Mechanical Behavior of Materials
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Lecture - 64
Fatigue - V

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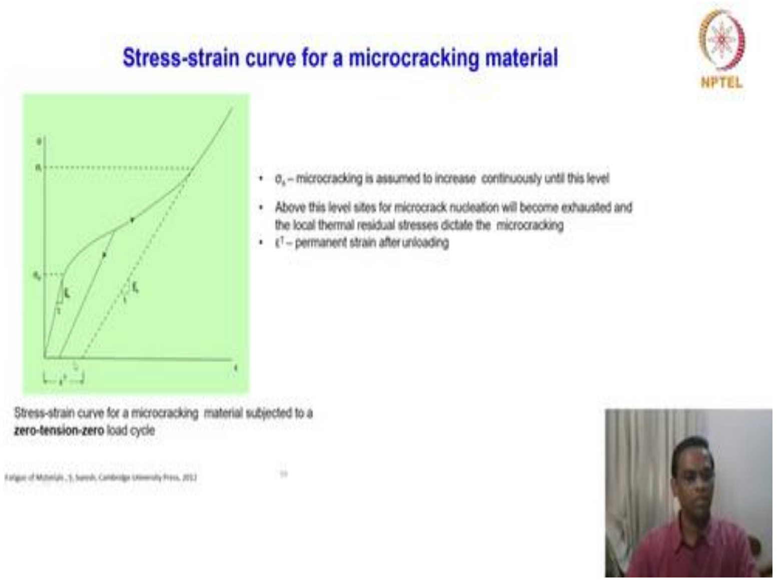

Stress-strain curve for a microcracking material

- σ_s – microcracking is assumed to increase continuously until this level
- Above this level sites for microcrack nucleation will become exhausted and the local thermal residual stresses dictate the microcracking
- ε^T – permanent strain after unloading

Stress-strain curve for a microcracking material subjected to a **zero-tension-zero** load cycle

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Hello, I am Professor S. Sankaran in the department of metallurgical and materials engineering. So, this is a stress versus strain plot and what we are seeing here is a kind of a nonlinear stress strain curve also having different features. Let us try to understand this up to elastic region or up to yield point σ_0. In a micro crack material how do we define σ? That is a question. The slope is E_0 and there is something called a σ_s.

And then we are again redefining something called E_s. This is reduced modulus and this is the ε_T, we will see all this. The stress-strain curve for microcracking material subjected to a zero-tension-zero load cycle. So, this is a there is no compression here, it is only tension, cyclic is only tension cycle, it is called zero tension zero cycle. There is no compressive stress. σ_s is microcracking is assumed to increase and continuous sleep until this level.

So, this is the moment it crosses this that is a proof stress kind of thing the material is expected to undergo deformation with the microcracking is keep on increasing in this material till this point. The microcracking is keep on increasing, here we have to talk in terms of like what we have assumed in dislocation mediated plasticity metals, the strain hardening takes place and then the number of dislocations keep on increasing till it saturates.

So, similarly the micro cracks keep on increasing till it saturates, there is no scope of further micro fact all the regime are consumed like a dislocation here there is no scope of generating new dislocation here it is no scope of creating a microcracks. So, it reaches a maximum so that is called the σ_s saturate σ. Above this level sites for microcrack nucleation will become exhausted and the local residual stresses dictate the microcracking.

Above this it is only local thermal residual stresses will be dictating whether the micro tacking will take place. ε_T is a permanent stain after unloading so, this is a reduced modulus and then up to this is the permanent stain unrecoverable irreversible stain.

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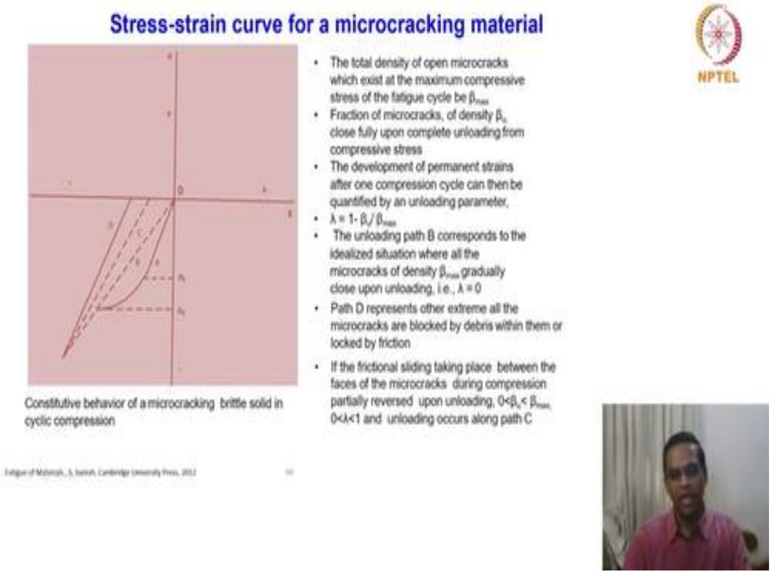

Stress-strain curve for a microcracking material

Constitutive behavior of a microcracking brittle solid in cyclic compression

- The total density of open microcracks which exist at the maximum compressive stress of the fatigue cycle be β_{max}
- Fraction of microcracks, of density β_c close fully upon complete unloading from compressive stress
- The development of permanent strains after one compression cycle can then be quantified by an unloading parameter,
- $\lambda = 1 - \beta_c / \beta_{max}$
- The unloading path B corresponds to the idealized situation where all the microcracks of density β_{max} gradually close upon unloading, i.e., $\lambda = 0$
- Path D represents other extreme all the microcracks are blocked by debris within them or locked by friction
- If the frictional sliding taking place between the faces of the microcracks during compression partially reversed upon unloading, $0<\beta_c< \beta_{max}$, $0<\lambda<1$ and unloading occurs along path C

So, how do we understand this mechanism? There is a more nice model. When it comes when the macro cracking material is subjected to compression load, what happens? So, this is very costly constitutive behaviour of microcracking brittle in a cyclic compression. That is zero tension zero, this is compression, cyclic compression, zero compression again zero. The total density of open microcracks which exist at the maximum compressive stress of fatigue cycle be β_{max}.

So, here we are defining a parameter based upon the Turing cyclic loading whether the micro crack is opened or get closed. So, that is the physics behind it. And the maximum compressive stress of the fatigue cycle is β_{max}, the total density of open microcracks. So, all the microcracks or the total density, how many cracks are completely open that is defined by this β_{max}.

Fraction of microcracks of density β_u close fully upon complete unloading from the compressive stress. There is another parameter which measures the number of microcracks they get fully closed upon the unloading. So, that means compression it comes back to zero, how many of the micro cracks keep closing. The development of permanent streams after one compression cycle can then be quantified by an unloading parameter λ.

Which is defined as $\lambda = 1 - \beta_u / \beta_{max}$. So, how do we understand this? The unloading path B corresponds to the idealized situation where all the microcracks of density β_{max} gradually close open upon unloading, that is $\lambda = 0$. So, what is B? The path B is shown here. It reaches 0 that means all the microcracks got close it just while loading it was just opening when it comes back, it is close.

So, here similar to the earlier plot here also you see that microcracks and beyond which, it goes it is supposed to be σ_s that is a typo here σ_0 and σ_s. So, if all the microcracks get closed following this part B then $\lambda = 0$. Path D is the, I mean which represent the other extreme all the microcracks are blocked by the debris within them are locked by the friction. So, all of them just kept open nothing come to close.

So, that is another extreme situation, so this is completely closed and this is completely open. If the frictional sliding taking place between the faces of the microcracks during compression partially reversed upon unloading then β_u will be in between 0 and β_{max} and the λ will be in between 0 to 1 and unloading occurs along path C. So, this is in between situation where the value of β_u, it will be between this whether the fraction of microcracks only get closed.

Only fraction is closed that is what define here β_u and when it comes to that kind of thing then this fraction this equation will give the λ is between less than 1 because it is less than 1. So, this will be the unloading path C will be dictated by this. So, this is one model which explains the how the microcracking material will be behaving when they subjected to cyclic loading. This one path tension, one path compression this is what we have seen.

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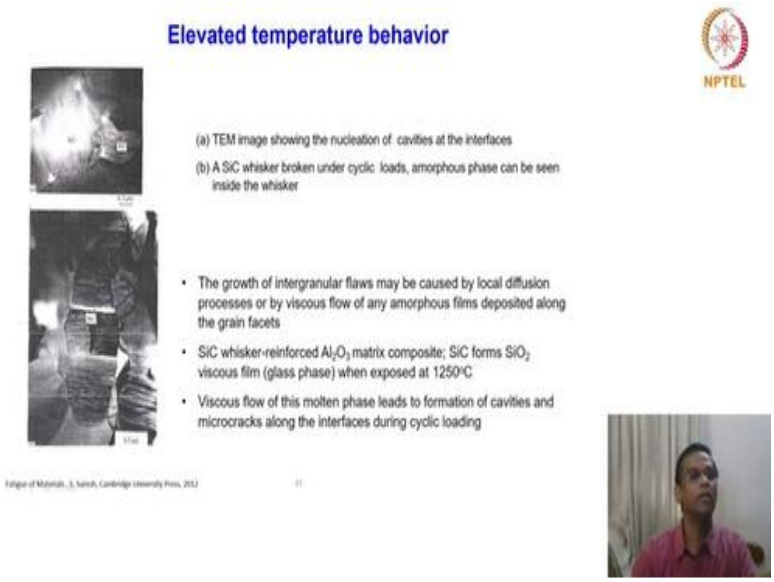

Elevated temperature behavior

(a) TEM image showing the nucleation of cavities at the interfaces

(b) A SiC whisker broken under cyclic loads, amorphous phase can be seen inside the whisker

- The growth of intergranular flaws may be caused by local diffusion processes or by viscous flow of any amorphous films deposited along the grain facets
- SiC whisker-reinforced Al_2O_3 matrix composite; SiC forms SiO_2 viscous film (glass phase) when exposed at 1250°C
- Viscous flow of this molten phase leads to formation of cavities and microcracks along the interfaces during cyclic loading

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So, what happens at high temperature for this brittle material? This brittle material you know this is a method of electron micrograph shown for the silicon whisker broken under cyclic loads amorphous phase can be seen inside the whiskers. So, you can see all inside this there are a lot of amorphous phase that is what is reported. The growth of intergranular flaws may be caused by the local diffusion process or by viscous flow of any amorphous builds depositing along the grain facets.

And silicon carbide whisker reinforced alumina oxide matrix composite, silicon carbide forms silicon dioxide viscous film forms which is a glass phase when exposed at 1250°C. So, what happens to this highly brittle material high temperature? That is just given some examples with some what are the new flaws or the new phase which comes and disclaim form and which becomes viscous flow or amorphous films formation all these aspects are shown this microcracks.

The viscous flow of this molten phase leads to formation of cavities. So, you can see that already there is a cavity here, here is a cavity, here is a cavity and the microcracks along the interface during cyclic loading. So, all the interface will have several microcracks. You can see that we can even see a lot of microcracks.

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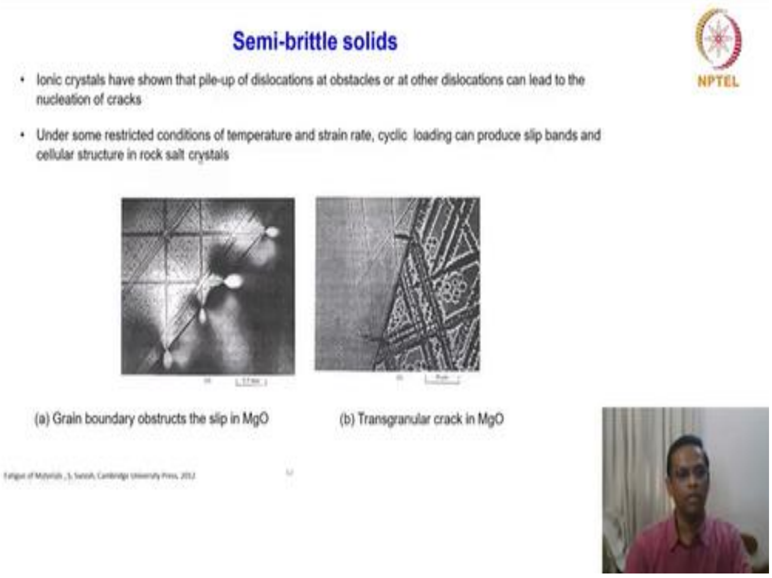

Semi-brittle solids

- Ionic crystals have shown that pile-up of dislocations at obstacles or at other dislocations can lead to the nucleation of cracks
- Under some restricted conditions of temperature and strain rate, cyclic loading can produce slip bands and cellular structure in rock salt crystals

(a) Grain boundary obstructs the slip in MgO

(b) Transgranular crack in MgO

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So, now we turn our attention to semi brittle solids what happens? Ionic crystals have shown that pile-up of dislocation at obstacles or other dislocation can lead to the nucleation of cracks. In a semi crystalline solid similar to metals and alloys, you have pile-up of dislocations and the boundaries and then we can see that grain boundary obstructs the slip in magnesium oxide and the transplant crack in magnesium oxides.

Under some restricted conditions of temperature and strain rate, cyclic loading can produce slip bands and cellular structure in rock salt crystals. So, you can see that no slip bands or there you can see the slip bands which are formed and cellular structure is also reported in the rock-solid structure.

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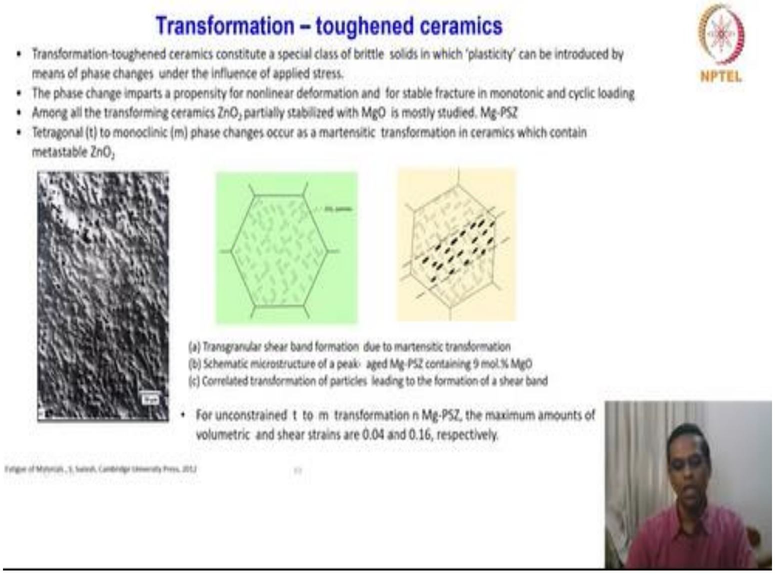

Transformation – toughened ceramics

- Transformation-toughened ceramics constitute a special class of brittle solids in which 'plasticity' can be introduced by means of phase changes under the influence of applied stress.
- The phase change imparts a propensity for nonlinear deformation and for stable fracture in monotonic and cyclic loading
- Among all the transforming ceramics ZnO_2 partially stabilized with MgO is mostly studied. Mg-PSZ
- Tetragonal (t) to monoclinic (m) phase changes occur as a martensitic transformation in ceramics which contain metastable ZnO_2

(a) Transgranular shear band formation due to martensitic transformation

(b) Schematic microstructure of a peak- aged Mg-PSZ containing 9 mol.% MgO

(c) Correlated transformation of particles leading to the formation of a shear band

- For unconstrained t to m transformation n Mg-PSZ, the maximum amounts of volumetric and shear strains are 0.04 and 0.16, respectively.

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So, that is about the semi brittle solids. Now I just want to give some idea about the transformation toughened ceramics, very important topic and very popular in material science. Transformation-toughened ceramics constitute a special class of brittle solids in which plasticity can be introduced by means of phase changes under the influence of applied stress. You see in a highly brittle material like ceramics.

If you look at the fracture toughness values of these materials you will be surprised. For example, if you take the high strength steels the, fracture toughness values will be in the order of 40 to 80 MPs per meter. But if you talk a ceramics fracture toughness will be less than 10 MPa square root meter, I mean even 10 is higher is much lower than that. So, improving the fracture toughness, suppose if I have 5 to 6 MPa square root meter or I have 2 to 3 MPa square root meter as fracture toughness.

If I can improve from this value to 6 or 7 or from 6 to 8 MPa square root and be a square root metre. It is considered to be significantly successful process or successful attempt that is the importance of toughening the ceramic. So, that is considered that huge achievement, because it ceramics are highly brittle and we are talking about a facture of this. So, that is one there are several ways people try to improve the fracture-toughness.

What are the popular methods is improving the toughness through phase transformation? The phase change imparts a propensity for nonlinear deformation and for stable fracture in monotonic and cyclic loading. We are talking about how to improve the toughness impact by plasticity used to track closure you now, there are also a toughness improving mechanisms. Here, if you consider the crack is there in the ceramic material and then ahead of the track the region is getting into our transform to do product.

Then what happens? That is the idea. Among all the transforming ceramic, zirconia partially stabilized with magnesium oxide is mostly studied Mg-PSZ is a partially stabilized zirconia system. Tetragonal to monoclinic phase changes occurs as a martensitic transformation in ceramics which contain metastable zirconia. So, metastable zirconia which is originally having tetragonal crystal structure changes to monoclinic space through martensitic transformation.

That means just a simple shear. So, this is one micrograph shows a transgranular shear band formation due to martensitic transformation. So, you see that there are some shear bands. And it looks like a lot of particles are embedded in a matrix yes, it is true, there is a lot of particles. In order to make you a little more appreciate this is what is shown here. I am just showing this schematic supposed to strain as having a lot.

Lens shaped zirconia particles, so this is supposed to be a schematic microstructure of a peak aged Mg-PSZ, partially stabilized zirconia containing 9 mol percent of magnesium oxide. So, what is shown here is a correlated transformation of particles leading to the formation of a shear band. So, this is a shear band formation because each particle of zirconia is now transformed to a monoclinic phase.

So, that is what is shown here and what is interesting in the schematic is it is again based on the experimental evidence only. The transformed particle from the tetragonal to monoclinic phase is having the same orientation. So, all this you know when you say that it is undergoing a martensitic transformation locally the shear strain it will cause some shear strain. So, when they are in the same orientation the individual particle.

Which experiences the shear strain will be totally it will be a cumulative effect for the bulk. So, in fact the orientation of this individual particle also contributes the shear band nucleation. What basically you are understand is? These particles are embedded in the elastic matrix obviously, when once the transformation takes place that there is a volumetric stream as well as the shear strain that you note.

So, this will trigger the shear strain, I mean the especially the shear strain contributed by individual particle will trigger the shear band formation. So, which will be contributing to the; total bulk volumetric as well as shear strain, to the bulk material. So, that is how we should understand. For an unconstrained tetragonal to monoclinic transformation in magnesium PSZ the maximum amounts of volumetric and shear strains are 0.04 and 0.16 respectively.

Though individual particles will have the volumetric strain this one, but if you look at the average shear strain of particles always will be less than this. This is about unconstrained curves transformation. So, the individual shear strain or average individual shear strain of these particles will be always less than this value that one has to remember.

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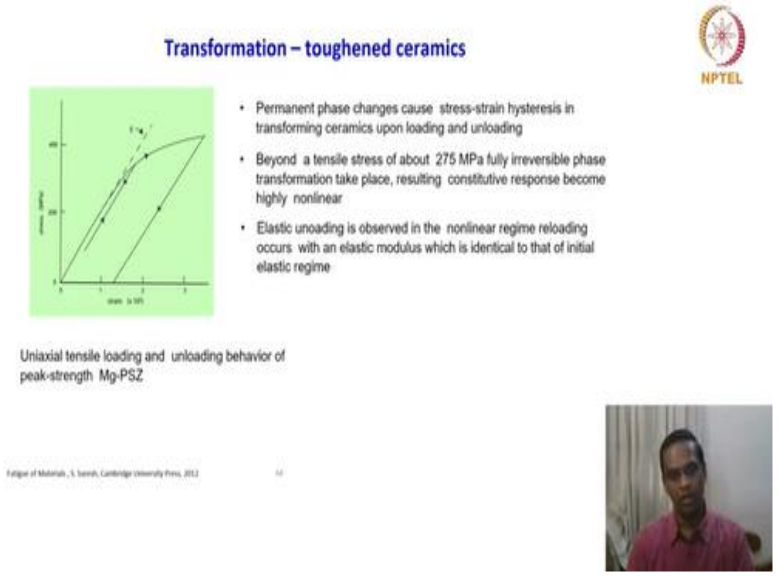

Transformation – toughened ceramics

- Permanent phase changes cause stress-strain hysteresis in transforming ceramics upon loading and unloading
- Beyond a tensile stress of about 275 MPa fully irreversible phase transformation take place, resulting constitutive response become highly nonlinear
- Elastic unoading is observed in the nonlinear regime reloading occurs with an elastic modulus which is identical to that of initial elastic regime

Uniaxial tensile loading and unloading behavior of peak-strength Mg-PSZ

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So, what is so, important by this? Permanent phase changes cause a stress strain hysteresis in transforming ceramics upon loading unloading. So, this is a stress-strain behaviour of the ceramic material, which is after transformation. Please remember ceramic materials be described as very highly brittle solid. Now, it is showing a nonlinear stress strain response after the improvement in the toughness, that is something which you have to appreciate.

So, beyond the plastic, I mean beyond the elastic regime, it also produces a permanent plastic strain upon unloading. But if you look at the elastic regime and nonlinear elastic regime even unload, then it traces back to the same path and then the elastic modulus of these two are almost similar. So, what is this implies? We will just discuss after going through this point. Beyond a tensile stress of about 275 MPa fully irreversible phase transformation takes place resulting in the constitute response becoming highly nonlinear.

So, that is what is shown here. Elastic unloading is observed in a nonlinear regime reloading occurs with an elastic modulus which is identical to that of initial elastic regime. So, this is what is shown here. Though it is a nonlinear elastic behaviour after unloading the elastic modulus is saying if you reload. So, what is that we are now discussing here? So, this phase transformation improves the toughness of the ceramics.

We are evidencing that by stress strain behaviour of this material, it is showing a nonlinear stressed in behaviour. That means toughness is significantly improved. So, what you have to understand here is in a metallic material, we are talking about dislocation mediated plasticity. Here we are talking about transformation mediated plasticity and one difference is in a dislocation mediate plasticity it is volume is conserved.

But contrary here it is slightly different, that is what I just showed some of the numbers. The volumetric strain is 0.04 and shear strain is 0.16. So, you can compare these two-transformation induced plasticity and dislocation induced mediator plasticity of materials. So, the final point to appreciate is the highly brittle material like zirconia partially stabilise in zirconia can be toughened by the phase transformation in this; that is the idea.

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Fatigue in semi-crystalline and noncrystalline solids

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So, now, we will look at very briefly fatigue in the semi crystalline and nano crystalline solids.

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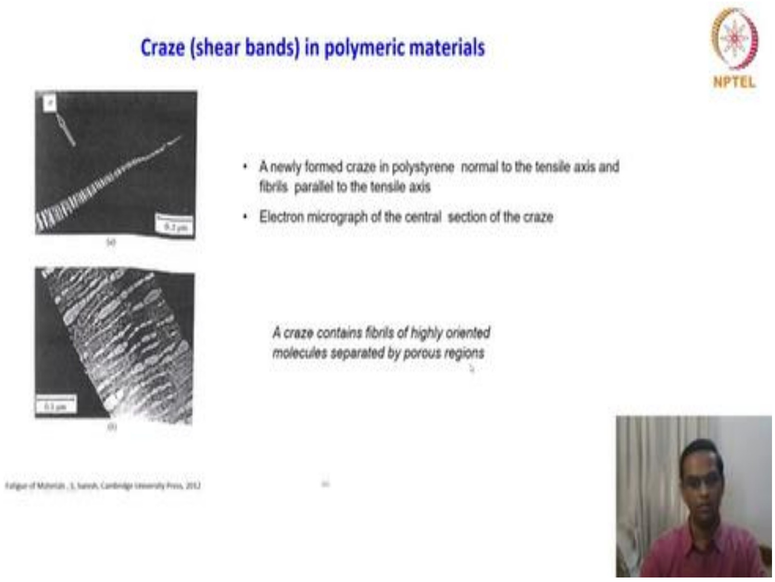

Craze (shear bands) in polymeric materials

- A newly formed craze in polystyrene normal to the tensile axis and fibrils parallel to the tensile axis
- Electron micrograph of the central section of the craze

A craze contains fibrils of highly oriented molecules separated by porous regions

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Craze in polymeric materials something related to you know, metallic materials and non-metallic materials the deformation heavy deformations figure deformation is always characterized by the formation of shear bands. In polymeric material is something close to that is called a craze. So, the craze is shown in this micrograph. So, this is a newly formed craze in our polystyrene normal to the tensile axis and the fibrils parallel to the tensile axis.

So, these are fibrils parallel to tensile axis and this is perpendicular to this the total entity is called craze, which is perpendicular to the tensile axis and the details of this structures are shown here. So, you can all the fibrils are aligned along the tensile axis and in between there is a voids. A craze contains fibrils of highly oriented molecules separated by porous regions.

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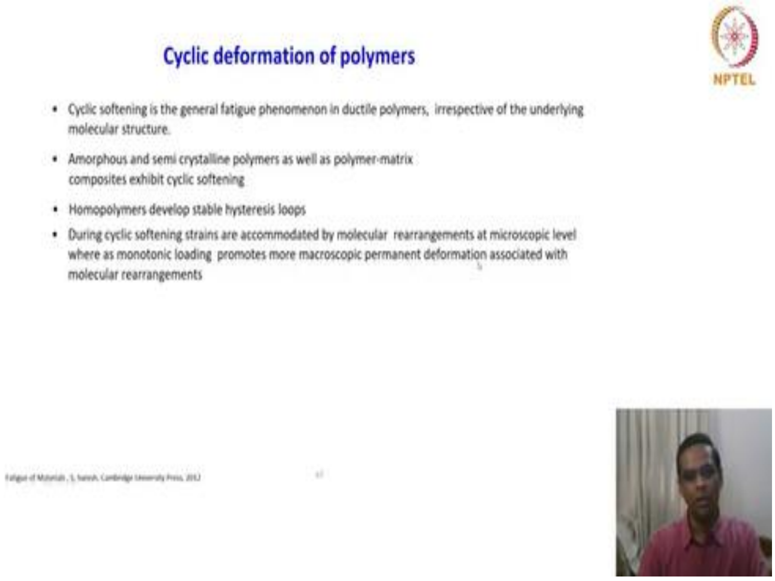

Cyclic deformation of polymers

- Cyclic softening is the general fatigue phenomenon in ductile polymers, irrespective of the underlying molecular structure.
- Amorphous and semi crystalline polymers as well as polymer-matrix composites exhibit cyclic softening
- Homopolymers develop stable hysteresis loops
- During cyclic softening strains are accommodated by molecular rearrangements at microscopic level where as monotonic loading promotes more macroscopic permanent deformation associated with molecular rearrangements

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What are the important points for doing cyclic differentiation of polymers? Cyclic softening is a general fatigue phenomenon ductile polymer, irrespective of underlying molecular structure. Amorphous and semi crystalline polymers as well as polymer matrix composites exhibit cyclic softening. Because of molecular rearrangements this is quite understandable do we have we have seen that amorphous materials and polymeric material deformation in well by even discussing tensile deformation.

It is completely know molecular rearrangement that takes the time to complete control. And homopolymers develop the stable hysteresis loops. During cyclic softening strains are accommodated by molecular rearrangements. At a micro level microscopic level whereas, the monotonic loading promotes more macroscopic permanent deformation associated with the molecular rearrangement. So, the cyclic behaviour is quite interesting in this polymeric material.

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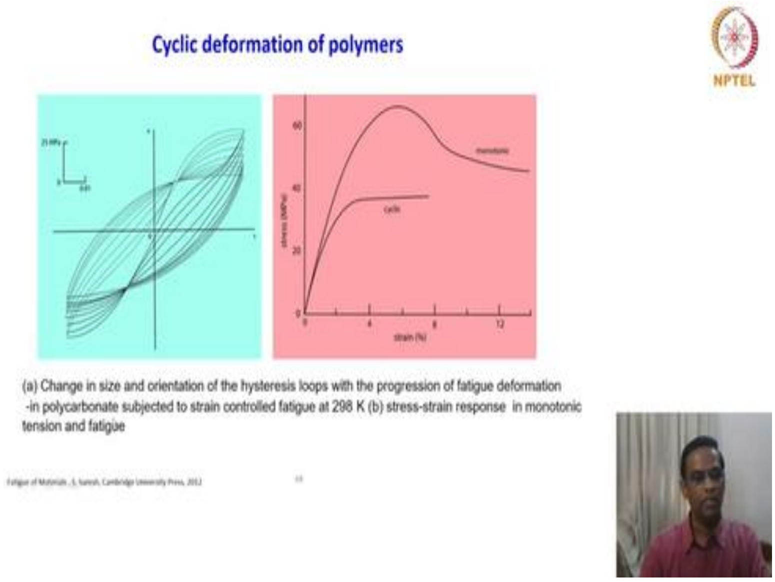

Cyclic deformation of polymers

(a) Change in size and orientation of the hysteresis loops with the progression of fatigue deformation -in polycarbonate subjected to strain controlled fatigue at 298 K (b) stress-strain response in monotonic tension and fatigue

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Just let us see that. What you are seeing? Here is the hysteresis loop, it is completely nonlinear I mean unusual stereos is I would say not it is not nonlinear, it is not symmetrical asymmetric completely asymmetric. So, what is this reason? Before it reaches saturation, it can traverse all this. Change in size and orientation of hysteresis loops with the progression of fatigue deformations in a polycarbonate is shown here, which is subjected to strain-controlled fatigue at 298 K.

So, this is a typical characteristic of hysteresis behaviour exhibited by polymeric material. And what is shown here is monotonic versus cyclic, there is a huge difference. This is what the last point in the previous slide mentions. The cyclic behaviour is quite different from the monotonic behaviour because of the even the monotonic behaviour it promotes hardening because of molecular arrangements oriented along the tensile axis.

It promotes cyclic hardening sorry monotonic work hardening. In a cyclic deformation it is completely dominated by the cyclic softening because of the molecular rearrangement and collapse.

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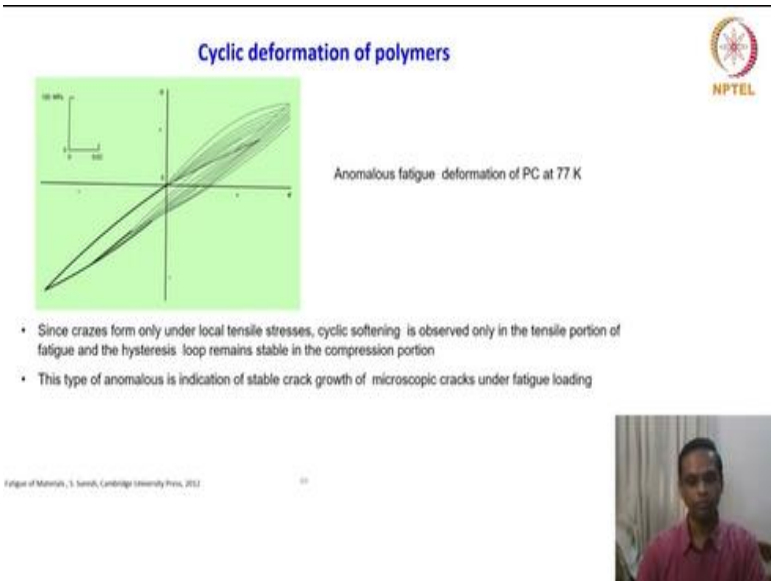

Cyclic deformation of polymers

Anomalous fatigue deformation of PC at 77 K

- Since crazes form only under local tensile stresses, cyclic softening is observed only in the tensile portion of fatigue and the hysteresis loop remains stable in the compression portion
- This type of anomalous is indication of stable crack growth of microscopic cracks under fatigue loading

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So, in a typical fatigue cycling there is an anomalous fatigue behaviour by the polycarbonate at 77K. What is anomalous about this? Since crazes form only under local tensile stresses, cyclic softening is observed only the tensile portion of the fatigue and the hysteresis loop remained stable in the compression portion, very interested. In polymeric material we talk about crazing craze formation and how it responds to the applied load.

So, when it becomes a complete reversal cycles like tension compression kind of fatigue. In tension the craze will form in compression it will be a normal behaviour. So, this is very interesting behaviour. This type of anomalous is indication of a stable crack growth of microscopic cracks under fatigue loading. So, even in polymers we are talking about a stable crack growth.

If you recall in fracture mechanics very interesting chapters we have come through, we use the archer to talk about stable crack growth. So, this kind of polymeric material also will come under that category, is a archer material. Any material which exhibits stable crack growth. They are also preferred in literature like archer materials. So, very interesting point to remember.

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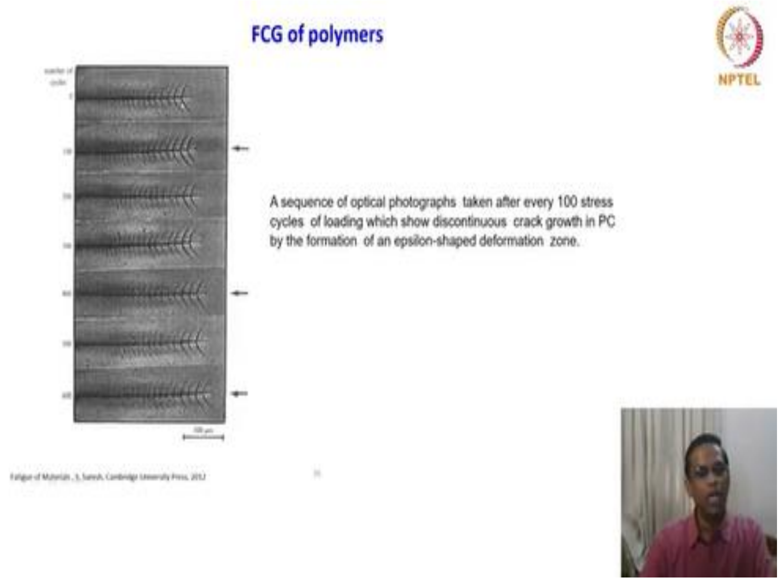

FCG of polymers

A sequence of optical photographs taken after every 100 stress cycles of loading which show discontinuous crack growth in PC by the formation of an epsilon-shaped deformation zone.

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Finally, I just want to just briefly discuss about the fatigue crack growth in polymers, very interesting point. A sequence of optical photographs taken after every 100 stress cycles of loading which show discontinuous crack growth in a polycarbonate by formation of epsilon-shaped deformation zone. You see it is ε shaped deformation zone.

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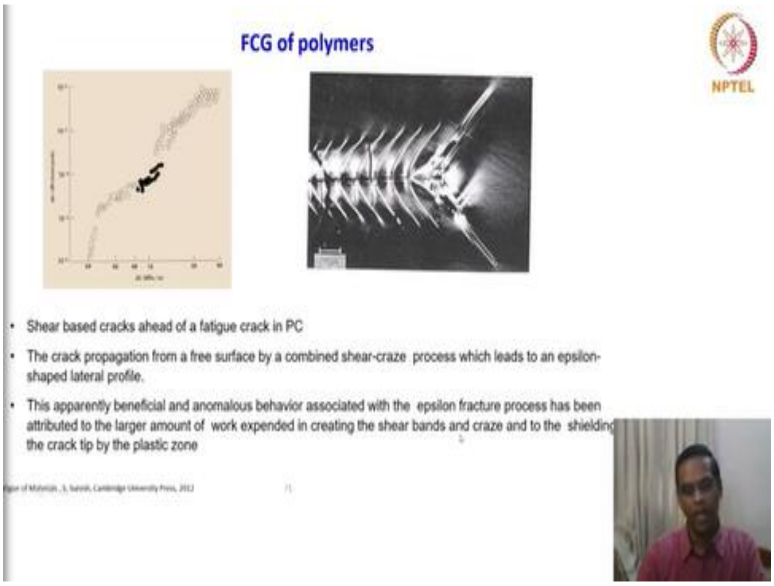

FCG of polymers

- Shear based cracks ahead of a fatigue crack in PC
- The crack propagation from a free surface by a combined shear-craze process which leads to an epsilon-shaped lateral profile.
- This apparently beneficial and anomalous behavior associated with the epsilon fracture process has been attributed to the larger amount of work expended in creating the shear bands and craze and to the shielding the crack tip by the plastic zone

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Why it forms? We will now see why it forms. So, this is a typical da/dN versus Δk crack growth curve and this photograph is very magnified version of the same crack growth. So, what you see here is very interesting events, you just closely observe this ahead of the crack curve the craze forms, you can see the craze. The craze is forming here but this shear band is forming at the angle of 45 degrees.

So, ahead of a crack, the craze forms and then it just moment the craze forms then it branches into shear bands. So, the shear band formation takes place as the crack advances. First craze forms, shear band forms. So, it is called shear craze mechanism. Shear band cracks ahead of the fatigue crack in a polycarbonate. The crack propagation from a free surface by a combined shear-craze process which leads to an ε-shaped lateral profile.

So, because of the sheer craze process occurs quickly and you can just go back and see now this one. What happens is? Once it forms like ε-shaped shear bands, the crack jumps immediately jump. It does not carry the deformation there. It just jumps from that so, that is what it is shown here. This apparently beneficial and anomalous behaviour associated with the ε fracture process has been attributed to the larger amount of work expended in creating the shear bands.

And the craze and to the shielding of the crack tip by the plastic zone. So, this is one classic example, where how the crack growth is retarded by the plastic zone formation in a metallic material you would have attributed this to a plastic zone which is quite big. Here we are talking about a craze formation (()) (30:40). So, that is something which is similar to what we are discussing the metallic materials.

So, with that I will stop the brief introduction on, I mean semi crystalline and amorphous materials, highly brittle materials. I have not gone into detail which is not required in this type of a course but at least some glimpses some highlights are to be known. So, do not worry about the details but at least try to see whether you are able to see what is happening at this some highlights, some basic idea when you look at the material spectrum, how we are able to appreciate it. That was my intention. Thank you.