**Smart Structures**
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**Week - 08**
**Lecture No - 41**
**Introduction to Shape Memory Alloys**

Welcome to the first lecture of 8th week.

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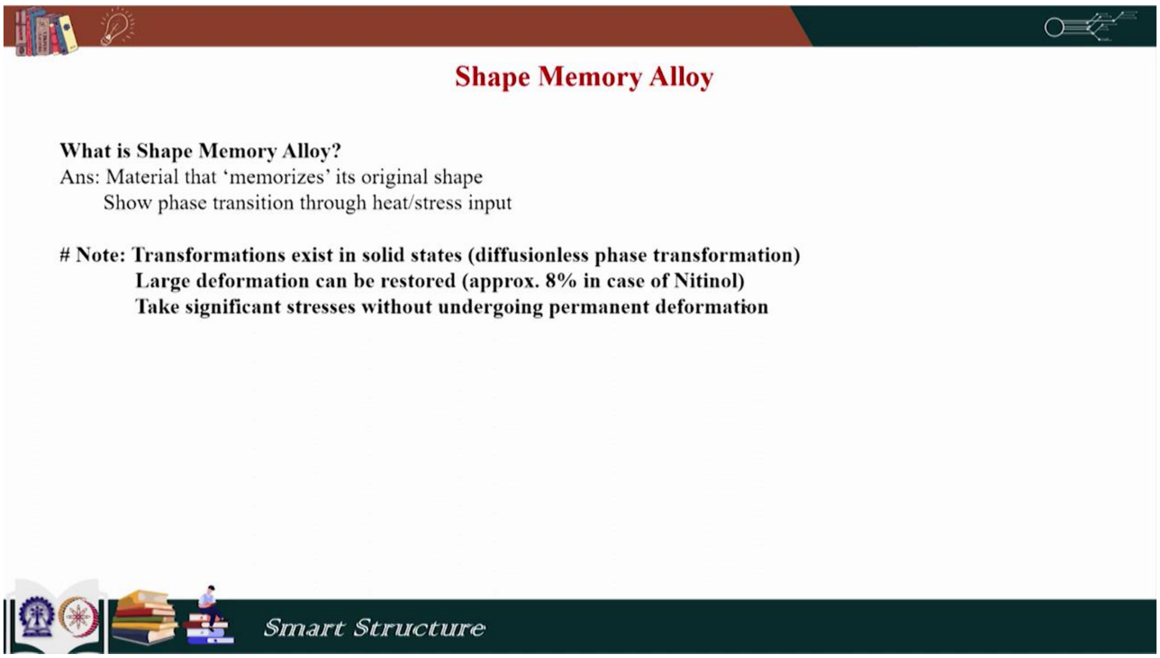


In this week we will start discussing about a new class of smart material that is shape memory alloy. At first we will see the behavior of this shape memory alloy, we will see what makes this material smart and then we will talk about their mathematical modeling, I mean the constitutive relations and after that we will see some applications and we will see the corresponding formulations. So, first what is shape memory alloy? Shape memory alloy is a material that memorizes its original shape and these materials show phase transition or phase transformation and through this phase transformation the shape memory effect is seen and this phase transition happens through heat or stress input. Now here the transformations are in solid states. So, here it transforms from one solid phase to another and we see large deformation can be restored through it.

So, in case of nitinol which is one type of shape memory alloy around 8 percent of deformation can be restored. We will see in details what these means, what the restoration of deformation mean, what is mean by phase transition as we progress and these materials can take significant stresses without undergoing permanent deformation.

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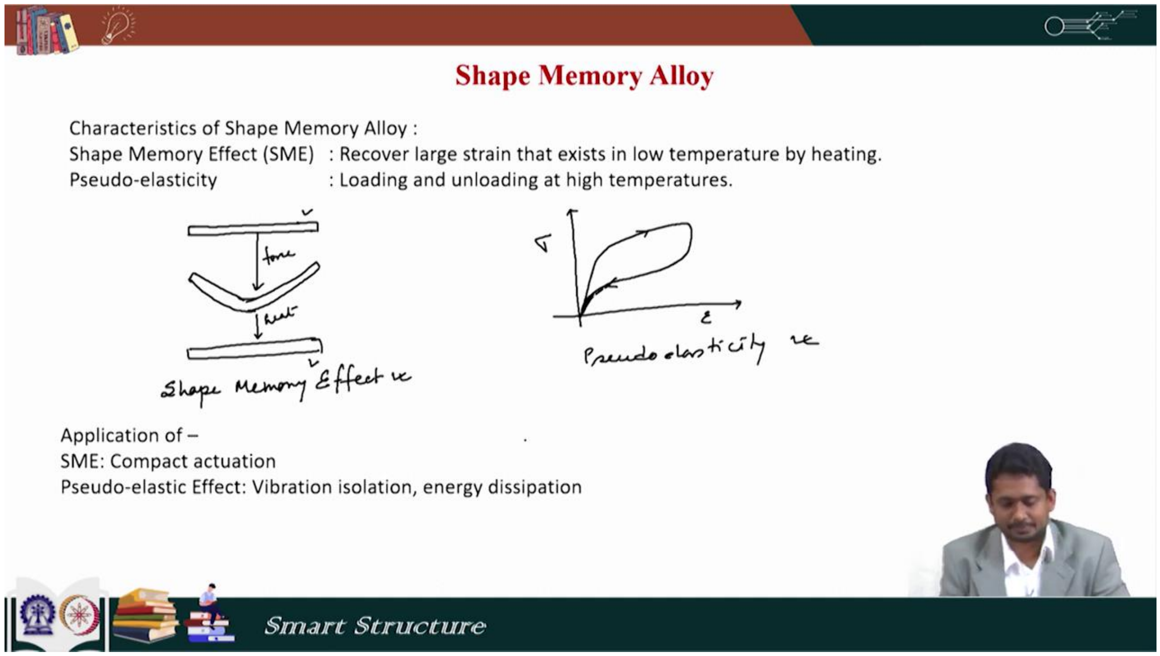


So, shape memory alloy shows two type of special behavior, one is shape memory effect and another is pseudo elasticity. Shape memory effect if you want to understand it let us assume that we have a shape memory alloy wire maybe and this is its undeformed shape and suppose that we give it some deformation and we deform it in some fashion, maybe deform it to this shape.

Now this deformation is large. So, if we remove the load, this material does not go to the previous original shape. So, some deformation remains. So, its kind of plastic deformation, but if we give heat input to it i.e. if we heat the material then upon actuation by heat, this material regains its original shape. So, this shape and this shape are same. In the mean time this shape is different. So, we get this shape by applying force and then by applying heat, we regain the unstressed shape. So, in some sense this material although here the deformation seems to be permanent, but it had its previous shape in memory.

So, under heat actuation, it could regain its previous shape. So, its shape memory effect. Now, there is another effect called pseudo elasticity that is called sometimes super elasticity also. So, under some conditions like under some temperature condition or under some stress range, the stress strain behavior of this material looks like this. So, the loading path is this while unloading it comes back through this path and it comes back to where it started.

Now because after unloading it came it came back to where it started. So, it is kind of elastic behavior, but here the behavior is hysteretic. We can see that the loading and unloading path are not same. So, this kind of behavior is generally associated with energy dissipation. So, this is called pseudo elasticity.

Now the shape memory effect make these materials a good candidate for use as actuator because we can always keep the material in this kind of different configuration in the structure and by giving heat input it it it will try to regain its original shape and that will generate actuation force. And here because we can see energy dissipation, these are ideal material for use as damper. So, vibration isolation, energy dissipation all are different application of the pseudo elasticity and actuation is the application of shape memory effect.

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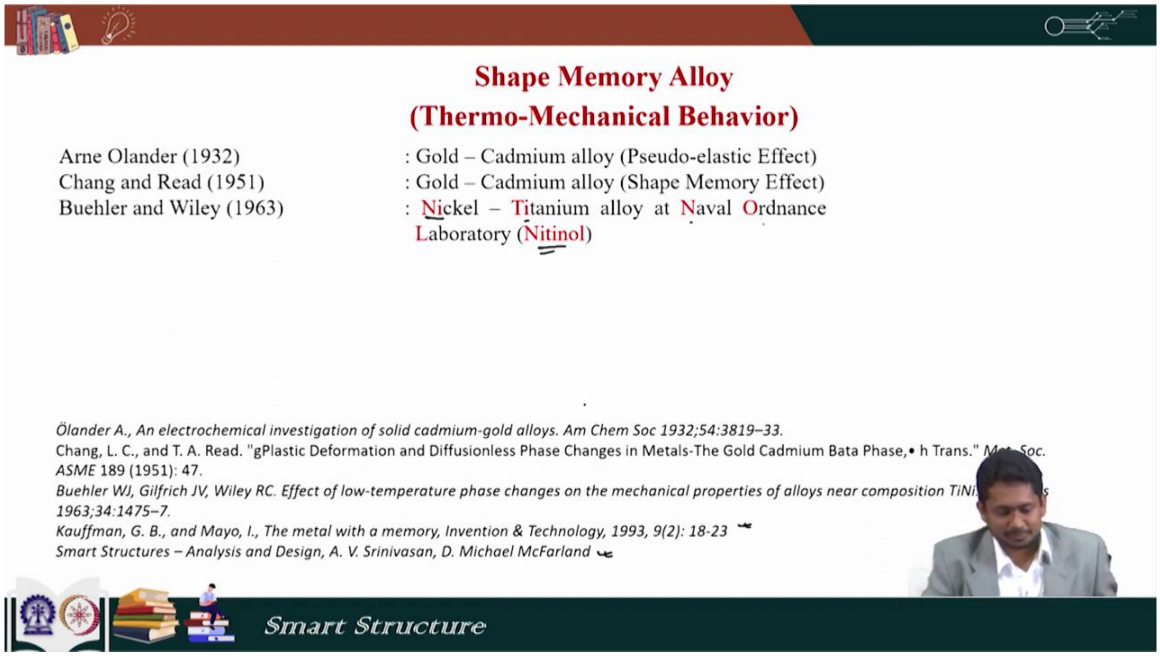


So, this pseudo elastic effect was found first in gold cadmium alloy by Arne Olander that is in 1932. Then in 1951 Chang and Reed observed shape memory effect in gold cadmium alloy. After that in 1963 Boehler and Wiley observed this shape memory effect and pseudo elasticity in nickel titanium alloy called nitinol and after that the tremendous development in this field started taking place. So, Boehler first observed that an alloy which has titanium and titanium and nickel in almost equal proportion shows some phase transition at different temperatures and those are the phase transformations that leads to shape memory effect. And they also observed that these by varying the proportion of these constituents the transformation temperature can be varied. Now there is a nice history given by Kaufman and Mayo in this article and that is presented in the book by Srinivasan and Macfadden also on of how this material was invented. So, Boehler was a metallurgist in naval ordnance laboratory and he was looking for potential good materials for use in cone of a missile.

So, out of around 60 materials he shorted out 12 materials and tested it and out of those 12 he found that an alloy of nickel and titanium shows good impact resistance as well as good fatigue property also. So, he named this material nitinol - nickel (Ni), titanium (Ti) and naval ordnance laboratory (NOL), nitinol and then they started doing further experiment of these materials. So, they casted around 5 samples i.e. 5 bars of this nitinol in their furnace and they left it for cooling.

Now when one of the sample was cooled down he wanted to take it to a different place for for some surface treatment i.e. grinding and then while taking it he dropped it on the ground and he observed a dull sound from it dull thud, but then he tested other materials at different temperatures and he observed various other sounds. So, those at higher temperature were observed to show more of metallic sound. So, that was very interesting observation and finally, after doing various tests they concluded that these materials undergo some atomic structure rearrangement some phase transition at different temperatures and that is showing these various behaviors at various temperatures.

And after that series of experiments, series of work has work have been done in this area and the theory of shape memory alloy has got a good amount of maturity and that is what we will discuss in this course.

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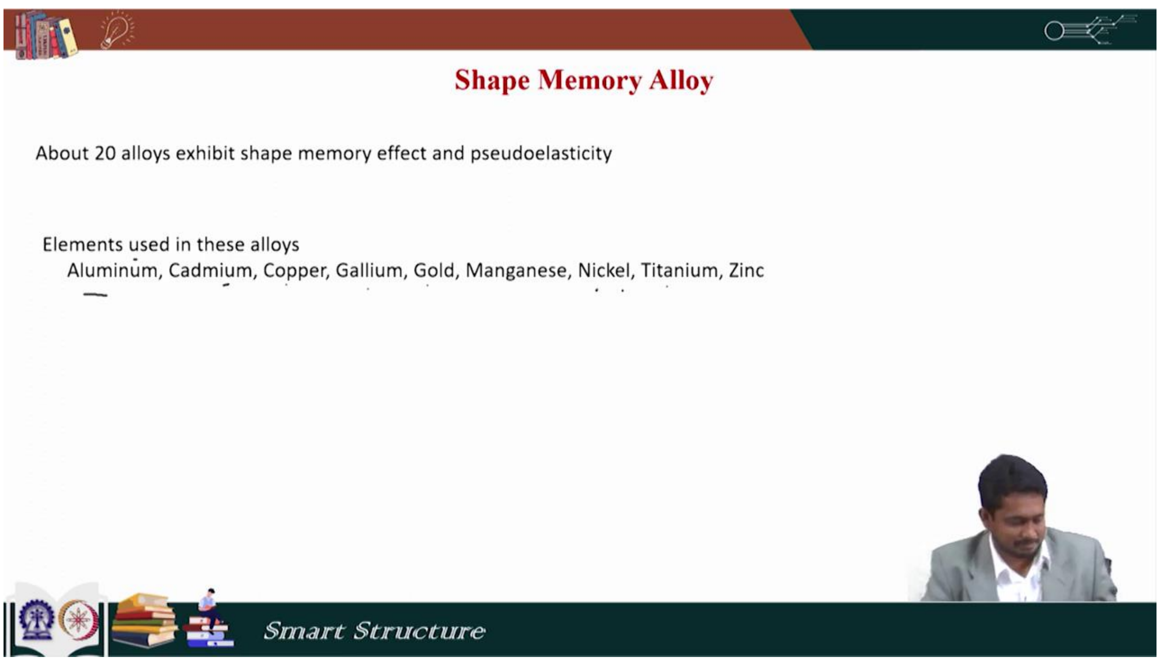


Now shape memory alloy are generally there are around 20 alloys that exhibit shape memory effect and pseudo elasticity and these alloys have generally 2 or more of these materials as constituents' aluminum, cadmium, copper, gallium, gold, manganese, nickel, titanium, zinc.

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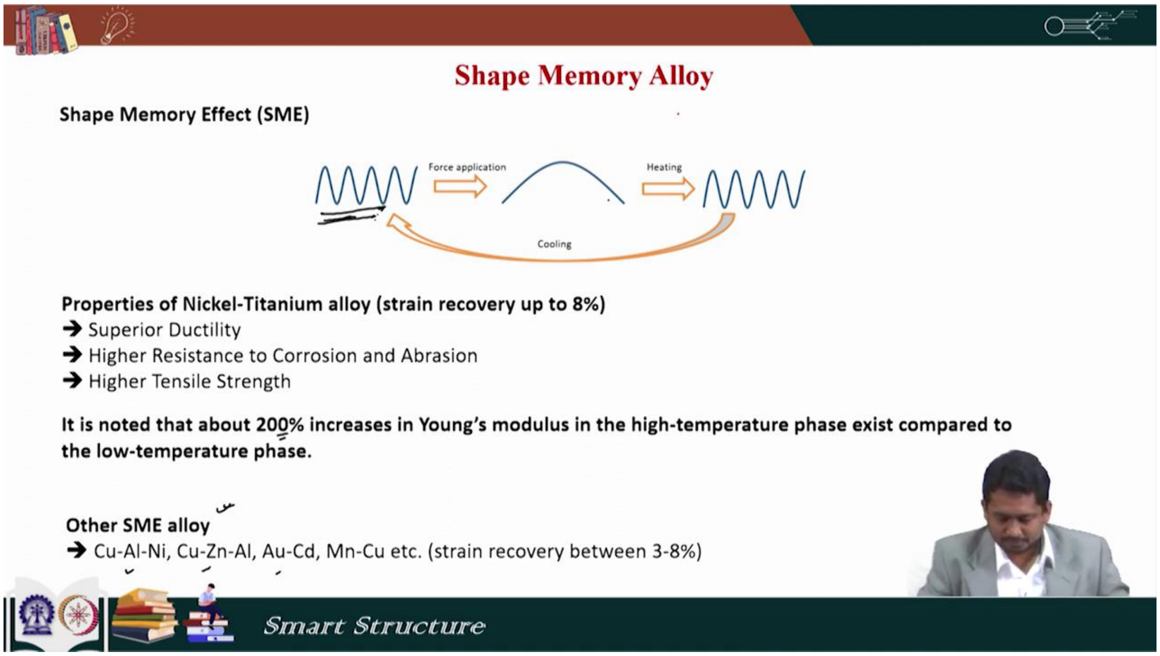


Here shape memory effect is again shown. So, this we can think to be the initial configuration and after force application it is deformed to some shape and then again by heating it regains the original shape and again if we cool it, it remains in this shape. Now, nickel titanium alloy is one of the most widely used shape memory alloy.

These alloys can recover up to almost about 8 percent strain. So, if the amount of strain is about 8 percent, it can be recovered by heating. This material shows super ductility. They have higher resistance to corrosion and abrasion and they have higher tensile strength. Now this shape memory effect comes into picture because this material remains in one of the two phases depending on the temperature and temperature history and these two phases shows distinct material behavior.

For example, Young's modulus there can be around 200 percent variation of Young's modulus in between these two phases. That is in case of ah nickel titanium alloy. Other shape memory alloys examples can be copper aluminum nickel, copper zinc aluminum and gold cadmium and so on. And the strain recovery is between 3 to 8 percent depending on the alloy.

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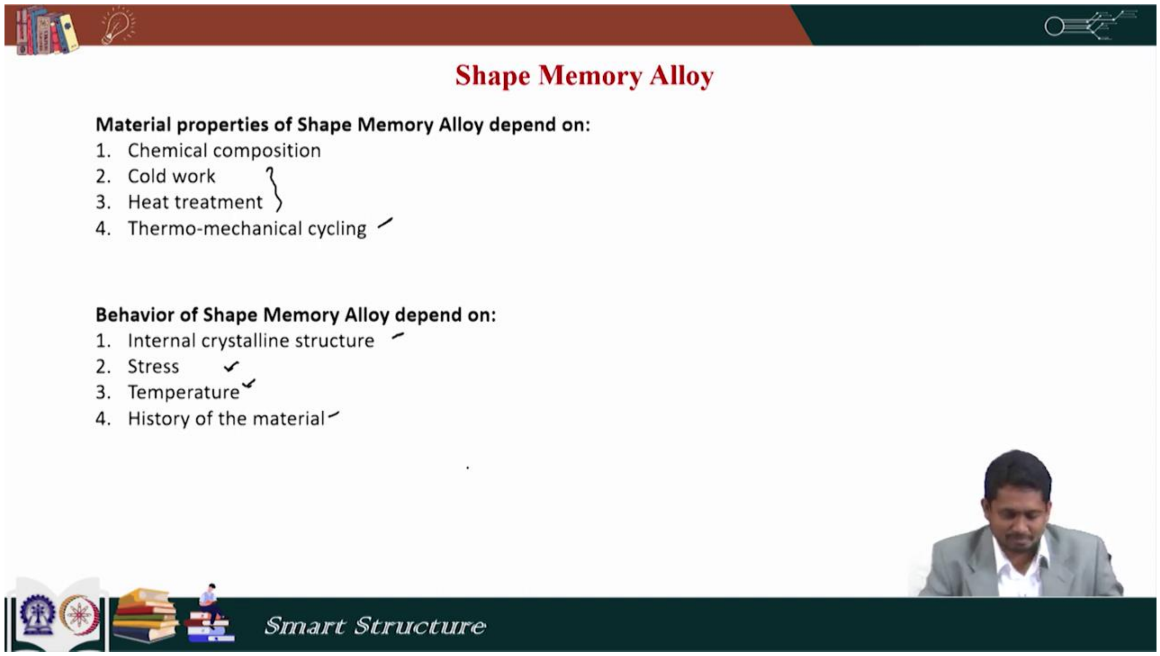


The material properties depend on the chemical composition, cold work heat treatment these are the processes that are generally followed while manufacturing and thermo mechanical cycling. And the material behavior depends on internal crystal structure, stress temperature and history of the material. So, just stress and temperature is not sufficient to know the present behavior of the material. We also need to know the history of it like how the stress was before, how the temperature was before because this material shows something called path dependent behavior and we will understand that as we progress.

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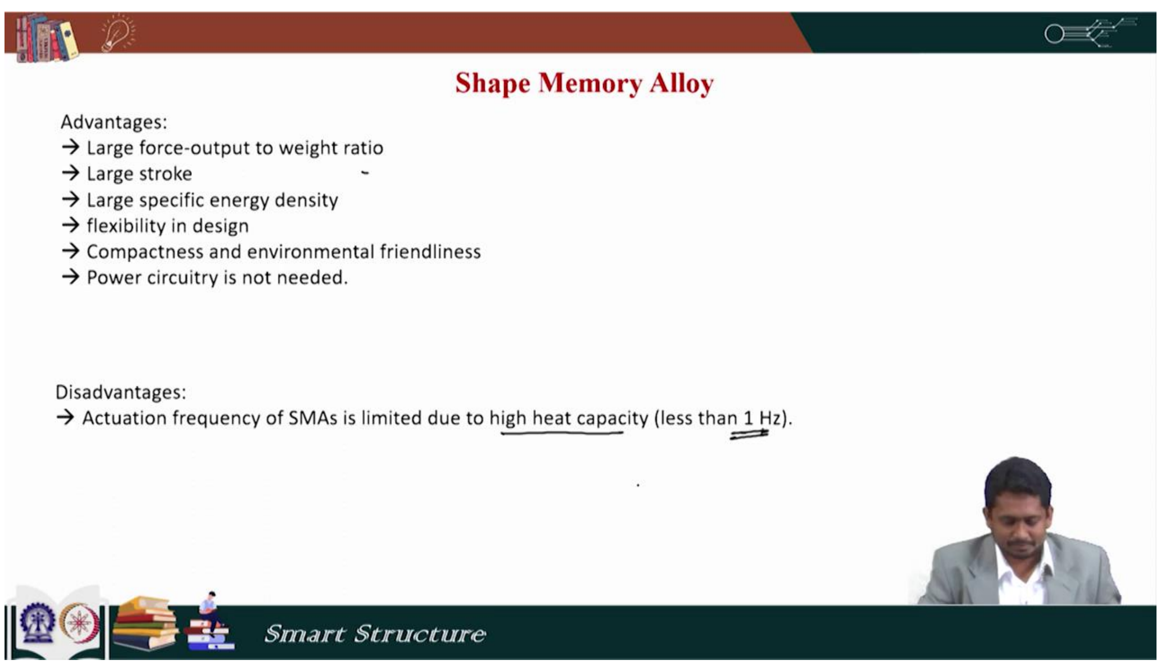

The advantages of these materials include large force output to weight ratio, large stroke because we have seen that they can be strained up to 3 to 8 percent depending on the material and that amount of strain can be recovered. So, there is large displacement large force when the material tries to recover the shape and there is large specific energy density and it offers flexibility in design because here the actuation can be in various modes like axial mode, bending mode, torsional mode and so on.

And a compact system or actuation system can be formed from it and these materials are environment friendly. In fact, we saw that the nickel titanium alloy has good corrosion resistance and power circuitry is not needed. However, there is one problem. Here the actuation is through heat and this material has high heat capacity. So, that is why the actuation is not so fast. It takes time to warm the material to raise the temperature. That is why, here the actuation frequency is generally around 1 Hertz. Now, at the beginning of the course, in the first week we saw comparison of different actuators made of smart materials and we saw that in case of piezoelectric materials, the actuation force is less than the shape memory alloy, but the frequency is high and in this case the frequency is less, but the actuation force is higher and the frequency is less because of the thermal mode actuation and high heat capacity.

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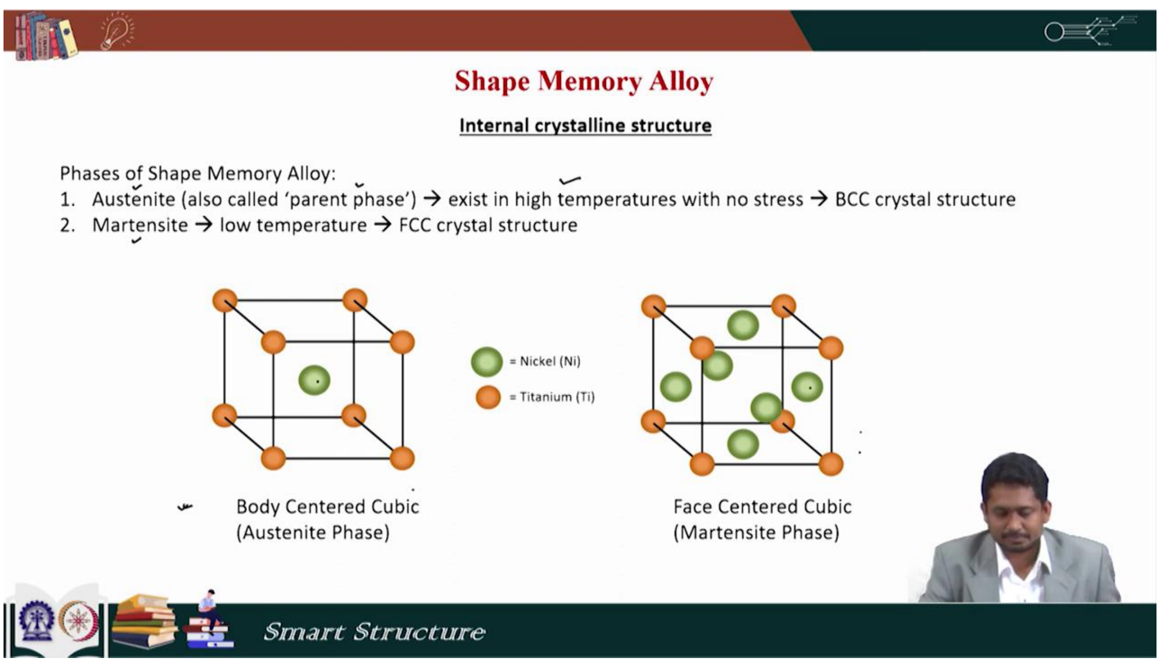


Now, we will try to gradually understand what this shape memory effect means and how it is possible. Now, to understand the shape memory effect or even pseudo elasticity, we need to understand that this material remains in one of the two phases depending on the temperature and these two phases are austenite and martensite.

Austenite phase is also called parent phase and they are high temperature phase. They are stable at high temperature. In the austenite phase, the material shows a body centered cubic structure that is shown here. So, we have titanium and nickel. So, nickel is at the center and titanium is at the corners and nickel is at the center of the volume whereas, in the martensite phase, martensite is stable at lower temperature and martensite shows a phase centric crystal structure.

So, phase centric means here the nickel is at the phase center of each phase, not at the center of the entire volume. So, it is a body centric structure which is shown by austenite and this is phase centric structure. Phase centered cubic structure is shown by martensite.

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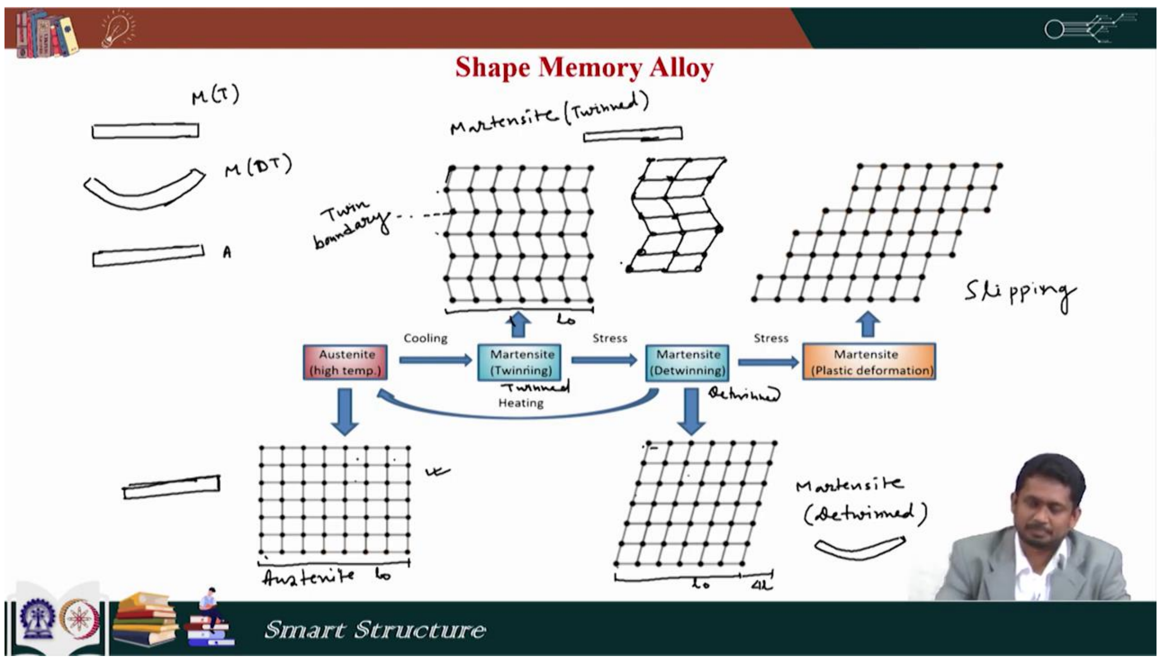


Now, this diagram explains the entire shape memory alloy behavior and the phase transition. So, these are simplified 2D diagrams of the martensite and austenite variants.

So, this is a austenite structure in 2D. So, these black dots shows the position of the atoms. So, this is how it looks like in austenite again it is a simplified 2D diagram and this is how it looks like. So, this is austenite and this is how it looks like when it is martensite. Now, if we compare these 2 diagrams we can see that there is microscopically small difference.

Here, this kind of structure is called a twin structure because if I take a line like this with respect to this line, the upper part and lower part seems to be mirror image of each other and this is called twin boundary. So, it has a twin structure and this is a twin boundary. Now at this twin boundary the structure does not break. It just shows a twin shape. Now if I compare the overall dimension of these 2.

So, if this is $l_0$ this is also more or less $l_0$. So, macroscopically they are same although microscopically they are different. Now if on this twin structure, some force is applied maybe a shear force like this then this twin structure changes and this entire thing detwins and it looks like this. Now if I compare this with this then they are not even macroscopically same. They are microscopically also different.

If this dimension is $l_0$ then from here to here the entire dimension is $l_0$ plus delta l and this is also martensite. So, in the martensite it can be twinned. So, it is called a twin martensite and this is called a detwin martensite. Now if I have a shape memory alloy material in this phase in twin martensite phase, let us say, that is our shape memory alloy wire that we saw before and then if we apply load to it. So, there is stress and then it deforms and it becomes twinned and it can further deform after the twinning breaks.

So, the deform shape suppose macroscopically looks like this. So, that is the deform shape that we created. Now if we remove the load from it, it does not just go back here. So, this deform seems to exist or this deform shape seems to be maintained to some extent. So, here we had a twin martensite undeformed and then we apply stress to it, it became detwin martensite and it deformed.

Now if we apply heat to it then on heating, this material martensite phase becomes unstable because at the high temperature, the austenite phase is the stable shape. So, if I apply heat to it, it transforms to a austenite phase and then it comes back here. So, we know that macroscopically this and this look same. So, again we get our original shape back. So, that is how this entire shape memory effect comes into picture.

So, we started with this kind of a material and that was martensite twinned and then we deformed it and that is martensite D twinned and then we applied heat to it and it becomes austenite and as we know that macroscopically austenite and martensite they look same. So, although by heat actuation it regains it original shape, but it does not go to the twinned martensite phase because it is at the higher temperature and at the higher temperature the stable phase is the austenite phase, but macroscopically they look same. So, that is what it is. So, we have martensite twinned, we have martensite detwinned and then we apply heat to it and it becomes austenite. Now from this austenite if you want to get a martensite twin structure, we can just cool it down and when it cools down the austenite phase becomes unstable and the martensite phase becomes stable.

So, it becomes a twinned martensite. So, if I cool it down from here it will go back to the twinned austenite phase. So, it is twinned and it is detwinned. Now if we take a martensite which is already detwinned and if we keep applying stress to it then a stress level comes at which one layer slips over the another layer and it can be seen here. So, we can say that these two layer is slipping over the third layer. So, these two layers just shears off and that is called slipping.

So, for slipping to happen we need even higher stress, but once it has gone to this range or once it has slipped, this cannot be recovered. So, it is a permanent deformation. This is all about the shape memory effect. It explains how the material remembers it memory or what it means when we say that the material remembers it memory. What are the different phases, how to go from one phase to another phase?

Now just one thing to remember, here it is a simplified diagram of a twinned structure. Now there can be various types of twinning, for example, something like this is also possible. So, this can also be called a twin structure and then again this and again this is in 2D. So, if we think about a 3D structure there can be several variants of these twins.

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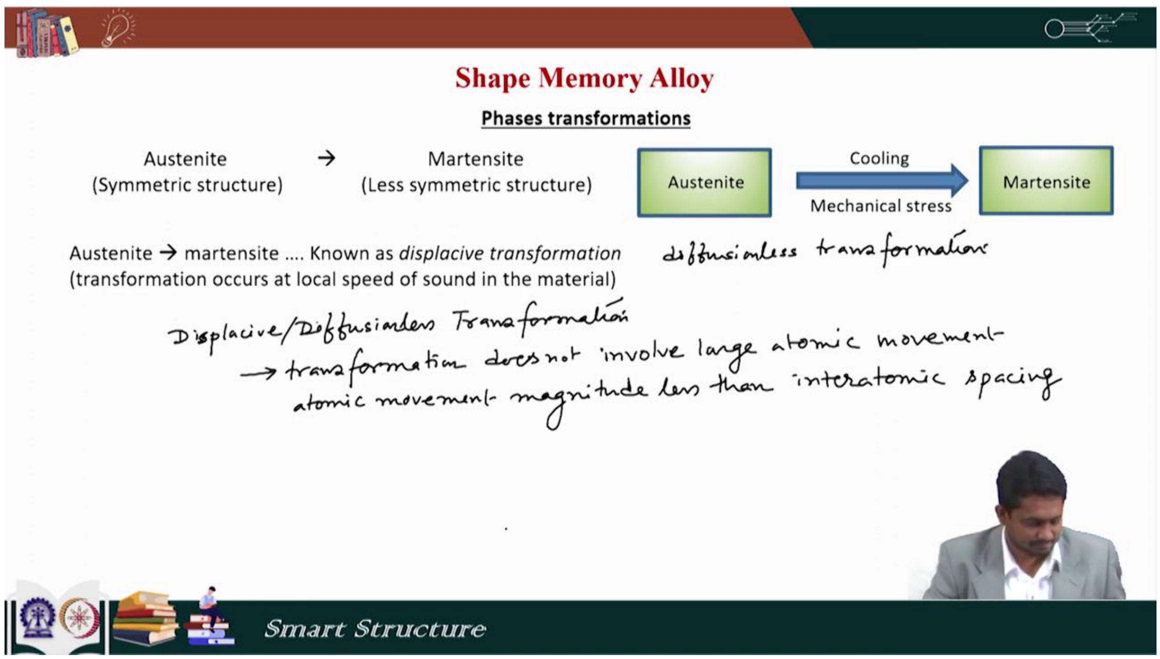


So, we have austenite phase which is more of symmetric martensite phase which has less symmetry. If we want to go from austenite to martensite, we can go there just by cooling and there is from austenite to martensite if you want to go we can go by applying mechanical stress also. We will see that. Now this austenite to martensite transformation is a displacive transformation. It is also called diffusionless transformation.

So, it is a diffusionless transformation. So, displacive or diffusionless transformation and this means that transformation does not involve large atomic movement and that we can see here also. If we look at and if we compare this phase with this phase, the amount of movement that of atoms take place is not large. So, they do not involve large atomic movement. In fact, the atomic movement magnitude is less than inters atomic distance or spacing.

That is why they are displacive transformation. So, it occurs at local speed of sound in the material. However, there is a problem as we said that for this to happen heat actuation is needed and these materials have high heat capacity. So, to raise the temperature, it takes time and that is what puts a constraint on the speed of this transformation.

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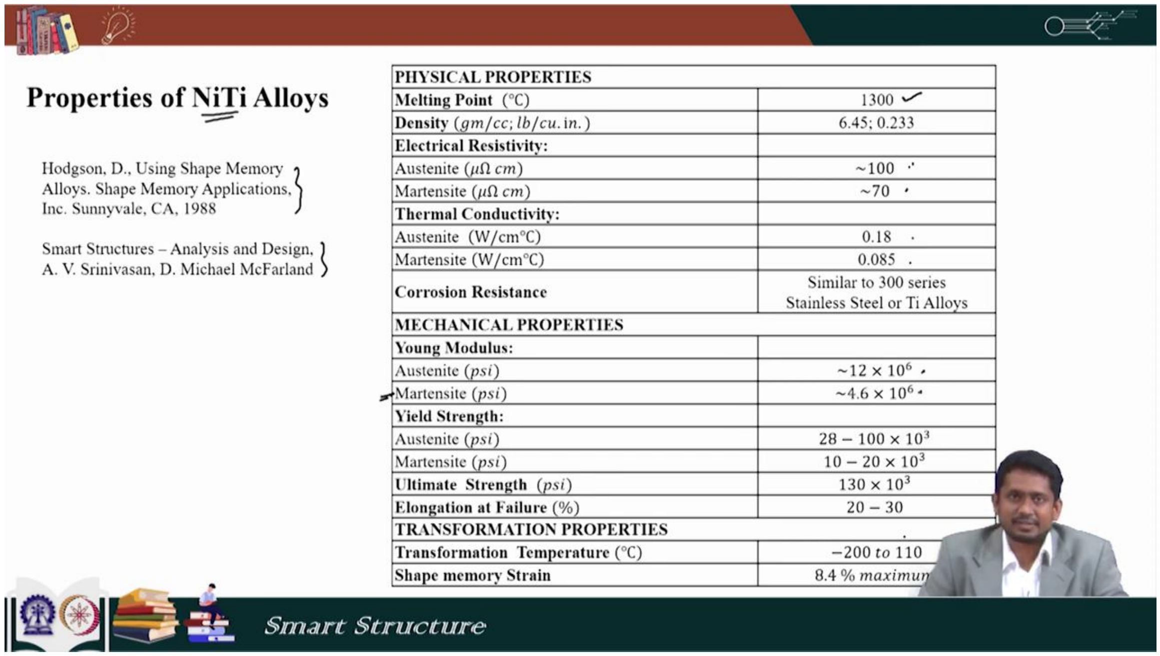


Now, we look into some of the properties of one of the shape memory alloys which is nickel titanium alloy i.e. nitinol. Now, these properties can be found in this article and they are also present in the book by Srinivasan and Mcferland. So, melting point of these alloys are around 1300 degree centigrade, density in gram per cc is 6.45, electrical resistivity in austenite phase is around 100 micro ohm centimeter, in martensite it is 70 micro ohm centimeter. So, we can see that the properties change when phase transformation takes place.

Thermal conductivity in austenite it is 0.18 watt per centimeter degree centigrade. In martensite it is 0.085. Again we can see, it is less than half. Corrosion resistance it is similar to 300 series stainless steel or titanium alloys, austenite young modulus 12 into 10 to the power 6 pound per square inch, in martensite it is 4.6. Again we can see that there is a large variation of the young modulus between martensite and austenite phases. In fact, martensite phase is much more flexible than the austenite phase. Yield strength in austenite it is 28 to 100 into 10 to the power 3 psi, in martensite it is 10 to 20. If we talk about ultimate strength it is 130 into 10 to the power 3, elongation at failure 20 to 30 percent and we have transformation properties, transformation temperatures minus 200 to 110 in degree centigrade.

We will see what this transformation temperature means. And shape memory strength as we saw that these alloys can recover around 8 percent of strength. Now so, this was a basic introduction about this material. We have seen what are the two special features of these materials and how phase transformation can explain one of these shape memory effect. Now, gradually we will look into some mathematical formulations of the behavior of these materials and with that I will finish this class here.

Thank you.