Smart Structures
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Week 06
Lecture No: 44

Stress-strain Curve at Low Temperature, Pseudoelastic, Two-way Shape Memory Effect

Part 04

Today, we look into stress strain behavior of shape memory alloys at various temperatures, at low temperature and at high temperature.

So, we will start with low temperature behavior. Now, again we are familiar with this diagram, the characteristic temperatures for shape memory alloys vary with stresses and this is M_f, M_s, A_s and A_f. And we know that in this region, it is martensite, in this region it is austenite. So, here by low temperature behavior means, when the temperature is below the martensite finish region, which means we will start from here. So, at this region at 0 stress, and when the temperature is below martensite, the material is in twinned martensite phase.

So, we will start from here, we will load it, and then we will unload it, and then we will see how the material behaves. So, below this we will draw the stress strain diagram. So, this is stress and this is strain. So, as we keep loading the material, the stress strain diagram initially looks like this, initially it is linear elastic. So, it is linear elastic because if you unload it comes back to where it started.

Now, as we know that after some value of stress the material starts transforming to detwinned martensite. So, here the slope of the material becomes very bare minimum, it is quite low. And after the slipping ends, the detwinned martensite again shows some elastic behavior. And then after that slipping takes place, and again we see a plastic behavior. So, if we call this as our zone 1. So, in zone 1, we have linear elastic behavior and this is in the twinned state. This entire study is being done below M_f and that is what we mean by low temperature. Then we can call this as zone 2. So, this we can call zone 2. So, zone 2 plastic behavior, this is because of detwinning. So, the twinned martensite starts detwinning. So, the detwinning starts here and and the detwinning finish here. So, we can see that this is sigma critical start. This is sigma critical finish. So, this is the stress at which detwinning starts. This is the stress at which detwinning ends. Now, if we load it beyond this then the detwinned martensite shows a linear stress strain behavior. So, again linear behavior after detwinning, and slope same as 1. So, slope here and here are almost same. Now, this shows a linear behavior up to some range. Then beyond this the material starts slipping and the behavior is again plastic. So, we can call this as zone 4 and plastic deformation due to slip.

Again we started from here, the material was initially linear elastic which is this. Then after some time, the material crosses sigma cr s, and till sigma cr f, the detwinning takes place and within this, the slope is very less. After that it is already detwinned and the behavior is linearly elastic. And then beyond some stress, slipping takes place. So, maybe we can call it sigma cr, cr with sl, sl starts from slipping. So, beyond this slipping takes place and that is what is shown here.

Now, we will see if we start unloading at various points, how the material behaves. Or, if we vary the temperature at various phases, how the behavior looks like.

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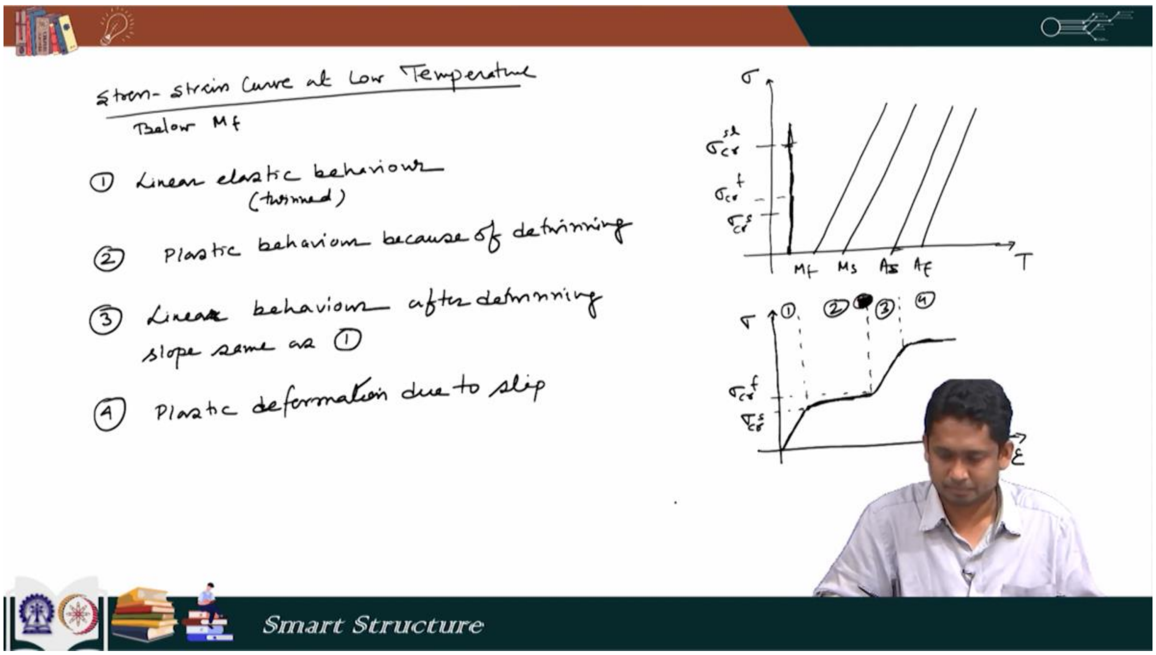

So, now we will draw another diagram, and in this diagram, apart from stress and strain, we will have temperature as well. So, we have stress here, we have strain here, and we have temperature here, and along this line the stress is 0. So, we have martensite finish, martensite start, austenite start and austenite finish. Now, when the temperature is below M_f, we have the low temperature stress strain behavior that we drew just now. Same diagram.

Now, see we are increasing the stress and then we have point A here, and we have point B here. So, point A slipping, not slipping, it is detwinning. At point A, detweening starts, at point B, detwinning ends. Now, before detwinning when the material is linear, if we unload it, it follows the same path and it becomes 0. In between A and B, when the detwinning takes place, suppose here, if we unload it, then it follows this path. It does not come to the 0 strain, rather it goes down from here, and a permanent deformation remains here. Now, again this deformation is not permanent, if we heat it up, the material becomes austenite and the deformation becomes 0. Till B, we get the same behavior because till B the slipping takes place. And B also, if you unload it, it unloads in the same fashion. Now, from here if we suppose increase the temperature, the material is martensite. So, till A_s, it remains like this. After A_s, the transformation takes place and the material becomes austenite. Once it becomes austenite, it regains its original shape due to the shape memory effect.

Same thing happens here. So, here it was fully detwinned, here it was partially detwinned. On being unloaded, some amount of strain remained and then on being heated it transformed to austenite and it regained its original shape. Now, suppose if I load it further, it goes till a point C, and point C is a point where slipping starts taking place. So, onset of slipping. In between B and C, as we saw that its linear and the slope is same. So, slope between O and A, and slope between B and C is same. So, here in between B and C, if at any point if I unload, it follows the same path and it comes back here. Now, this amount of strain, let us call it epsilon p. So, the epsilon p is the strain which is the maximum strain which can be recovered. So, epsilon p maximum strain that can be recovered.

Now, after slipping, if we keep loading it, after sometime, the material fails. Now, if we unload it from here before failing, it takes this route and then, it is if I increase the temperature, it does not come back totally here. So, if I increase the temperature after A_s, some transformation takes place, but it does not go back to where it started. So, if I show you by a different color. So, it goes back to somewhere here. Now, this is the amount of strain that is shown here that cannot be recovered and let us call that as may be epsilon p u. So, epsilon p u cannot be recovered fully. So, if we load it beyond slipping, then on unloading and even after heating we cannot recover the entire strain. So, some amount of permanent deformation remains in the material and maybe we can call this as O dash. So, O dash the strain that remains remaining unrecovered strain.

Now, let us imagine that we are at B after loading we are at B. Now, from B instead of unloading, let us say that we are increasing the temperature of the material. So, again if we draw the previous diagram showing stress temperature, this is what it is. Now, when we are at B, that means, we are somewhere here, the initially the temperature is below M_f and the material has already de twined. So, stress is relatively higher. Now from here, the material is fully martensite. So, if I look at the xi versus T diagram at this level, it would look like this. So, this is our xi versus T diagram. So, xi versus T at sigma corresponding to B. From here, if we start increasing the temperature, it takes this root which means the xi follows this path. Initially xi was 1 because it was martensite and then it follows this. So, the temperature increases. Once it is in this region, the temperature increases and our xi decreases. And once it crosses this here it becomes 0. So, it becomes fully austenite.

So, starting from B, if I increase the temperature, the material becomes austenite and once the material becomes austenite, its elastic modulus increases austenite phase has higher elastic modulus than the martensite phase. So, the slope of the stress strain diagram here increases. So, the strain value changes because the stress remains same, but the young modulus increases. So, the stress reduces. Now, from here, if I again reduce my temperature, it will follow this path and it will become martensite. So, again it will become stress induced martensite and it will get the same strain, which it had before. Now, once the material is austenite, if I unload it. So, now, from here, so, initially we started from here, we followed this path. Now, suppose if I want to go to this side by unloading, then the material will still remain austenite. So, no more change to take place.

However, instead of doing that; so remains austenite. However, if I reverse the temperature from here as we discussed, then the material becomes again a stress induced martensite and the stress strain, I mean, stress this point B again is achieved. So, the stress and corresponding strain remains of this amount. Now, from here, once it has become stress induced martensite, I can unload it. And if I unload it, it will again follow the same path path and it will show some amount of remaining strain, like it is shown here epsilon p, and then on heating from here. So, if I unload it from here, it will come back here, and then by heating, I can go here and the material becomes again undeformed.

So, we can take different paths from a certain position in this diagram and accordingly the material behavior will change. We can we could directly unload and then heat it up. We can heat it up and again cool it down and unload, and accordingly as per these two diagrams, the material behavior will change. Next we will talk about –

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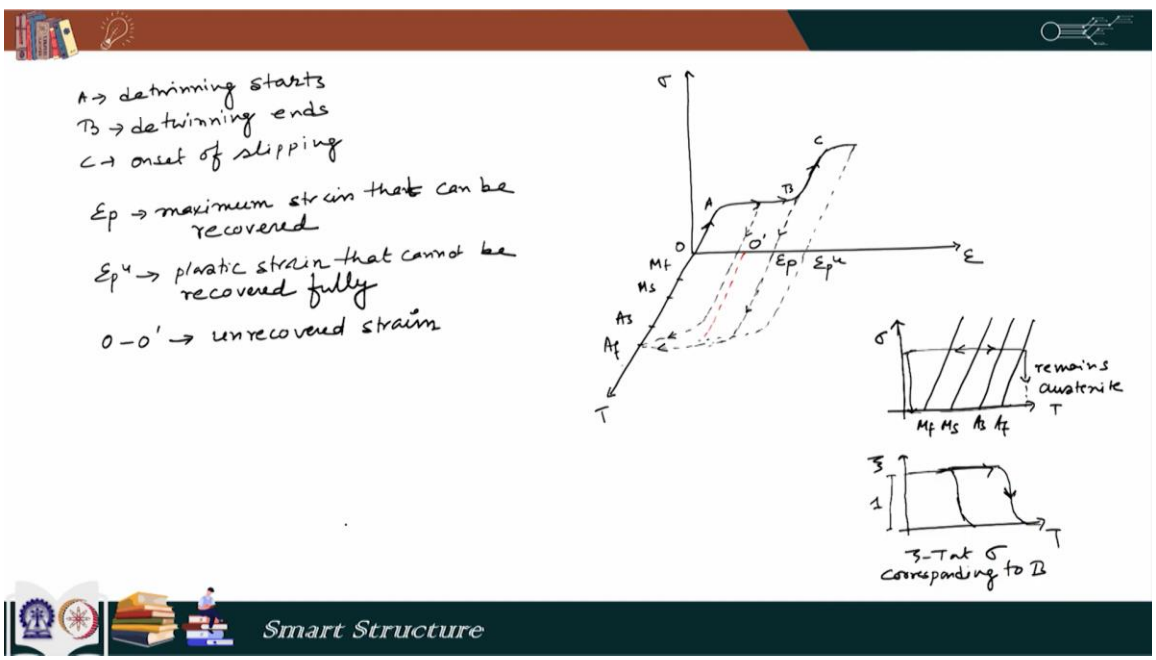

Now, we will talk about pseudoelasticity. Now, pseudoelasticity, to understand, again we have this diagram and we have M_f, M_s, A_s, A_f. Now, here instead of having a low temperature stress strain behavior, we will look at high temperature stress strain behavior. So, at temperature which is beyond epsilon f and also it should be less than M_d. So, that stress induced martensite can takes place. As we saw in the last lecture that, if you cross a temperature called M_d, then stress induced martensite, martensite transformation is cannot takes place before we achieve the required stress. The critical stress corresponding to slipping is achieved and the material slips. So, we have to be within M_d and A_f to observe the pseudo elastic behavior.

So, what happens here is – once we start from here and if we keep increasing the stress then as the material crosses these lines M_s and M_f, the transformation takes place. So, initially, initially the material is austenite. So, it has a linear stress strain behavior. So, as we keep increasing the strain, initially it is austenite. So, it shows a linear stress strain behavior. Once it crosses these lines, then the material starts becoming stress induced martensite and then the slope of the stress strain curve changes, and it becomes very close to 0. And then from there, if we unload it, then initially the relation is linear and after that while unloading, once it crosses these regions in the downward direction, the austenite transformation takes place and it is recovered quickly. So, that is how the diagram looks like.

So, this is when our temperature is between austenite finish temperature and M_d. Now, suppose, we are starting at a temperature here, between A_s and A_f. In that case also, and also assume that the initially the material is austenite. So, in that case also the initial part of the stress state diagram is same because initially it is austenite. Then the martensite transformation takes place. Once the stress crosses this M_s and M_f lines and then, it shows a behavior like this reduced slope. And on unloading, initially the behavior is like this same thing, but at the end, it comes back to where it started so here. So, while unloading, when it crosses these lines A_s and M_f, from martensite to austenite transformation takes place. But because the temperature is less than A_f, the full transformation does not take place. So, some part of the strain is yet to be recovered. So, the behavior here looks like this. So, full recovery is not possible here. And this is when the initial temperature is between A_s and A_f. Now, this phenomenon is called pseudoelasticity and it is known as superelasticity also. So, here we can see that in the stress strain diagram, there is a hysteresis. So, it is associated with dissipation of energy. So, that is why it is elastic because it is coming back to where it started. So, this makes it ideal for use as damper or any energy dissipation applications.

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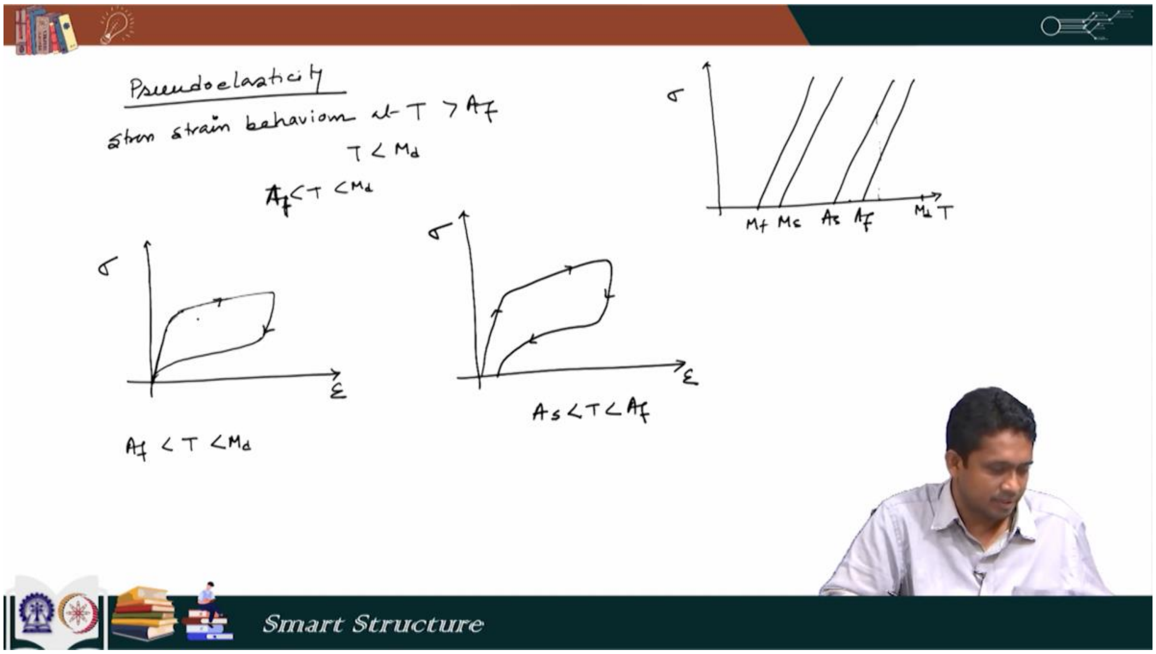

Now, we will talk about two way shape memory effect.

So far, we have seen that our shape memory effect is like this. We have a material in undeformed shape, it looks something like this and then, in the deformed shape it becomes like this, and then on heating it regains the shape. But in case of two way shape memory effect, it may not the material may not show a full recovery, it may show a partial recovery like this. So, this is deformation. This is heating. Here the material is in the martensite phase. Deformation is again in the martensite phase. We are heating it. So, it is beyond austenite, but here, full recovery is not happening. And then on cooling, the interesting thing is that – on cooling it can again get its bend shape. So, previously when we are talking about one way shape memory effect, after that by cooling, we were not getting this shape back. It was remaining in the undeformed shape, but in a two way shape memory effect by cooling and heating, the material can switch between these two shapes. So, this is T less than M_f.

So, it is a two way actuation. Once the material is here, if I cool it, it gets the bend shape. If I heat it up, it gets this shape which is not fully undeformed shape, but it is very close to the undeformed shape. So, that is a two way shape memory effect. Now, to impart the two way shape memory in the material, there is a process called training. So, through training, the material is made to behave like a two way shape memory effect. And there are different methods of training. So, mostly it involves some kind of thermo mechanical cycle. The material is gone through a thermal cycle or a mechanical cycle or a combination of both. Aand that imparts two way shape memory in the material.

And there are different techniques for doing this training. There can be over deformation. There can be repeated cycling which is SME. So, repeated cycling of shape memory effect means it is not stressed only the temperature is varied and the shape memory effect is seen and it is repeated few times. And there is repeated cycling which can be pseudoelastic. Again pseudoelastic means our temperature is constant, we are varying the we are cycling the stress. And the pseud elastic behavior is observed. And that is cycled quite a few times. And there can be combined SME and pseudoelastic cycling. And there can be constant temperature cycling. So, these are the various techniques by which the shape memory alloy is trained to show two way shape memory effect. Now, these methods are described in more details in the book by Chopra and Sirohi. So, if you are interested you can refer to the book and learn more about this training techniques.

So, this was about today's lecture. We have seen the stress state behavior in low temperature and high temperature. And we have seen that at high temperature, if we cycle the stress strength, it shows pseudoelastic effect. Now, gradually we will move on to the constitutive modeling constitutive modeling of this materials.

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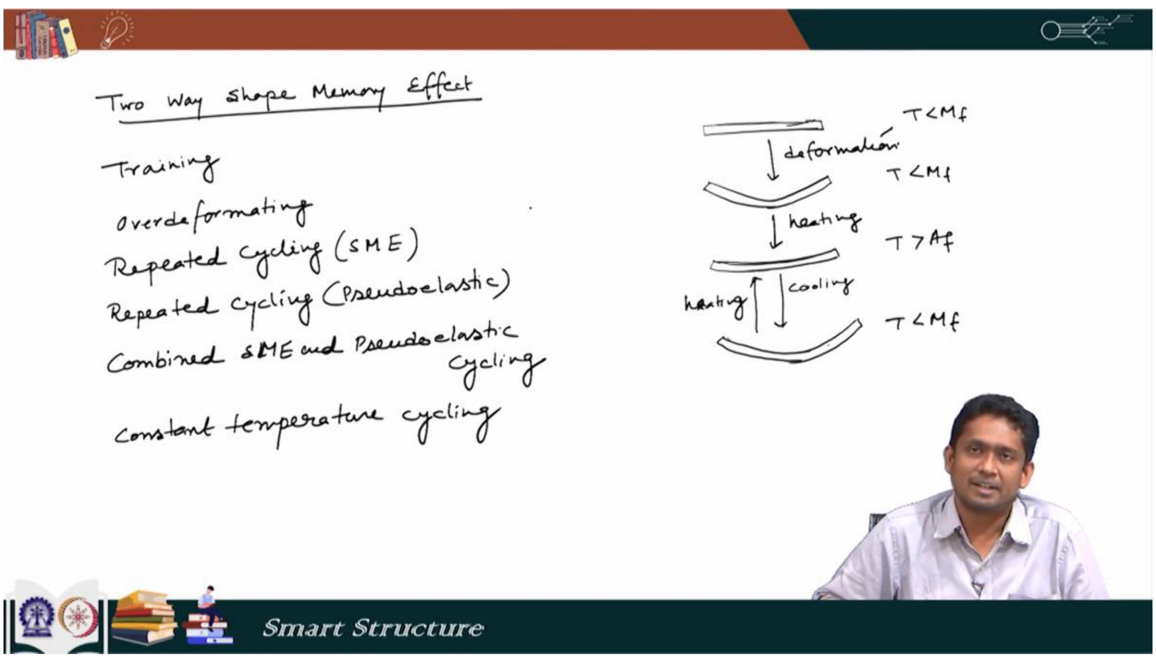

So, with this let me conclude this lecture here.

Thank you.