# Properties of Materials (Nature and Properties of Materials: III)
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## Lecture 14
## Mechanism of anelasticity

So welcome again to the new lecture of the course, Properties of Materials. Let us just briefly first recap what we did in the last lecture.

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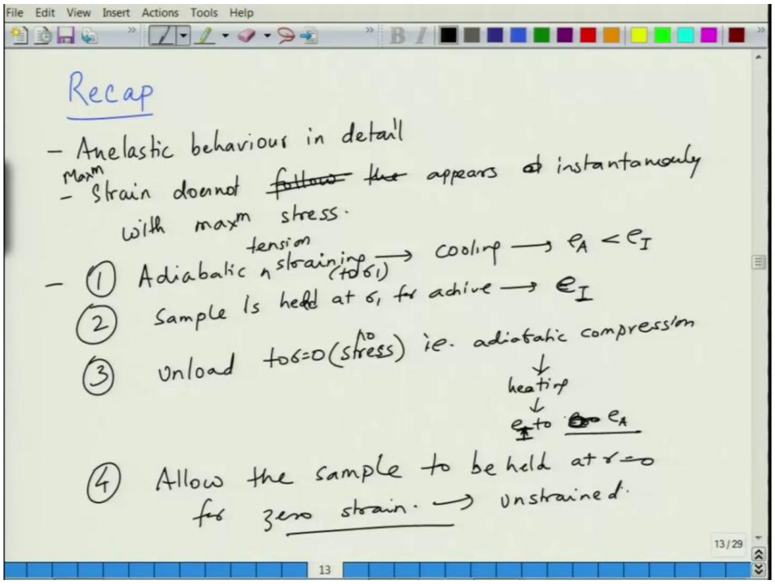

Recap

- Anelastic behaviour in detail
- Max$^m$ Strain doesnot ~~follow~~ ~~the~~ appears ~~at~~ instantanouly with max$^m$ stress.
- ① Adiabatic tension straining (to $\sigma_1$) → cooling → $e_A < e_I$

② Sample is held at $\sigma_1$ for achive → $e_I$

③ Unload to $\sigma = 0$ (no stress) ie. adiabatic compression ↓ heating ↓ $e_I$ to $e_A$

④ Allow the sample to be held at $\sigma = 0$ for zero strain. → unstrained.

So in the last lecture we looked at the anelastic behavior in detail. So, essentially, when you do anelasticity generally occurs when a strain does not follow the, so maximum strain essentially does not appear instantaneous with maximum stress.

So what happens is that when you apply, let us say, stress very fast in the beginning, then the first step that occurs is you have adiabatic straining. So, let us say, if it is tensile then it leads to cooling down for crystalline materials. And then you basically allow the sample to, sample is held, so to sigma 1, held at sigma 1 to achieve, so eI. So the first you achieve eA, which is smaller than eI, and you wait for some time at sigma 1 for sigma I to be, eI to be achieved.

And then you unload to 0 stress, no stress, that is basically adiabatic compression. This will lead to sample heating and again eA, eI will drop to a value eI minus eA or drop by the value eA. And then, again, you will have to allow the sample to be held at sigma is equal to 0 for 0 strain to appear, sample to become unstrained. So basically this is the process which gives rise to a hysteresis.

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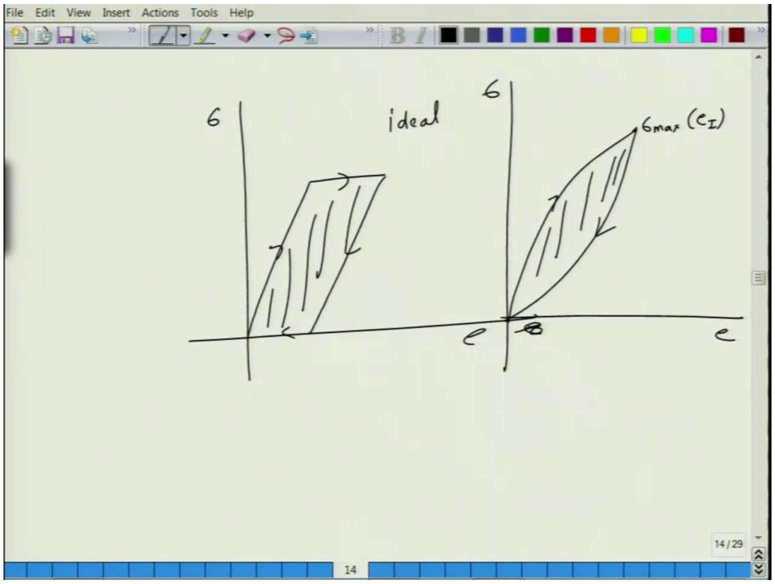

So what we see is that this kind of hysteresis. In ideal world, you will see something like this. So there will be some energy dissipated. But in reality, what we see is that. So this is ideal we are talking about. In reality, what we see is something like this. So this is sigma max, correspondingly you have eI and then this is the energy that is dissipated in the process of straining and deep straining, loading unloading.

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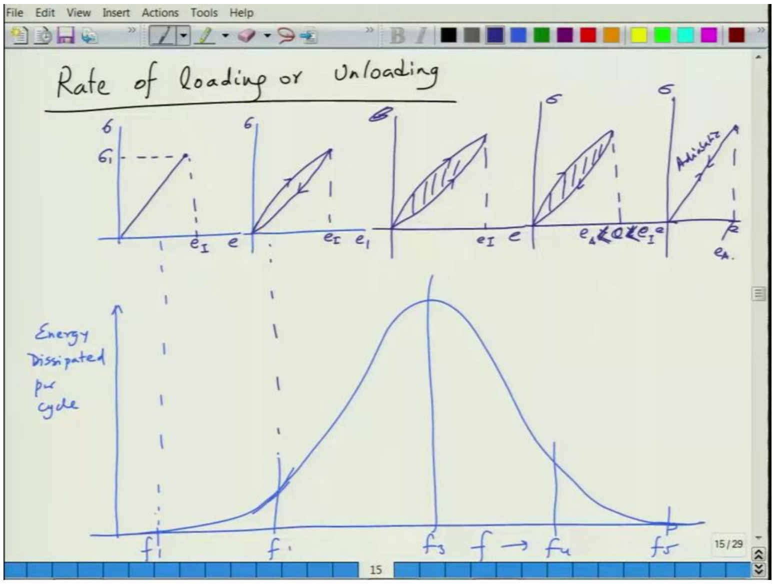

And so this energy which is dissipated is essentially now dependent upon the rate of loading, dependent upon the rate of loading and unloading. The energy dissipated shows a behavior which is something like this. So when you plot energy dissipated, let us say, per cycle and as a function of frequency f, it has a behavior which is something like this.

So let us say we take different regimes f1, let us say f2, this is f3, f4, and this is f5. So at very low frequency, when you strain the sample at very low frequency, what might happen is that the sample will achieve the requisite strain in an isothermal manner, because sample has sufficient time to equilibrate with the surroundings. So you are achieving sigma 1 and eI. So this is eI.

Now when you go to this particular region, let us say, and when you again plot this at slightly higher frequency, so at slightly higher frequency what might happen is that, your loading rate is faster. So as a result, strain is not able to keep up with the stress. So as a result, you will obtain certain amount of hysteresis and you will reach this strain.

When you go to very high values of frequency, higher values of frequency, then you might reach a state which is. So in all these cases the strain achieved is eI. So you go to eI and your hysteresis increases. So this leads to maximum energy.

Now when you go to even higher frequencies, then what happens is that, you are not letting the sample to equilibrate at the rate you would like to. So basically what will happen is that, your initial cycle will take you to a strain, it will go to a little bit higher strain and then it will come down. So your hysteresis will be something like this. So let me just redraw this plot, so essentially the strain will be lower than eI, but higher than adiabatic strain, lower than eI, but higher than adiabatic strain.

And when you go to very fast rates, so this is sigma, e, sigma, e, sigma, e, then basically the strain does not, you are straining it very fast, so basically you have no time for equilibration. So basically this process as well as this process is adiabatic, both are adiabatic. You have no gap left for any equilibration to occur. So as a result, you will achieve a strain which is only adiabatic strain. There is no relaxation strain that you will obtain since it is very fast.

So on one hand, at low frequency, the sample equilibrates with the surroundings very easily. As a result, you are able to achieve full strain. So you are going to achieve full strain here. At very fast rates, sample is not able to equilibrate at all with the surroundings. So both the processes loading and unloading are adiabatic, but the strain that you obtain is lower. So, in this case, you are obtaining a strain eA. At moderately high strain, you will obtain the isothermal strain, but with a bit of hysteresis.

When you have a little bit higher strain, where you have maximum energy dissipated, will again reach eI, that is isothermal strain, but with larger energy dissipated, but when you go further beyond this, you sort of allow less time for sample to thermally equilibrate after you have reached adiabatic strain and hence your strain that you, maximum strain that you get out of sample reduces, eventually it becomes only the adiabatic strain. So this is what the behavior of energy dissipated as a function of frequency of loading and unloading is.

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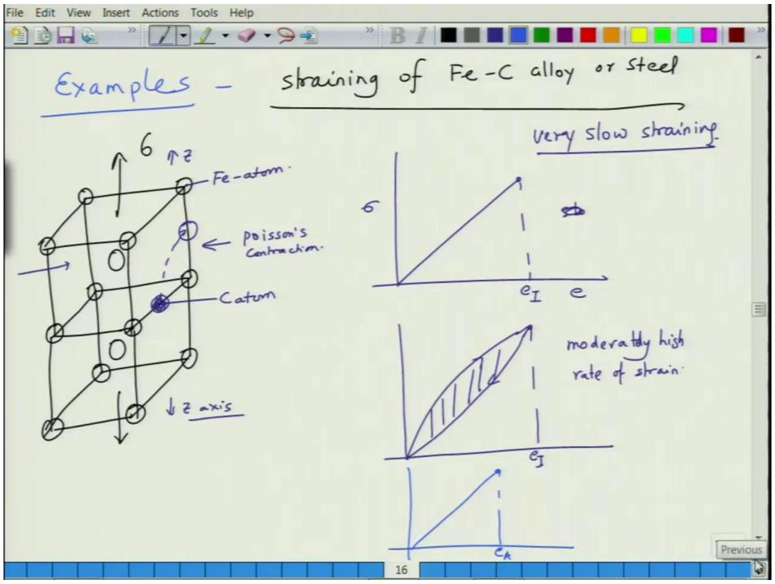

Examples – straining of Fe-C alloy or Steel

So one of the examples one can take is straining of iron, iron-carbon alloy or steel, let us say. Now steel, as we know, it has a BCC structure. So if I make the structure of steel, something like this, so this is the steel sample that we have. When you apply stress, let us say, along this axis, we also have a small carbon atom sitting at certain locations.

Now when you apply strain, so this is carbon atom and this is iron atom. So when you apply, let us say, strain along the axis which is shown, then in this direction you will have poisson's contraction. So which means this can only elongate in this, so let us say, if this is z axis, you can only elongate along z axis. If you are able to move this carbon atom out of the way to another position along the z axis so that it has a space to go to a place, empty place along z axis, but at the same time, it also allows the other direction to contract, otherwise it would not happen because the carbon atom is quite big as compared to the space that is available.

So essentially what happens is that this is again a function of loading rate. So this carbon atom will have to be jumped to another position, interstitial position, let us say, this position, when you do the straining, and that is dependent upon the rate of loading.

So if you do very slow straining and unstraining, then carbon atom has sufficient time to move from this position to that position and you are able to obtain a curve which is like this and you able to obtain the strain which is eI.

However, if you are able to, if you are at a rate of loading and unloading which is faster than this, so this is slow and moderately high, so you might obtain a behavior something like that. So you may still reach the value eI, but with a hysteresis. You can say this is moderately high rate of straining, because then you have to wait for carbon atom to move to this position before you completely achieve the isothermal strain. So that will require for some time. So as a result, the strain will lag the stress.

And of course, when you go to higher rates, then at higher rates, what will happen is that, at even higher rates, you will eventually have this kind of behavior, where you may end up with the strain which is eA, because you have no time for this carbon atom to jump to this position. So you will obtain only adiabatic strain, not the. So this is what happens in alloys in which you have various, so iron-carbon alloys is alloys are interstitial, carbon is interstitial impurity, but this can happen in other systems as well.

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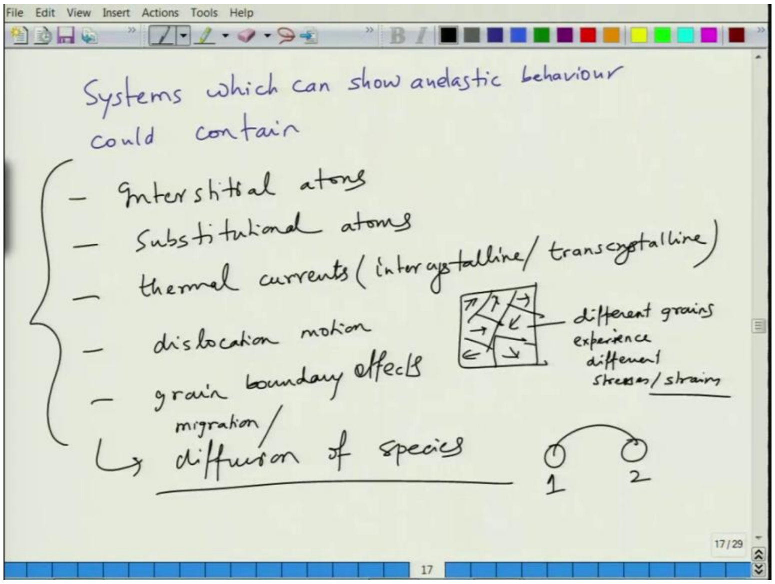

Systems which can show anelastic behaviour could contain

- Interstitial atoms
- Substitutional atoms
- thermal currents (intercrystalline/ transcrystalline)
- dislocation motion
- grain boundary effects

↳ migration/ diffusion of species

different grains experience different stresses/strains

So systems which can show, they could contain things like interstitial atoms, it could be also substitutional atoms, it could be also related to thermal currents inside the material. So it could be intercrystalline or transcrystalline currents. Basically what it means is that, if you have a polycrystalline structure then since different orientations are there, different grains are deformed differently, stresses and strains and as a result their temperatures could be different.

So then temperatures need to equilibrate. So you can have thermal currents. You can also have dislocations which can move, so dislocation motion and you can have grain boundary effects. All of these effects are basically, all of these things they require diffusion, basically diffusion of a species from one place to another, diffusion or migration.

So which means it is basically, so you have one atom going to another position. So this is one position, this is second position. So when you take the one atom from another position, you are basically performing some sort of work and this process is essentially a thermally activated process.

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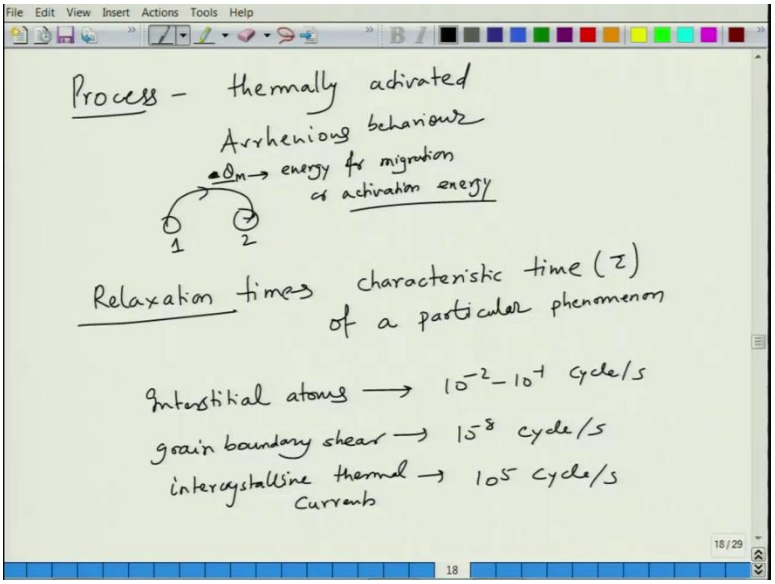

Process - thermally activated

Arrhenious behaviour

$Q_m \rightarrow$ energy for migration

or activation energy

Relaxation times characteristic time ($\tau$) of a particular phenomenon

Interstitial atoms $\longrightarrow$ $10^{-2}-10^{-1}$ cycle/s

grain boundary shear $\longrightarrow$ $15^{8}$ cycle/s

intercrystalline thermal currents $\rightarrow$ 105 cycle/s

So basically it is a process which is thermally activated and it is well represented by Arrhenius behavior. So you go from one to another place. So you require some energy delta Q, a Q, which is let us say Qm, the energy for migration or let us say activation energy.

So it becomes easier, the process of migration of atoms or species, it becomes easier when you increase the temperature or when you apply, give them more time. So this is depicted by a quantity called as relaxation time, when the relaxation time. So this is basically a characteristic time of a particular phenomenon. So it could be interstitial migration, it could be substitutional migration, it could be thermal migration, it could be dislocation, whatever it is, there is a characteristic time tau which is, which belongs to a particular phenomenon and there are different time scales for various things.

So, for example, if you look at interstitial atoms, for them the timescale is 10 to power minus 2 to 10 to power minus 1 cycle per second. If you look at, for example, grain boundary shear that operates at a time which is 10 to power minus 8 cycles per second.

But if you look at intercrystalline thermal currents, because of temperature differences, they work at a time scale of 10 to power 5 cycles per second. So these have different time scales. So relaxation time is a quantity, which is basically the average time that is needed to go from one state to another state for a given process of diffusion or for a given phenomenon.

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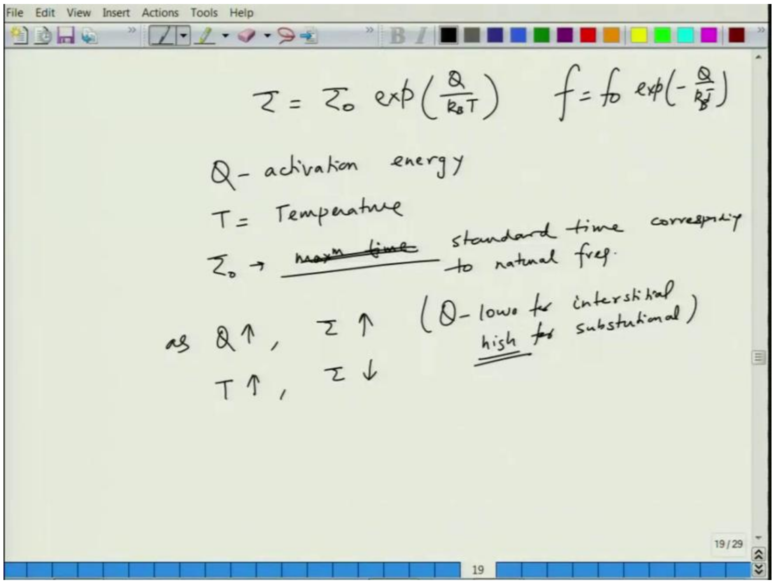

$\tau = \tau_0 \exp\left(\frac{Q}{k_B T}\right)$ $f = f_0 \exp\left(-\frac{Q}{k_B T}\right)$

Q - activation energy

T = Temperature

$\tau_0 \rightarrow$ ~~max^m time~~ standard time corresponding to natural freq.

as $Q \uparrow$, $\tau \uparrow$ (Q - lower for interstitial, high for substitutional)

$T \uparrow$, $\tau \downarrow$

And this relaxation time, tau, is given as tau naught into exponential of Q divided by KBT. So Q here is activation energy, T is the temperature and tau naught you can say is the, some standard time or you can say corresponding to natural frequency of vibration or whatever. So tau naught is a standard time natural frequency of vibration of a particular specie.

So you can see that as Q increases, tau will increase, as temperature increases, tau will decrease. Q increases means the activation energy goes up, which mean the process is difficult. For interstitial atom, the Q will be lower, but for a substitutional atom the Q will be higher. So Q is low for interstitial, but high for substitutional. This is because, interstitial atoms are smaller, they do not need to dilate the lattice as much as substitutional atom would have to. As a result, you will require higher time, you will have to operate at lower frequency for, because if you do the frequency transform, this will be f naught exponential of minus Q by KT.

So essentially you will have to operate at lower frequencies for bigger atoms. Similarly, we increase the temperature, the tau decreases because temperature will increase the mobility and hence your atoms will be diffusing faster at higher temperatures. So this is basically the phenomenon of relaxation that occurs in the materials showing with regard to anelasticity.

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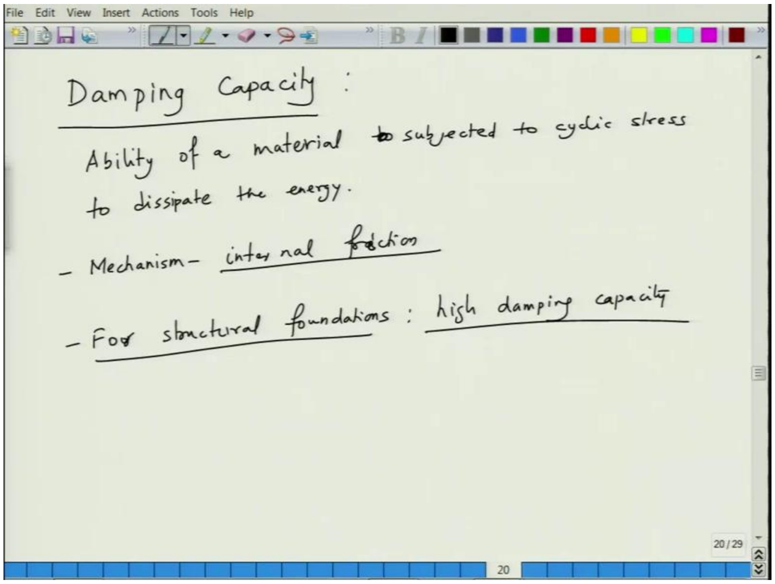

Damping Capacity :

Ability of a material ~~to~~ subjected to cyclic stress to dissipate the energy.

- Mechanism - internal friction

- For structural foundations : high damping capacity

So the next thing in this anelastic, since you have energy dissipated, you can define a term which is called as damping capacity. And this damping capacity is basically corresponds to ability of a material which is under subjected to cyclic stress to dissipate the energy and this happens via mechanism. So mechanisms could be, for example, internal friction.

So basically damping capacity would be how much, when you apply a material, let us say, a building structure or a structural, any structural application where you have these vibrating or cyclic stresses, how much the material dissipates the energy as the damping capacity. So especially for foundations and things like that for structural foundations, you would not want them to permanently deform, you would just want them to have high damping capacity.

So basically you would like them to absorb the stresses in such a fashion so that more energy is dissipated. So that building is not affected. So any application where you require energy to be absorbed or dissipated, you would require materials or you would require compositions which can give you high damping capacity.

So this is what it is we have done in this class. We have looked at the phenomenon of anelasticity in terms of rate of loading and unloading. We see that when the frequency is very low, then you are able to achieve the isothermal strain. When the frequency is very high, you do not, you basically have adiabatic contraction or expansion and then all you are able to achieve is the adiabatic strain, which is lower than the isothermal strain.

And at intermediate frequencies, you go to higher strains. So if you, but there is a maximum, there is a critical frequency at which you are able to obtain the maximum strain of eI, but also with maximum energy dissipated the process and the time corresponding to this frequency is called as relaxation time. So this peak basically corresponds to tau that is the relaxation time.

And then we also looked at the example in terms of iron, how the motion of carbon atom is related to the phenomenon of anelasticity and then there are other things like substitutional atoms, thermal currents, dislocation motion which also show similar behavior. And since this is all related to process to Arrhenius kind of thermally activated behavior where relaxation time is a function of activation energy as well as temperature.

So this is what we have done in this class and the lastly we introduced the term damping capacity. We will look at this in detail in the next lecture. Thank you very much.