing but the applied load by the instantaneous or the original cross section area. And once it breaks then you can easily estimate the fracture stress of the sample.

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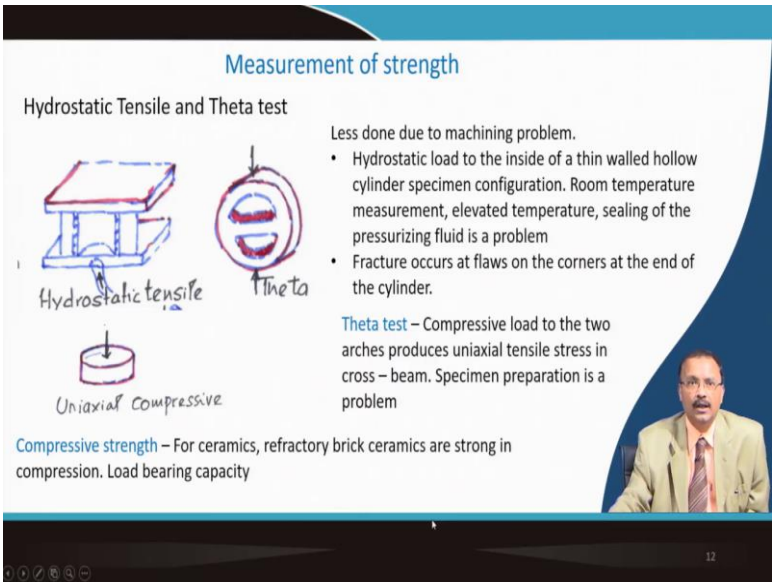

Usually that tensile sample preparation is a bit tricky, but this hydrostatic tensile strength measurement is also done, but that is also having a machining problem. So, the hydrostatic load inside the thin walled cylinder at room temperature you can measure its strength elevated temperature ceiling is important. And fracture usually occurs at the corner or at the end of the cylinder. And this is one way to measure the strength of the material.

Sometimes, it is done by theta test where a compressive load to the two arches that is applied. And so the uniaxial tensile stress in the cross beam is applied, and specimen preparation for this kind of measurement is a problem. Compressive strength measurement is usually straight forward for ceramic refractory brake. They are strong in compression. So, the load bearing capacity is usually higher as compared to the other type of geometry.

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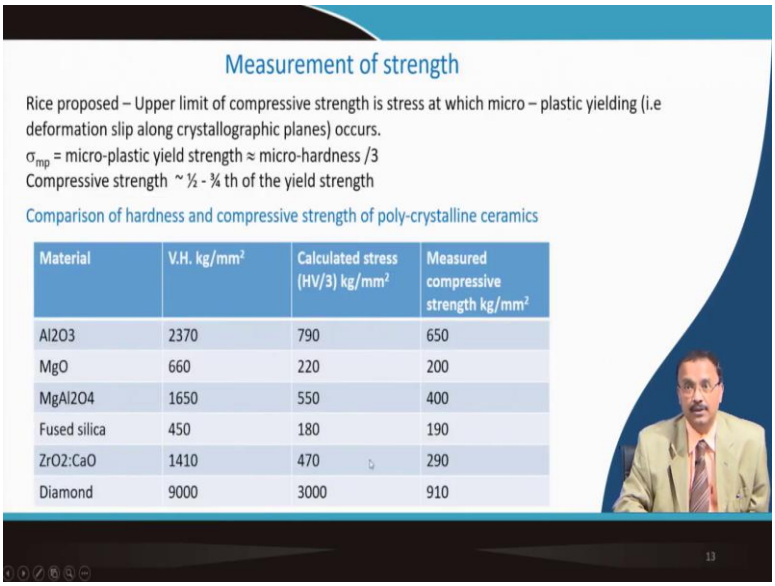

You can also estimate the compressive strength of a material by measuring its weaker hardness. So, this proposition was made by rice who told that upper limit of the compressive strength is the stress at which the micro plastic yielding that is the deformation slip along the crystallographic planes occur.

So, this micro plastic strength we call it is a micro hardness divided by 3 that is a rough estimate, and compressive strength is actually half to three-fourth of the that yield strength. So, this example has been given for a variety of materials. First the weaker hardness is measured so that is given in kilogram per millimeter square.

So, it is one-third of this micro hardness, so that is the calculated stress value microplastic yield strength, and the compressive strength should be one-third to three-fourth. So, experimentally this is measured. So, it roughly is very close. So, you can measure the hardness and then actually estimate the compressive strength of the material.

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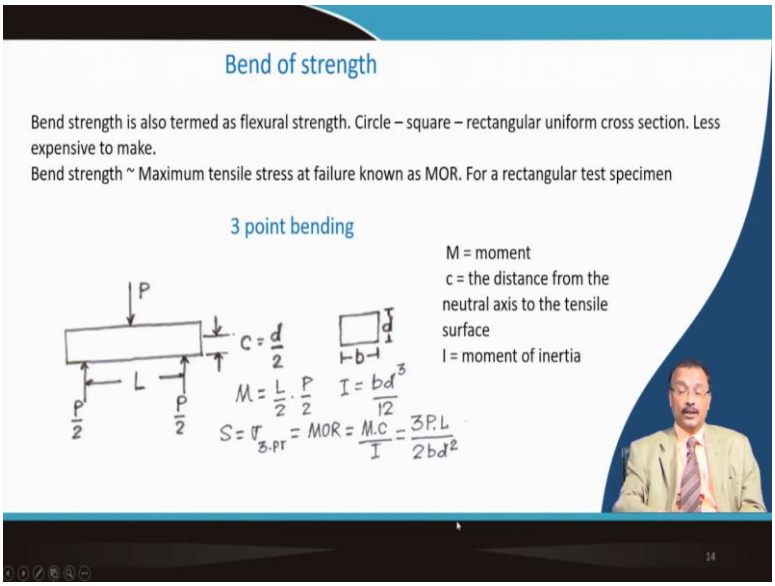

Usually, we measure the bend strength. So, this already I have described earlier. So, 3 point bending is done. Two supports are there. So, you know that this is the span length. So, first you calculate the moment, and moment of inertia.

Then the value of the modulus of rupture is moment into c; c is this length from neutral axis till the surface. So, you can estimate the load that is applied into the span length, b is the width, and d is the thickness. So, you can calculate the modulus of rupture in the 3 point bending test.

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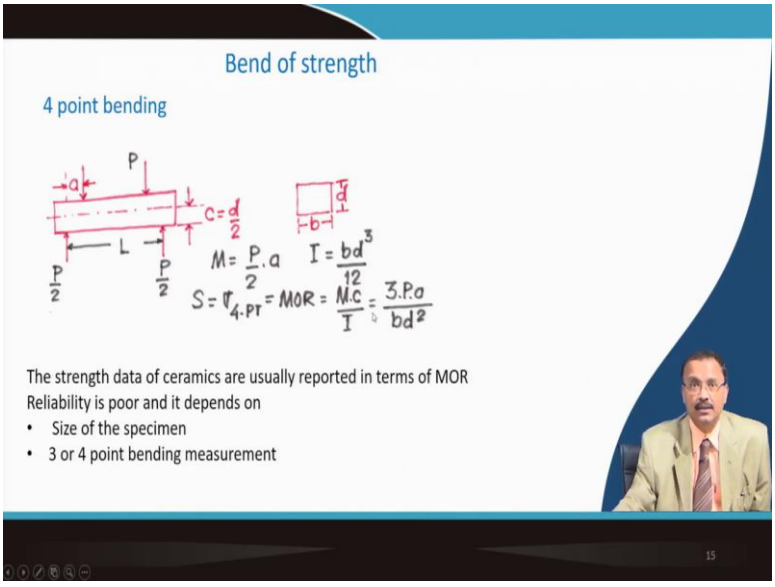

In 4 point bending test, the formula is a bit different. But here the similar kind of arrangement is made, and it depends the strength data of ceramic is usually reported in case of most of the ceramics like the MOR value – Modulus Of Rupture. So, the reliability is one factor. And the reliability depends on the size of the specimen and whether you have done either a 3 point or 4 point bending that also is important for you to accurately predict the strength value.

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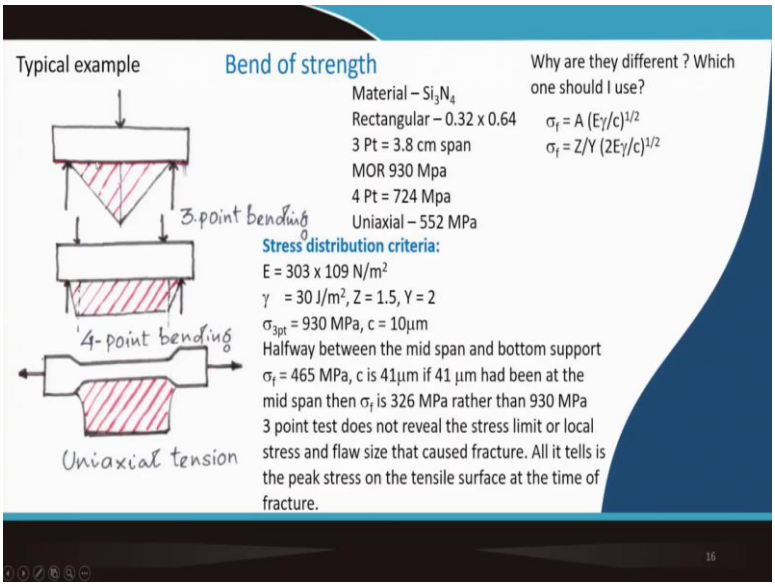

Now, this is an example. A centered material is formed in the form of silicon nitrite. It is a rectangular size 0.32 by 0.64 centimeter is the cross section. And in case of 3 point, this span was 3.8 centimeter. So, the MOR was measured as 930 Mega Pascal. If you do the same experiment in case of 4 point, the value is reduced to 724 Mega Pascal.

And if you do the same sample in uni-axial strength measurement, the value is reduced to 552 Mega Pascal. So, there is a wide variation. So, it depends on the stress distribution criteria.

So, as you can see here when you are applying a load here so maximum load is at the midpoint, and here it is 0, and here also in the support it is 0. So, actual load whatever you are applying that is seen by the sample only at the midpoint. So, enough estimates can be made. The elastic modulus is taken about 303 into 10 to the power 9 Newton per meter square.

Gamma you can take 30 joule per meter square. And this dimensionless parameter this Z and Y what I have talked about Z by Y 2E gamma by c to the power half the Tappin's formula. So, you can apply that and estimate the stress value. And in case of the stress fracture stress, if it is 930 Mega Pascal, so if you convert it to the corresponding crack it is about 10 micron.

So, half way between the mid span and the bottom support, your sigma fracture value is 465 Mega Pascal, then the c value is 41 micrometer. So, it tells that if 41 micrometer had been at the mid span, then your sigma fracture would have been 326. You can estimate that. You can calculate it from this formula. So, it will not be 930. So, it is important that wherever the stress is being applied what is the maximum crack size that is having there in case of 3 point bending, because the load is really concentrated at the midpoint.

If you go ahead and do the same measurement in the 4 point bending, then the distribution of the load is pretty uniform. And in case of tensile – uniaxial tension, it is pretty uniform. So, no matter I mean it has it the sample will have a distribution of crack length. So, no matter what crack is there.

So, basically that will get average out. And it will underestimate the fracture stress, but it will be more reliable as compared to the 3 point bending. So, therefore, 4 point bending or if possible uniaxial tension, this measurement will give more reliable value as compared to the 3 point bending test.

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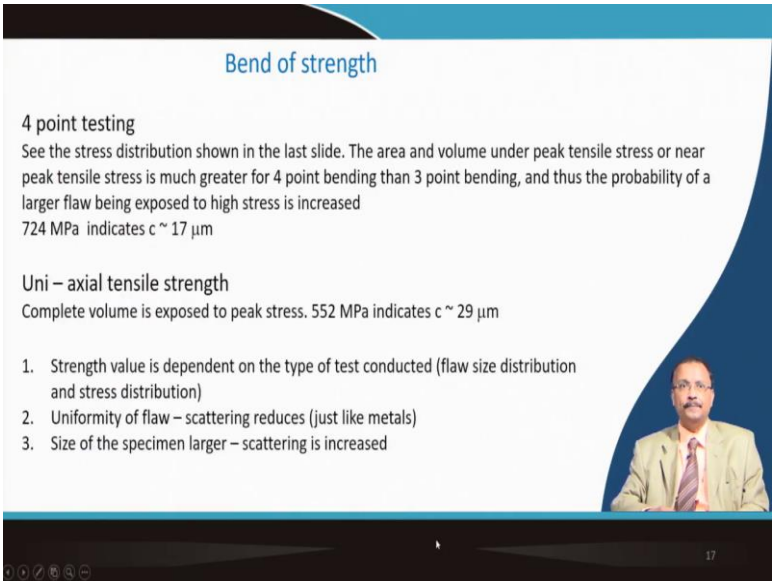

So, in case of 4 point bending test, as I told that you will have to look at the stress based distribution. The area and the volume under the peak tensile stress or near peak tensile stress is much larger for 4 point bending as compared to the 3 point bending test, thus the probability of a larger flow being exposed to high stress is increased. And therefore, the actual stress value is less.

Uniaxial tensile strength is complete volume is exposed to that stress. So, the fracture stress value is lower as compared to even the 4 point bending test. So, strength value is dependent on the type of test conducted, flow size distribution and stress distribution is important.

Uniformity of flow size is always desirable because the scattering is reduced just like the metal. Size of the specimen if it is larger, then the scattering is increased. So, separately I will devote one lecture how to get the design stress by statistical method as a part of my another lecture. We will discuss we will come back to this issue to elaborate it further.

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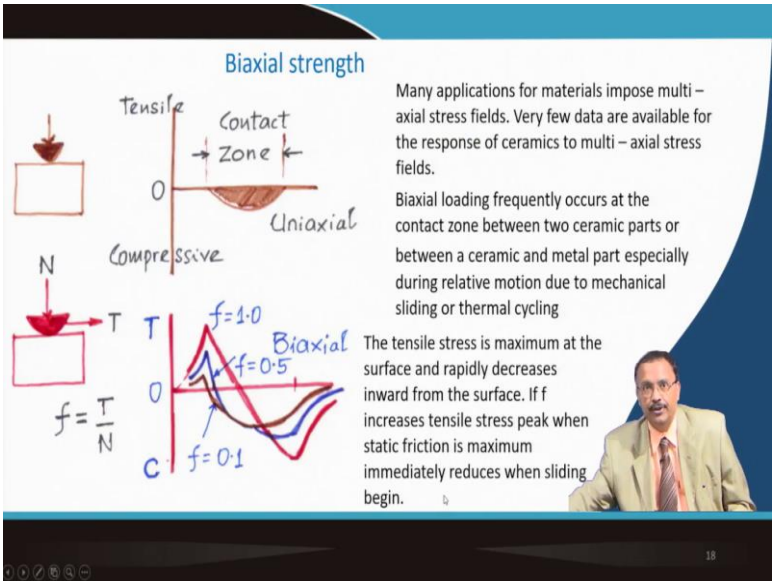

Now, in case of biaxial strength, it is not the uniaxial strength which is important, but it is the compressive load along with the tension that is also important. So, many application for materials that impose this multi-axial stress field and very few data they are available for the response of ceramics to multi-axial stress fields.

So, biaxial loading is frequently occur at the contact zone between two ceramic part or a ceramic and glass part, so as you can see that in the contact zone the tensile stress is maximum here at the surface, and then rapidly it decreases inward from the surface. So, if the value of f that increases, so then the tensile stress is also peak.

When the static friction is maximum and then immediately it reduces on the sliding, and that is the fact this due to this fact the chipping etcetera is occurred. And when I will talk about the machining of the ceramics, you will see that this is particularly important when the machining is done at the final stage of the ceramic fabrication. And the effect of the biaxial strength is elaborated at that point.

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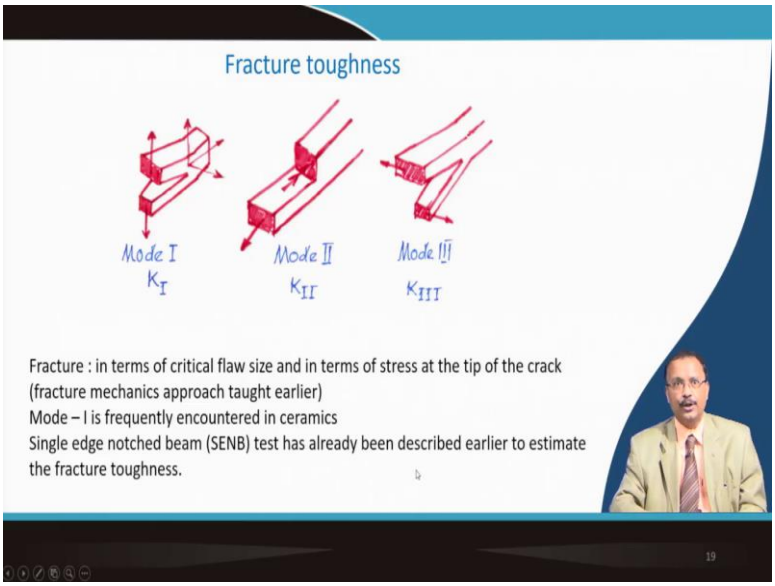

Fracture toughness already we have described earlier. And usually mode one is frequently encountered in the ceramic. And as a part of my earlier lecture already we have described that single edge notch beam test abbreviated as SENB is actually this is used to estimate the fracture toughness of the brittle ceramics.

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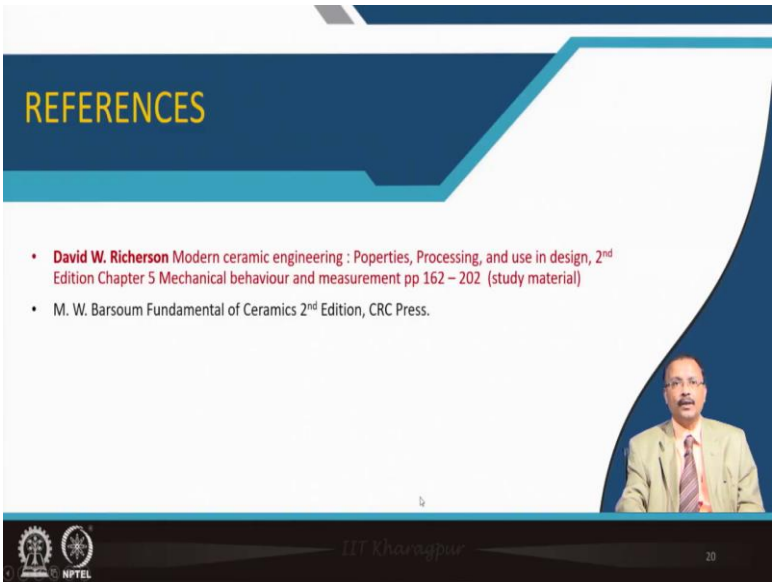

So, the reference is from the book by Richerson and also Barsoum Mechanical Properties as a study material.

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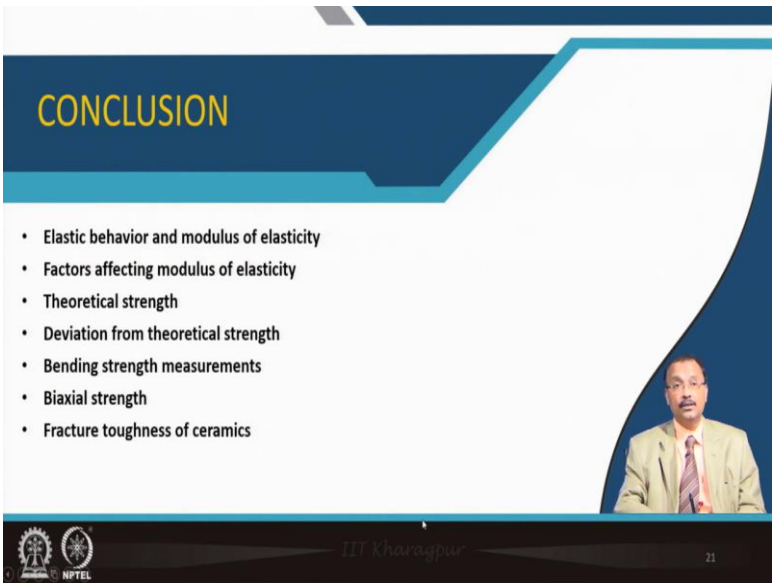

And in this lecture, we talked about the elastic behavior and modulus of elasticity. Then we talked about the factors affecting the modulus of elasticity, the concept of theoretical strength and why the theoretical strength is never been achieved, why the deviation from the theoretical strength. Then we talked about the bending strength measurement. And

we introduced the biaxial strength concept and ceramic material. And finally, the fracture toughness of the ceramic and their measure measurement is pointed out.

Thank you for your attention.