Properties of Materials (Nature and Properties of Materials: III)

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Lecture 12

Composites, Anelastic behaviour

So welcome again to the new lecture of this course, Properties of Materials. Let us just do a brief recap of last lecture's contents.

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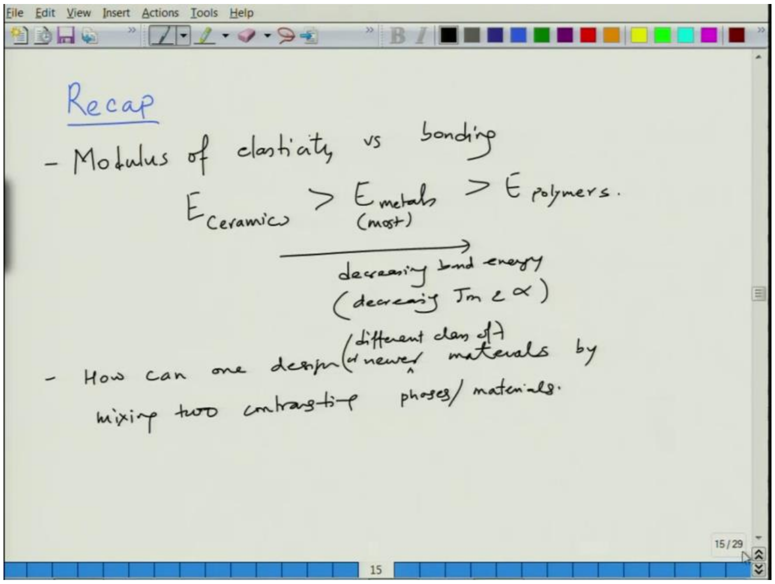

Recap

- Modulus of elasticity vs bonding

$E_{Ceramics} > E_{\underset{(most)}{metals}} > E_{polymers}$.

$\xrightarrow{\hspace{3cm}}$

decreasing bond energy
(decreasing T_m & α)

- How can one design (different class of) (or newer) materials by mixing two contrasting phases/ materials.

So in the last lecture, we looked at the values of modulus, modulus of elasticity versus bonding for different materials. So we saw that E of ceramics is generally higher than E of metals most, and this is higher than E of polymers and this is basically related to decreasing bond energy, which is also manifested in decreasing melting point and coefficient thermal expansion. And then we saw that how can one design newer materials or let us say different class of materials, different class or newer, materials, by mixing two contrasting phases or materials.

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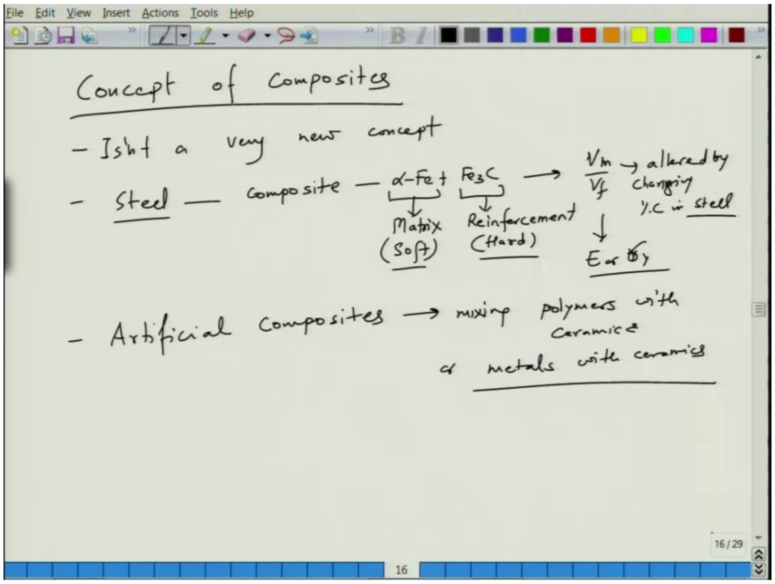

Concept of Composites

- Isn't a very new concept
- Steel — composite — α-Fe + Fe_3C $\rightarrow$ $\frac{V_m}{V_f}$ $\rightarrow$ altered by changing %C in steel
  - α-Fe $\rightarrow$ Matrix (Soft)
  - Fe_3C $\rightarrow$ Reinforcement (Hard)
  - $\downarrow$ E or σ_y
- Artificial Composites $\rightarrow$ mixing polymers with ceramics or metals with ceramics

So this concept of composite, by the way, it is not a very new concept. So, for example, if you look at a steel, steel is a composite. It is a composite of iron, which is alpha iron and Fe3C. So here alpha iron is basically the matrix and Fe3 is the reinforcement. So this is the soft phase and this is the hard phase. And these, blend of these two in steel, so the proportion of these two has changed. So proportion Vm by Vf can be altered by changing percentage carbon in steel. And that also changes the properties. So this leads to change in the E or y, sigma y, which is yield stress.

So this is a composite which is basically when you mix iron and carbon melt it and make steel, you will get a composite. So this is what happens in a material like steel. Whereas, here we are making composites which are sort of artificial composites in some sense by mixing polymers with ceramics or metals with ceramics. You can have other combinations as well, but we will primarily deal with this metals and polymers with ceramics.

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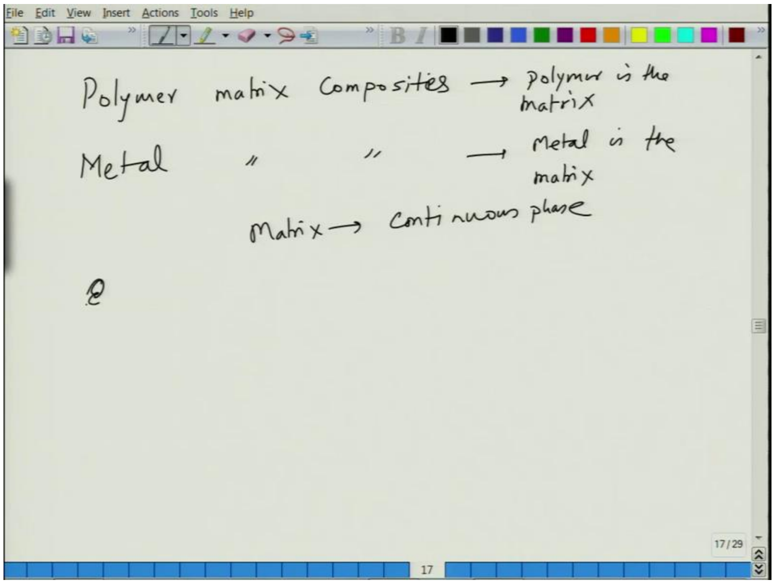

Polymer matrix Composites → polymer is the matrix

Metal " " → metal is the matrix

Matrix → continuous phase

e

So these ceramics are called as either polymer matrix composites, where polymer is the matrix and other is called as metal matrix composites, here metal is the matrix and matrix is basically you can say is the continuous phase. And this is basically because, because you would like the matrix to be tough and ductile so that matrix does not crack up on loading.

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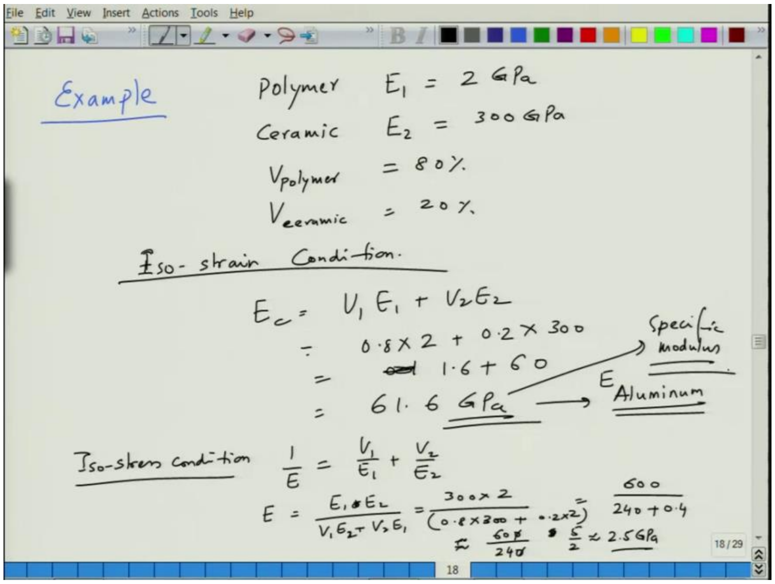

Example

Polymer $E_1 = 2$ GPa

Ceramic $E_2 = 300$ GPa

$V_{polymer} = 80\%$

$V_{ceramic} = 20\%$

Iso-strain Condition.

$$E_c = V_1E_1 + V_2E_2 = 0.8 \times 2 + 0.2 \times 300 = 1.6 + 60 = 61.6 \text{ GPa}$$

61.6 GPa → Specific modulus

61.6 GPa → $E_{Aluminum}$

Iso-stress condition $\frac{1}{E} = \frac{V_1}{E_1} + \frac{V_2}{E_2}$

$$E = \frac{E_1 E_2}{V_1E_2 + V_2E_1} = \frac{300 \times 2}{(0.8 \times 300 + 0.2 \times 2)} = \frac{600}{240 + 0.4} \approx \frac{60\cancel{0}}{24\cancel{0}} = \frac{5}{2} \approx 2.5 \text{ GPa}$$

So now let us take an example. Let us say, we choose a polymer with modulus of, let us say, E1 of, I do not know, 2 GPa let us say, and then we choose a ceramic which is modulus of, let us say, 300 GPa, and let us say volume fraction of polymer is 80 percent and volume fraction of ceramic is 20 percent. Now let us see what is the modulus and this is, let us say, first is the iso-strain condition. Assuming that it is iso-strain condition, we get Ec is equal to V1E1 plus V2E2 and this is 0.8 into 2 plus 0.2 into 300. So you can see that this is, sorry, 1.6 plus we will get 60. So this will be 61.6 GPa.

You can see this value is much higher than the value of ceramic. So you can see that the modulus of, modulus of elasticity of composite has significantly improved and so it is anywhere closer to let us say aluminium, very close to aluminum, approaching aluminum value of, aluminium value of modulus elasticity.

If you look at the values for iso-stress condition, then we can see there is 1 over E is equal to V1 over E1 plus V2 over E2. So E will be equal to, essentially, E1 into E2 divided by V1 E1 plus, sorry, V1 E2 plus V2 E1. So you can see that this is 300 multiplied by 2 and this is divided by 0.8 into 300 plus 0.2 into 2. So this is 600 divided by 240 plus 0.4. So essentially it is almost equal to 600 divided by 240, which is nothing but 5 divided by 2, which is nothing but 2.5 GPa.

So you can see that there are different configurations lead to different increase in the value. So if you have iso-strain condition, under those conditions the increase in modulus will be substantial. Whereas, for iso-stress condition, the increase in modulus will be marginal or moderate, depending upon the volume fraction and values of modulus is. So this is how you can design composites by mixing two materials of different elastic properties and achieving a value, which is higher than the lower of one of the, lower phase, a lower value phase.

What this can also, what you can also do is that you can also calculate the net specific, net density of the material. Since polymers and ceramics have, polymers, of course, are lighter, ceramics are little heavier, so you can calculate the net density of the material and then look at the, what is the value of a specific modulus, that is modulus per unit weight or modulus per unit density you can calculate.

So one can also convert this into specific modulus, which is modulus per unit weight. So we will finish this discussion on composites here. The idea was to tell you that if you have these materials with contrasting properties, how can you mix and match things.

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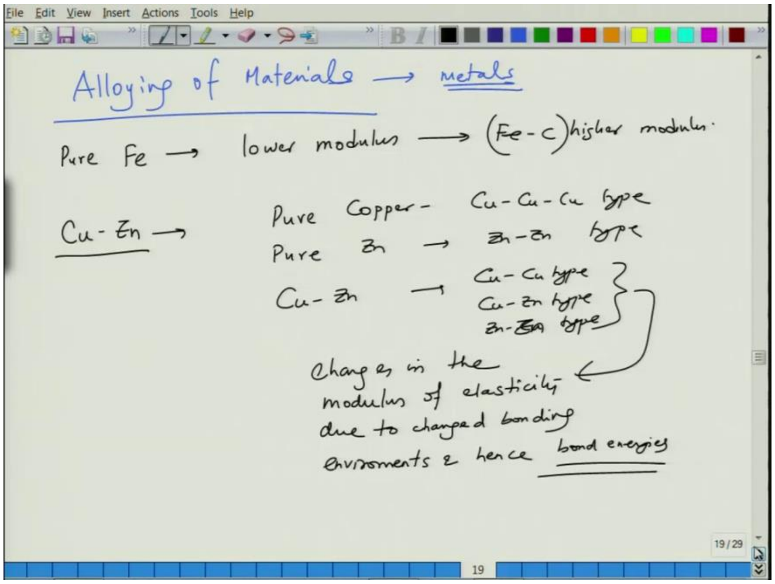

Alloying of Materials → metals

Pure Fe → lower modulus → (Fe - C) higher modulus.

Cu - Zn →
Pure Copper - Cu - Cu - Cu type
Pure Zn → Zn - Zn type
Cu - Zn → Cu - Cu type, Cu - Zn type, Zn - Zn type

changes in the modulus of elasticity due to changed bonding envirnoments & hence bond energies

There are other factors which also leads to change, lead to change in the modulus. The other factors are, you can also change the modulus by alloying. And this is generally something which is done with the metals, metals and alloys. So, essentially, so, the best example you can see is the, is iron itself. So you have pure iron, which has lower modulus as compared to iron carbon, which has higher modulus. But this is mainly because, mainly because of formation of hard phase which is the iron carbide phase, as I showed you here. So, hang on, this is the iron carbide phase which is harder.

Now you can increase the modulus again without making the hard phase that is, if you look at, for example, of copper zinc. So you have pure copper where the bonds of are copper-copper type, you have pure zinc, where bonds are of zinc-zinc type, but if you have Cu-Zn, you may have bonds of copper-copper type, you may have bonds of Cu-Zn type, and you may have bonds of Zn-Zn type.

So these three different bonds will have three different bonding properties as a result bond energies and this will lead to changes in the, changes in the modulus of elasticity due to changed bonding environments and hence bond energies. So this will show, so, for instance, there is a possibility that when you mix these elements together, sometimes mixing of these elements lead to formation of, as we saw structure of materials, in the structure of materials course, that sometimes these elements can form intermetallics.

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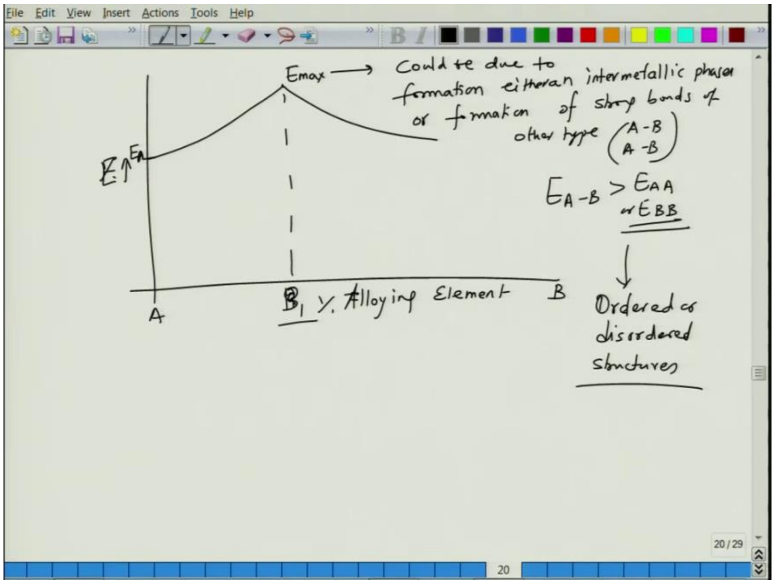

Emax → Could be due to formation either an intermetallic phases or formation of strong bonds of other type (A-B A-B)

$E_{A-B} > E_{AA}$ or E_{BB}

↓

Ordered or disordered structures

So when they form intermetallics, so suppose when you mix elastic modulus as a function of, let us say, this is modulus of elasticity, this is percentage, let us say, alloying. So, let us say, you have A and you are mixing B, there is a possibility that you start with EA, you may increase the value of E at certain point then decrease. So this EA, E max, so this is let us say B1, this is E max. This could be due to either an intermetallic phase, which is stronger or formation of strong bonds of other type that is more A-B, A-B bonds than A-A or B-B bonds.

So A, if A-B bond, if E A-B is larger than E A-A or E B-B then naturally when you have a certain combination of A and B when there will be more A-B bonds you will have and this will also depend upon whether you form ordered structures or disordered structures. So ordered or disordered structures.

So basically what I wanted to point out is alloying is intentionally done to change the bonding environment in the materials, which can also lead to sometimes formation of different phases, which are stronger, as a result you may have changes in the modulus of elasticity of materials. So this is one thing that is done.

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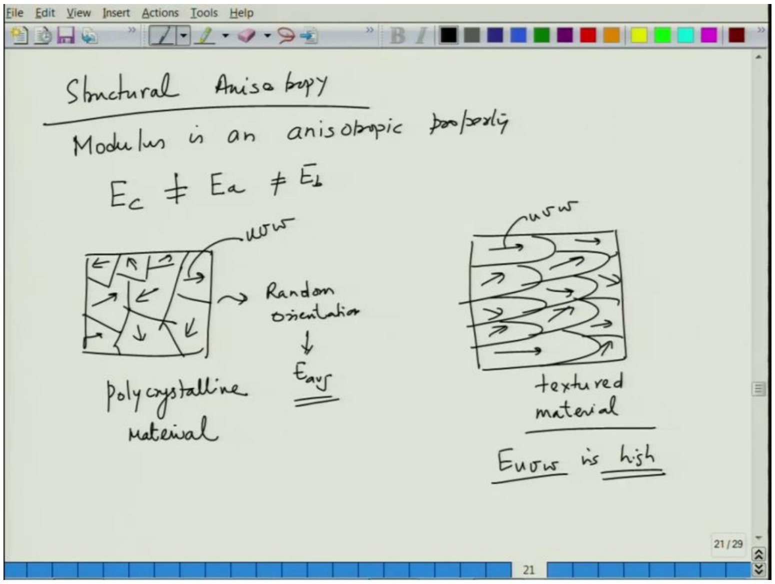

Structural Anisotropy

Modulus is an anisotropic property

$E_c \neq E_a \neq E_b$

Random orientation

$\downarrow$

E_{avg}

E_{uvw} is high

Second thing is structural anisotropy. So because modulus is a, modulus is an anisotropic properties, property, so E let us say along c could be different than a than b. So what you may do is that, let us, so if you have, let us say, a polycrystalline material in which all the grains have random orientation. So let us say u v w some, some direction. So, let us say, this is random orientation. So this is some direction u v w.

So, random orientation will mean that you will have E average. However, let us say, if you are able to align these grains in such a manner so that, and this is what u v w is like. So, this is u v w. So this is basically you can say it is a textured material. And if u, if Euvw along that direction is high, then obviously, you will get high modulus at least in this direction for the material.

So you can create this structural anisotropy by creating these micro structures, which will lead to material having different properties around different directions and you can engineer them to your advantage. So this is what is the overall discussion on atomic models of elasticity is.

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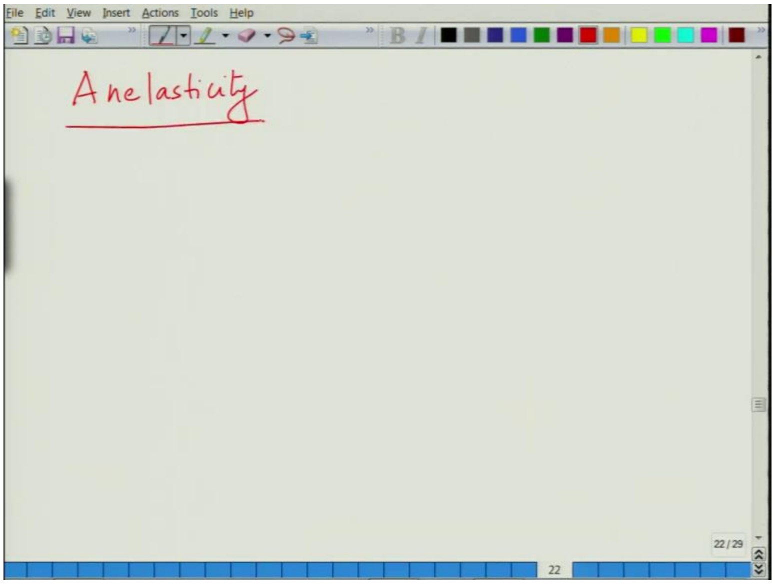
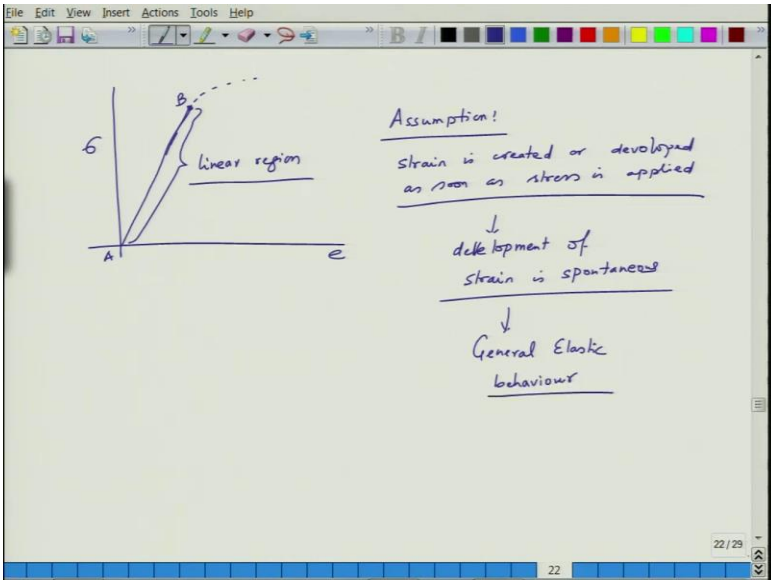

Anelasticity



Assumption:

strain is created or developed as soon as stress is applied

↓

development of strain is spontaneous

↓

General Elastic behaviour

Now what we will do is that we will move on to the next part, which is, next part of elastic behavior of materials is basically anelasticity.

So let me just briefly recap what we have done up to this point. We have looked at the modulus of elasticity using Hooke’s Law. And then we also looked at sort of simple model to, simple relation between elastic properties to work out how the shear modulus, elastic modulus, bulk modulus are related to each other and the poisson’s ratio.

And then we looked at the atomic model of modulus. How modulus is related to the equilibrium separation and the bonding, and how strong and how low energy and lower bond energy and higher bond energy materials have different modulus. How can you tailor the modulus by doing alloying and texturing? How can you make materials such as composites, where you can mix and match two different materials to achieve a modulus which is higher than the lower phases modulus, and so on and so forth.

So now what we are going to look as, look at the phenomenon of anelasticity in materials, which is, which occurs in certain classes of materials and we need to understand how does it do. So basically what happens is that, what we have seen until now is. So let me just rub this first, so what we have seen until now is when you have stress strain, when you apply this stress, so this is the linear region, and before it converts into a, now up to this point we have, so let us say this is A, this is B, so this is the linear region and here we have assumed that, so assumption was that strain is created or developed as soon as stress is applied.

So basically we are saying that development of strain is spontaneous. So we are saying that it is. So this is a general elastic behavior that we observe or that we talk about. So, let us say, this is general elastic behavior that we generally talk about.

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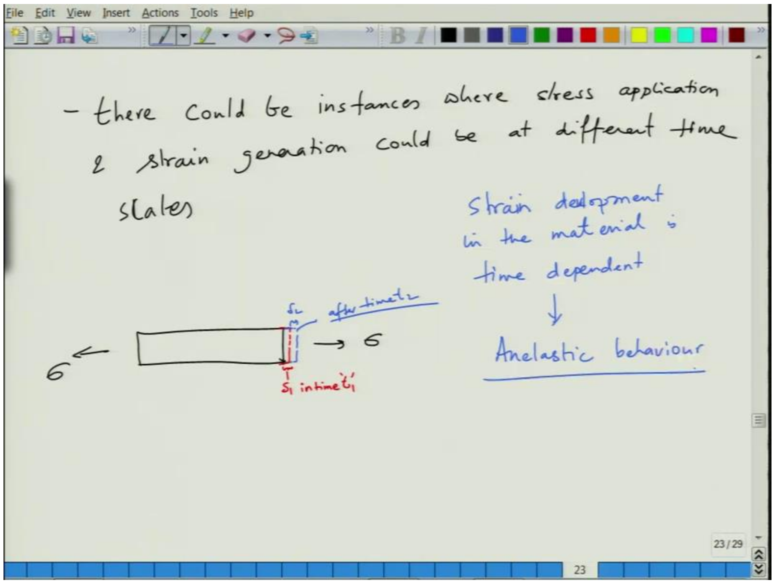

- there could be instances where stress application & strain generation could be at different time scales

Strain development in the material is time dependent
↓
Anelastic behaviour

However, there are instances where stress application and strain generation could be at different time scales. So essentially let us say you apply, this is a material, you apply stress to it, sigma.

The material increases to certain length. So, let us say, this is delta 1 in time t1 and then you stop loading, then you stop increasing the stress, the material further extends to this magnitude delta 2 after time t2. And as you release the load, depending upon the release rate of the load, this strain reverses to 0 strain situation in certain time.

So basically what we are saying is that the strain that develops in the material is not spontaneous. It depends upon the rate at which you apply the load. So essentially what we are saying is that the strain development in the material is time dependent.

So if you apply stress very fast, it does not develop to the value, to the maximum value and if you immediately release the load, you do not achieve the full strain. So basically strain development in the material is time dependent and this is called as anelastic behavior. So we will see that what it is in a little more details in next few minutes.

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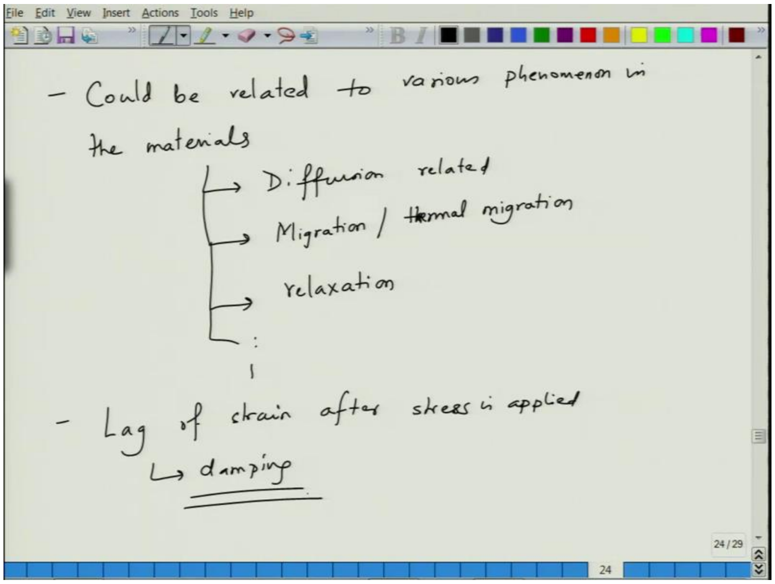

- Could be related to various phenomenon in the materials
  - ↳ Diffusion related
  - ↳ Migration / thermal migration
  - ↳ relaxation
  - ⋮
- Lag of strain after stress is applied
  - ↳ damping

So basically we are saying that a strain does not develop in the material at the same time when the stress is applied. And this could be related to various phenomena in the material. And these phenomena could be diffusion related, it could be related to, let us say, migration, thermal migration let us say, and then it could be related to, it could also be related to let us say relaxation and so on and so forth.

So basically you can say that is in most cases what we observe is what is lag of strain after stress is applied and this also leads to a phenomenon of as we see is called as damping. So damping in materials is mainly because of lag of strain after stress is applied.

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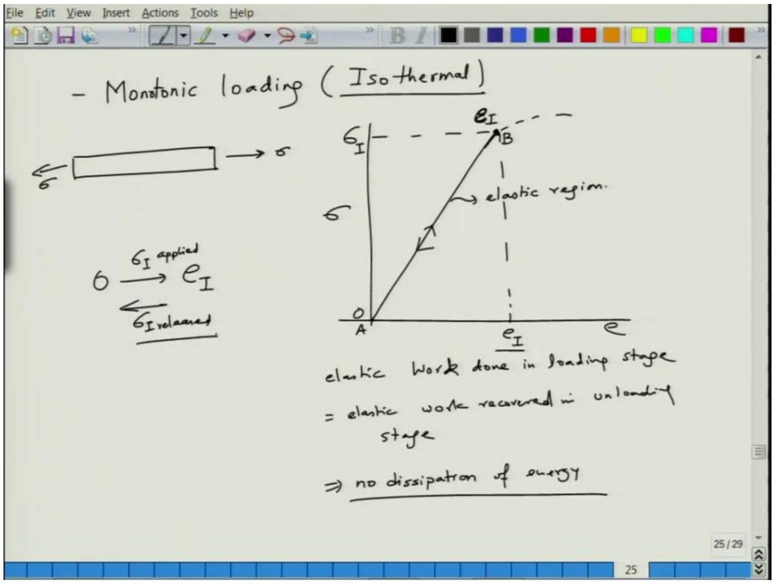

- Monotonic loading (Isothermal)

elastic work done in loading stage

= elastic work recovered in unloading stage

⇒ no dissipation of energy

So what happens generally is when you apply monotonic loading, let us say, and monotonic loading is let us say isothermal. So isothermal means the sample temperature, so this is the sample, you apply stress, you apply stress such that the temperature of the sample does not change. So this is you increase the stress without change in the sample's temperature in that case, when you apply stress versus, so if you plot stress versus strain, it follows up to certain point, let us say, from A to B. This is the elastic region. So this is the increase in stress.

So this is the sort of start of plastic point and when you release it, you come back along the same path. So this process is isothermal and there is no dissipation of any energy whatsoever. So whatever is the work done in the loading stage, so work done in loading stage or let us say elastic work not word. Now loading stage is equal to elastic work recovered in unloading stage. So that is, there is no dissipation of energy. That is what it means here.

Now what happens in case of anelastic behavior is and this basically the strain is completely recovered. So you go from 0 to let us say epsilon or eI. So this is let us say sigma 1, sigma I and this is eI. So you go to eI from 0 to eI, sigma 1, sigma I, and then you come back to so sigma I applied, sigma I released.

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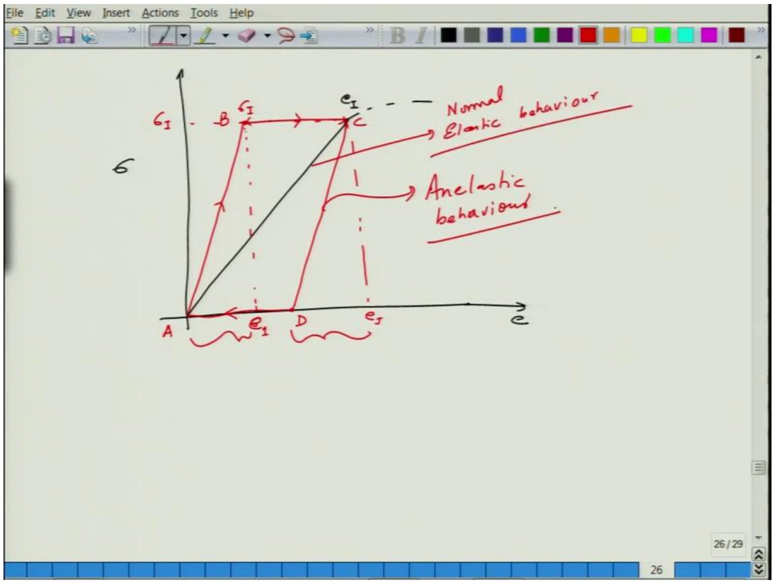

However, what might happen in the materials is that, so this is the isothermal behavior, let us say, let us keep this as our benchmark and this is eI. What might happen in material is, let us say, if you strain the material in such a manner, so that, let me just use a different color maybe, so let us say, this is the stress, sigma I, eI.

So, let us say, if I strain it like this, this is sigma I, I do not go up to the whole value of strain. I go to up to a value of, let us say, e1, and then I have to leave for certain time to achieve this strain, then again when I drop the stress at the same rate, and the rate which is shown here. So this is one, this is A, B, C, D. So I go from A to B. I do not achieve this strain even.

So I have to wait for some time to let the strain be achieved to eI because that is the isothermal strain. And then from this point C, I drop the stress back to 0 level coming to point D. Again the strain which is released during this point is this much amount of strain, which is similar to this strain roughly and then from this, from this point to that point again you have to wait for the material to come back to 0 strain.

So this is basically is related to change in the temperature of material. And as we will see in the next lecture, how does this, what are the mechanisms and processes responsible for giving this kind of behavior. So this is essentially you can say is the anelastic behavior. And this is you can say is the normal elastic behavior. And we will see the microscopic mechanism and thermodynamic reasoning behind it in the next class.

So what we have done in this lecture is we have looked at an example of how do you develop, design a composite with different properties by mixing the two materials and then we have started our discussion about, and then we also saw how can you change the modulus of materials by alloying materials with different elements or by texturing, by creating grains of different configurations to give rise to materials with different modulus'.

And then we have initiated our discussion on anelastic behavior in materials, which is basically about development of strain after the stress is applied in a certain period of time. So it depends upon the rate at which you apply the stress and strain lags the stress basically. It is like current plugging the voltage in case of dielectrics. Here you can say the strain lags the stress in these materials after you apply the stress. So strain development is not spontaneous, it needs some time. And we will see those microscopic understanding in the next lecture. Thank you very much.