Advanced Materials and Processes

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Lecture – 19
Shape Memory Alloys (Contd.)

Welcome to NPTEL; myself Dr. Jayanta Das, from Department of Metallurgical and Materials Engineering, IIT, Kharagpur. I will be teaching you Advanced Materials and Processes. Last couple of classes, we have discussed about Phase transformation; classification of different types of phase transformation, Diffusional phase transformation and Diffusional-less phase transformation. And mostly we have given more focus into the Martensitic transformation which is the military transformation. In martensitic transformation, we have seen that the temperature is not only important, but stress can also assist or oppose a martensitic transformation.

The reason why we have discussed so many different aspect of martensitic transformation is very simple. We need to discuss on Shape memory effect and Pseudo elasticity and for that we need a very deep understanding on the martensitic transformation and various type of defect that generate during martensitic transformation means parent austenite to martensite and the self accommodating nature of martensite by introducing some of the variant, we need to learn and part of them are already discussed. And today, we are going to start our discussion on Shape memory effect.

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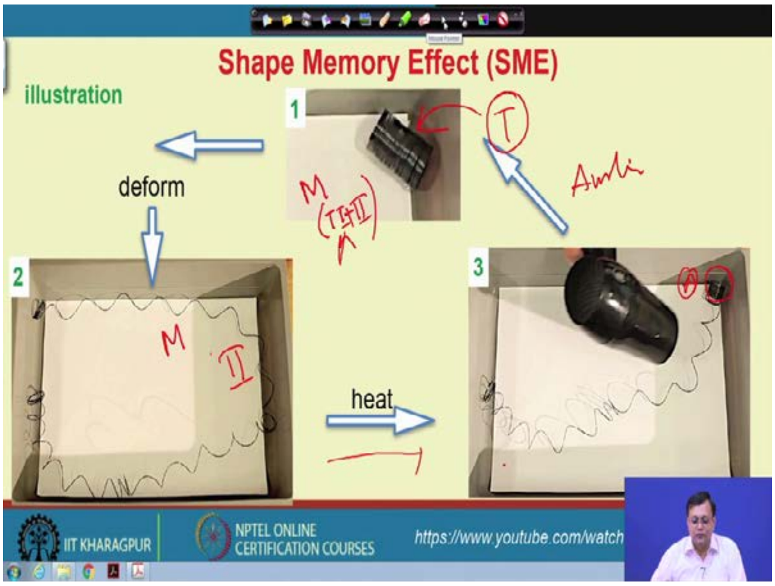

So, let us start with what physically we try to mean that what is shape memory effect? So, here to illustrate the shape memory effect, I have taken some images from this reference and the image number 1 that shows an alloy. It is a nickel-titanium alloy which shows shape memory effect and this is actually a spring. That spring is kept at a temperature below the martensite start temperature, martensite finish temperature. So, before going to the detail of this transformation temperature, let us first have a look what really happen if we deform this spring.

So, after deformation this spring is strained to a very long shape and a large amount of plastic deformation has been given; and then, we have released the stress. So, this is the shape of the spring in the on stressed condition means the apparent deformation has been already given. Now, I take this spring and then I heat it by some hair dryer.

The hair dryer have increase the temperature of this spring and you see some part is already recovered the initial shape and then after sometime, it completely. And this is very interesting that a material we can get back or we can recover the whole strain that has been given to a material just by changing some of the condition.

So, here the condition is the temperature, heat is given means basically we have increase the temperature. So, there must be some underline mechanism of these shape memory effect that a material possess and as a metallurgist, we must try to learn what are the microscopic and atomic scale mechanism involve in this shape memory effect and today, we all we will discuss detail into this aspect and let us try to discuss the same.

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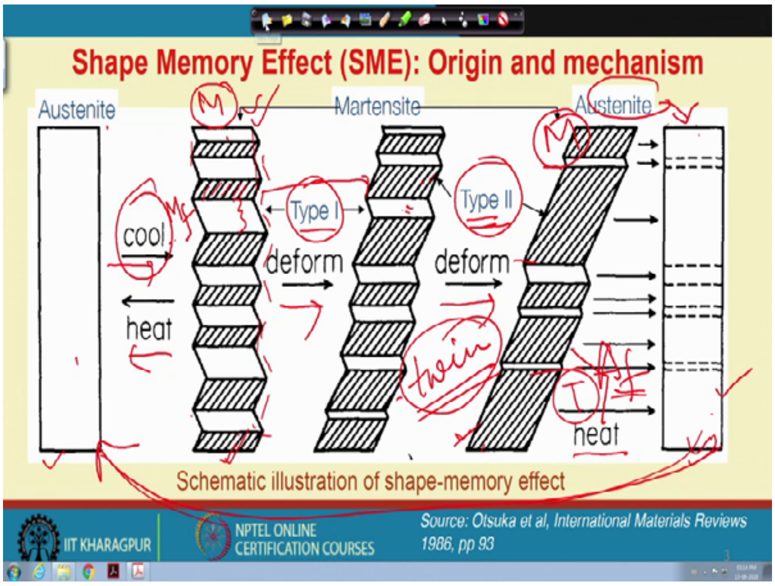

Here, I draw a schematic figure and this one is a rectangle as to represent the austenite and this austenite, if you cool it below martensite start and martensite finish temperature; why we talk about martensite finish because below this temperature, all the austenite will be transform into martensite. Now after cooling, we will get martensite. So, here this is the martensite and then, since martensitic transformation may incorporate some of the different lattice it is a lattice invariant deformation. So, it will incorporate some defect and for shape memory, the defect require is twin.

So, this is the only strain we will discuss detail. So, here twin has formed. So, these are the twin and in the last class we have discussed that there are many different variant of the twin. So, here for shape memory effect, we need two different variant of the twin. One is called as Type-I twin, another one is the Type-II twin.

Now this martensite has a particular macroscopic shape, now what we do? We deform the martensite. After deformation or during deformation here one type of twin grows in expense to the other one. What does it mean? You see this hashed region represent the Type-II twin and the blank part is the Type-I twin. So, Type-II twin here, this one has grown from here to here and you see that the area covered by Type-I twin has decreased in this figure.

Now, we further deform it. You see Type-II twin has been extended and covered almost 90 % of the of the martensite initial structure and we get this particular or we deform the martensite, we have such a structure then we simply employ some or we give some heat to this to this martensite and austenite will form. So, this one is the austenite; here it is still martensite and austenite will be here.

So, we get actually austenite which has the initial shape as it was we have started with. So, it means that austenite transform into martensite by cooling. This martensite again if we heat we will get back, However, this cooling that produces the martensite, we can deform the martensite by only one mechanism, that is the twin should be involved in this whole deformation process and this twin will again vanished when we will heat above austenite finish temperature.

So, we have provided heat or we have increased the temperature above austenite finish; we know that all the martensite will be transform into austenite. So, this austenite has the same shape. So, now, we can explain the behavior that I have shown you earlier with this figure. So, here it was actually a martensite and then, this martensite we have deform. So, we have increased Type-I, Type-II twin and Type-I and Type-II twin both are present here. So, this was initially it was martensite. Initially, it was martensite, here we have basically martensite means what Type-I twin and Type-II twin.

So, Type-I plus Type-II here, we have grown 1 Type of twin in expense to other one and then we have provided heat and here this part is already austenite and then, the whole part is recover which become austenite and then again we cool it. So, temperature has decrease to the nearer temperature we will get that martensite. So, this was the explanation of this particular diagram.

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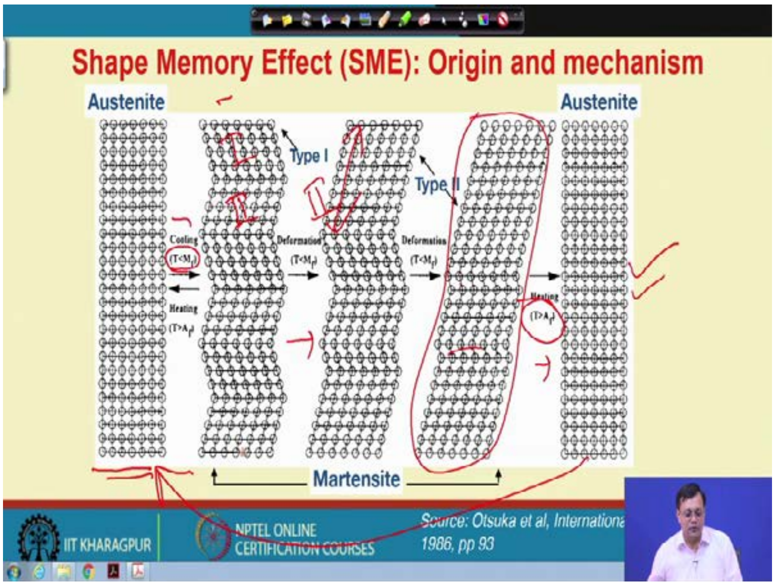

Now, let us look at in a little bit like an atomic scale, the same mechanism just to explain you within a minute. So, initially it was austenite once again just to repeat it and if the temperature is well below martensite finish temperature during cooling we will get this martensite microstructure and this martensite has basically Type I twin and Type II twin.

Now if we plastically deform it, the strain has to be accommodated and the strain accommodation is done here by the growth of Type-II twin; you have seen here that the twin has grown and now the Type I twin almost vanishes if we keep on deforming and giving more and more plastic strain and then ultimately, we will reach to such a condition.

Where almost Type-I type twin may vanishes. It could be also otherwise means Type-II twin instead of growing during the deformation plastic deformation, Type-I twin grows it depends on the direction and favored condition and then at the end if we increase the temperature which is above austenite finish temperature, then we will get the austenite; however, these austenite has the same shape as the initial one. So, this is something very much interesting.

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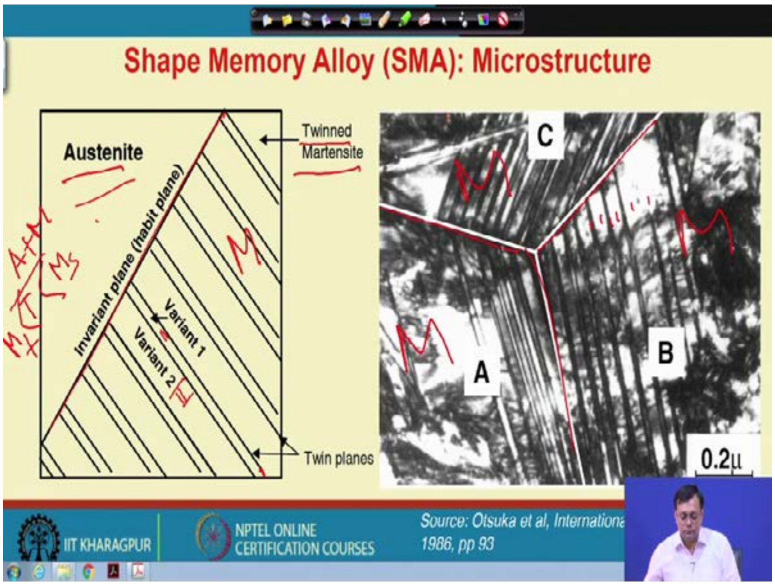

Now, let us have a look at some of the real microstructure and I show you some schematic how this twin variant lie and how the habit plane that interacts during this. So, here this is the austenite which is undergoing transformation during cooling. So, let us assume that the temperature is in between let us say the martensite start temperature and martensite finish temperature. So, what are the phases will be present? We have both austenite plus martensite because some part of the austenite which still have to complete the transformation.

So, here you see this is austenite and here this is the interface between austenite and martensite and the martensite has accommodated the transformational strain by introducing some twins. So, this is a twinned martensite. So, here the twinning has some variant. So, Variant 1 is the thinner one and Variant 2 here is the thicker one. Let us assume at this movement and in between we will have some twin planes.

Now if we look at some of the real microstructure in case of a nickel-titanium alloy, you will see these are the prior austenite grain boundaries. So, here in this case all the austenite phases has transformed into martensite. So, here it is martensite; here it is martensite; here is the martensite, but you can always ask; how this thing happen? Actually, this was the prior austenite grain boundary that still remains here which has transform into martensite and you can see here the different variant of twins that has form inside the martensite.

Now, in a more schematic way, we should try to understand how this strain accommodation occur inside the martensite with different twin variants because I told you that the initial shape of the martensite, we have deform by some plastically and so strain must have accommodated.

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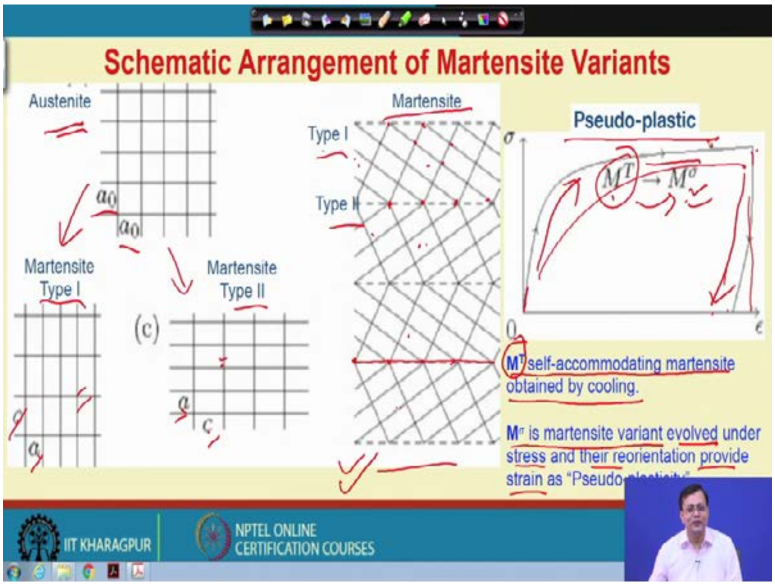

So, here just as a schematic, we show you here some austenite by this boxes and here let us say this has a particular crystal structure which is somewhat like cubic and so there is a_0 and a_0 and after cooling these martensite has basically two different type of twins. So, let us say twin-I and twin-II which has a different lattice variants and let us say this is c and a; here it is a and c and then, we put this two different lattice together and to make this whole martensite.

And let us say this is a coherent plane, where atomic positions are similar in both the case of two different type of twins. So, this is like a martensite crystal where we have 2 different twins with their different variants. So, here you see this is a Type I type of twin where the atomic positions are here and here these are the coherent boundary where the lattice sites are same for both the case and it looks like just like a mirror plane of the things.

So, it is basically a twin and now, if we take such a microstructure and material with that microstructure of martensite which has two different twin variants; then the martensite during cooling which has formed, we call it as self accommodating martensite obtained by cooling which is represented with M^T and we have taken M^T and we started giving some stress.

So, some stress has been given means some strain will be generated and then, if we keep on increasing then this self-accommodating martensite transform into M sigma. M^σ stands for that it is a martensite variant which evolve on the stress and their reorientation mean twinning. So, twinning means basically Type I; one type of twin grows in expense to the other one and their orientation changes. So, we are getting some strain and then if I release the stress, strain comes back and recovered; but I am only talking here about the deformation of martensite only.

So, this is the different martensite variant and so it basically comes back. So, this is this particular behavior which deform only by twinning variants is called as Pseudo plasticity. Pseudo plasticity because even though, the deformation is plastic, but if we warm it up or if we increase the temperature, if we provide heat then those twin variants will vanish and the martensite will be transform into austenite and the whole strain could be recovered. So, this is that is why we use this term Pseudo-plastic behavior. So, we understood the arrangement of martensite variant and how we really recover a strain.

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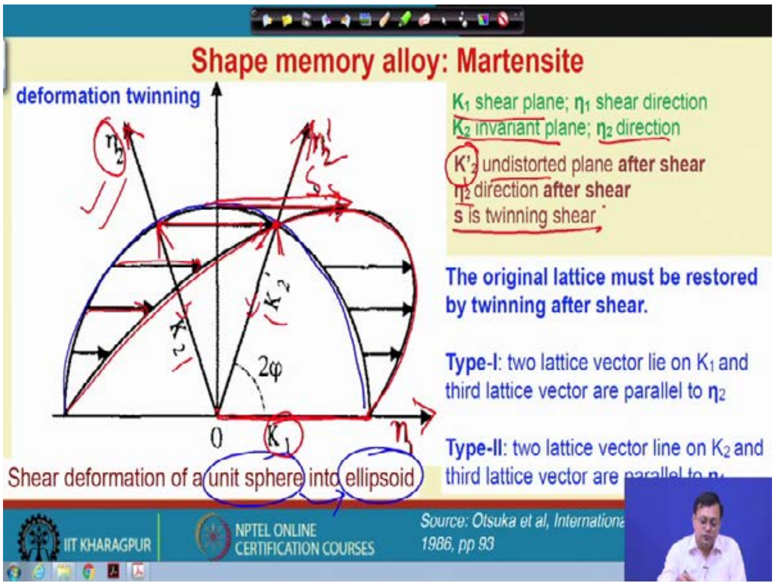

Now, it is for sure, we have to also understand when we talk about a giving some shear how this shear is accommodate in martensite. So, using some schematic model several scientist has tried to understand and this is the very important information. Let us first assume that we have a sphere which is shown here with this blue color. So, we are talking about a shear deformation of a unit sphere and then after giving the shear, the shape will be change; there is no sure there is it is for sure. So, it will be change into the ellipsoid.

So, ellipsoid means it is now the final position after providing the shear is here and these are the position which has shifted. So, we have given the shear which is which is S, a vector. So, S is a twinning vector that has been given to this unit sphere. And now, please have a look at some of the important vectors and their direction.

So, K_1 is this plane that we are talking about. K_1 is this plane we are talking about and shear is basically along this direction. So, shear is parallel to K_1 plane. $K_1$is the shear plane and the direction is the η_1. η_1 is the direction of the shear. Now I have taken an invariant plane; why I call you as an invariant? Because this is the point which after shear comes here.

If you see the vector then the length of these magnitude of the vector is the same. So, it is basically an invariant one and the initial direction was η_2; before deformation and now the direction has changed. It is now η'_2. So, K_2 is the invariant plane and η_2 was its direction. However, after shear K'_2 is the undistorted plane whose magnitude has not changed. So, if you compare K'_2 and K_2 and $\eta_2$is the new direction of shear. So, this is η_2. Now if we think about and we saw these diagram, then we can simply say the original lattice we can restore only by introducing twinning after shear.

So, Type I twin is basically the 2 lattice vector that lie on K_1. So, lattice vector which is lying on K_1 and a third lattice vector that are parallel to η_2. So, that will be actually the Type I type twin and Type II twin is that the 2 lattice vector that lie on the plane K_2 and it has a direction that is η_1. So, these are the 2 different variant just to explain schematically that what are these Type I type twin and what is the Type II type of twin.

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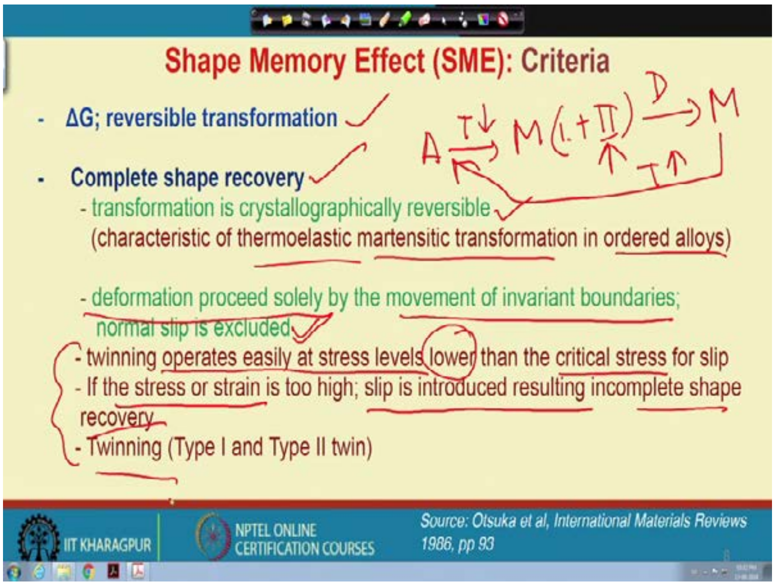

So, now if I summarize this whole shape memory effect, then we can easily understand that there should be a net decrease of the free energy of the transformation. What I want to mean that if we take a martensite; if we deform it, then after deformation again we heat it then it will be austenite. So, this net transformation there should be decrease in the free energy and this transformation from austenite to martensite with two different type of twins, then plastic deformation, then we reheat it. So, this whole transformation should be reversible. A reversible means austenite to martensite and martensite to austenite.

So, there should be a reversibility of the transformation, then only we can achieve the shape memory effect. So, this is one of the very important criteria for achieving shape memory effect and then, the second most important aspect that the shape of the material after plastic deformation of the martensite should be recovered, regained. How it is possible? Only when the transformation is crystallographically favorable means a austenite lattice and the martensite lattice, they should they should switch between them by basically increasing or decreasing the temperature and giving the stress and releasing the stress.

So, what I want to mean that I have started with austenite, I cool it. So, I decrease the temperature I get martensite with 1 or 2 type of twin; then I deform it, plastically deform it. And then, after deformation 1 type of twin has grown in expense to other it is still remain as martensite; then, I increase the temperature and then, I get back the austenite. So, this is actually the complete shape recovery occur and when the transformation is crystallographically feasible and reversible and this is a typical a character which can only be achieved when this martensitic transformation are the thermo-elastic in nature.

So, in ordered alloys, most of the cases, such kind of behavior has been observed. Now another most important criteria to achieve shape memory effect is the deformation proceed solely by the movement of the invariant boundaries, where normal dislocation slip should be excluded. If the dislocation any dislocation is involved in this process, then there will be no chance of getting back the 100 % original shape, means 100 % shape recovery will never be possible.

And therefore, what we really need? This means I am applying stress to the material and what really determine that there will be no formation or nucleation or multiplication of the dislocation? Only if the critical resolved shear stress for initiating dislocation is higher and the critical stress that is require for twinning is less or then only twin will form; is not it?

So, the stress level that operate for twinning must be lower than the critical stress for the slip and if the stress or strain is very high means I am taking a shape memory material and then, I am straining it high and high and high; then besides twinning and besides the growth of those twins Type II type of twin let us say goes in expense to Type I type of twin, then dislocation will be introduced. And if dislocation will be introduced, then even if we warm it up and heat it and we reach to the temperature above austenite finish; then we will never get 100 % shape recovery.

And therefore, the slip is introduced and it will result incomplete shape recovery because of the introduction of the dislocation or any other kind of defect. So twinning is very much important where Type I type of twin or Type II type of twin are basically introduced. So, this is one of the very important aspect of shape memory effect and so today, if we try to summarize what has been discussed so far that for shape memory behavior, we need the martensitic transformation and the self accommodation of the martensite due to the transformational strain; it will only be involved with twinning and not only one type of twin there must be other twin variant that should form during twining in the martensite.

And then, we will get the plastic strain only due to the movement of the invariant boundaries. Let us say one type of twin which grows in expense to the other one and then only after again reheating that martensite, we will be able to reach to the austenite finish temperature and martensite will be heated and the whole shape recovery will occur and this is the all about fundamental understanding of shape memory behavior .

So, now, I already discussed with you that twinning or during martensite transformation from austenite, we have we already know that there is involvement of twinning, dislocation, stacking fault, rotation. So, none of them can give you 100 % shape recovery. So, only where twin is involved and that twinning should have different variants. So, then only will be able to achieve 100 % shape recovery. So, today, we discussed up to this.

In the next class, we will continue this Shape memory effect and Pseudo electricity discussion.

Thank you very much.