Advanced Materials and Processes

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Lecture – 17
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 one class, we have just started our discussion on different types of phase transformations in metals and alloys. So, we have classified various types of phase transformations. In that particular field, we have tried to learn what diffusion-less transformation are and among them two transformations are very much important; one is martensitic or quasi-martensitic transformations.

So, a transformation is martensitic transformation, we cannot confirm or we should not confirm by its product or parent crystal structure; rather how it transforms or how the product transforms from a parent lattice is important. We have also discussed that there are 3 very important aspects of martensitic transformation. So, these 3 are that it is a lattice distortive type of transformation, there is no diffusion at all required. So, it is a diffusion less transformation or it is also called as a military transformation and the third is a high strain energy is involved in this martensitic transformation.

We are discussing the diffusion-less transformation because in this particular topic of Shape Memory Alloys, the role of martensitic transformation is very much important. We have learned that the martensite does not mean that it will be always a needle like or lathe type, rather there are total four major types of features involve in this martensitic product features or morphology. And therefore, how a product has formed that characterizes whether it is martensitically transformed product or not? And today, we will extend that discussion further and try to do some vector analysis and we will look at more insight into martensitic transformation.

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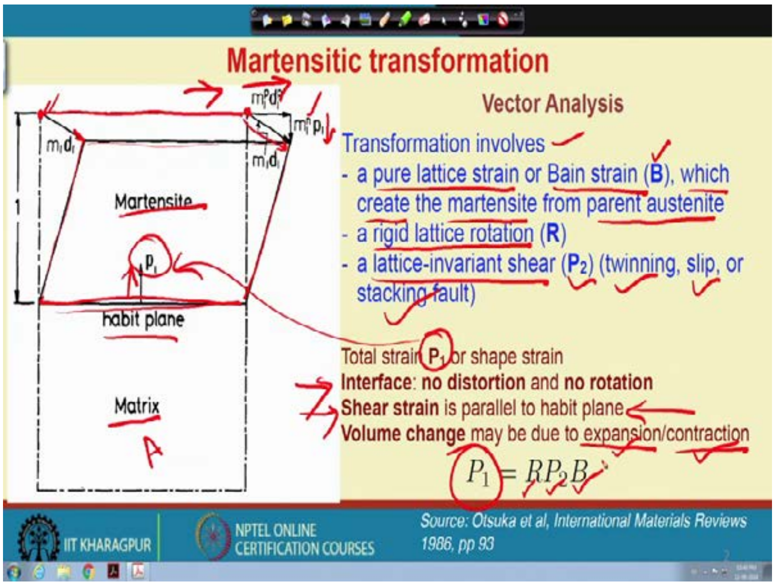

So, please have a look at the schematic shown in the left hand side. Here, you see that I have shown a matrix. Here, the matrix means the parent austenite. So, we have a matrix of austenite and martensitic transformation is proceeding. We also have discussed that the product martensite and the matrix austenite has a very sharp interface and that interface is the habit plane which is often called as an invariant plane. It is invariant because there is no distortion or no rotation occurred on that plane.

So, habit plane of that austenite remain as the same and now let us see, here the product lattice is this one and this one was the initial matrix austenite lattice and so the transformation, we consider here, this in the vector analysis that transformation involve a pure lattice strain or we call it also as a Bain strain which is represented with a vector B and this B vector which create a martensite from the parent austenite lattice. And the second part is that there is a rigid lattice rotation involve in it and now since, I said that there is a high lattice strain involve in it.

So, you need to consider a lattice invariant shear, which is represented with a P_2 and this lattice invariant shear involves introduction of different type of defects. And these are twinning or it could be dislocation slip or it could be stacking fault. In majority of the book or several discussion you will find that martensite means basically it always contain some twin. Yes, but it is not.

So, in reality the lattice invariant shear or when a parent austenite transforms into a product martensite, the transformation involve a high lattice invariant shear, which incorporate different type of lattice defects and this defects are 4 major types. It could be twinning; it could be slip; it could be stacking fault or even sometimes it has been seen or a rotation or even sometimes it has been seen that a mixture of twinning plus dislocation; we will come later on. But, let us first discuss the vector analysis.

Now here you see that a direction is shown which is normal to the habit plane and here one vector is shown as $m_1^p d_1^p$ and here is another vector is shown which is along the direction of the normal. So, n basically comes because of the normal and the net here this total strain is $m_1 d_1$ which is basically addition of these two vectors.

So, this particular point, it comes here. So, this is the total moment now the net strain or the total strain is represented with P_1 and we also considered that the interface, there is no distortion and no rotation which is basically the habit plane, which lie at the interface of the product and the parent. Now, the shear strain here is parallel to the habit plane.

How to understand? Here, this is the habit plane. This one is the habit plane and here is the shear. So, shear direction is parallel to the habit plane and now the net volume change that is involved in this phase transformation could be either expansion or contraction, why? Because the austenite has a lattice that unit cell has a particular volume and that transform by a diffusion less phase transformation process and it creates a different lattice. Even though, there is no civilian movement or the diffusion involved in this atomic rearrangement process; but the unit cell volume of the martensite may be different, then the austenite unit cell volume.

Like as an example, I can tell you like a steel. In case of a steel, the austenite is FCC crystal structure that is γ-austenite and in case of the martensite, it is body centered tetragonal structure and you have seen that the body centered tetragonal have a different volume than the austenite. Therefore, the expansion or contraction of the product should be considered here. And the P_1 this is equal to R which is the lattice rotation; P_2 that is the lattice invariant shear and the P_o lattice strength that is B. So, these are the product of this 3 different vectors good.

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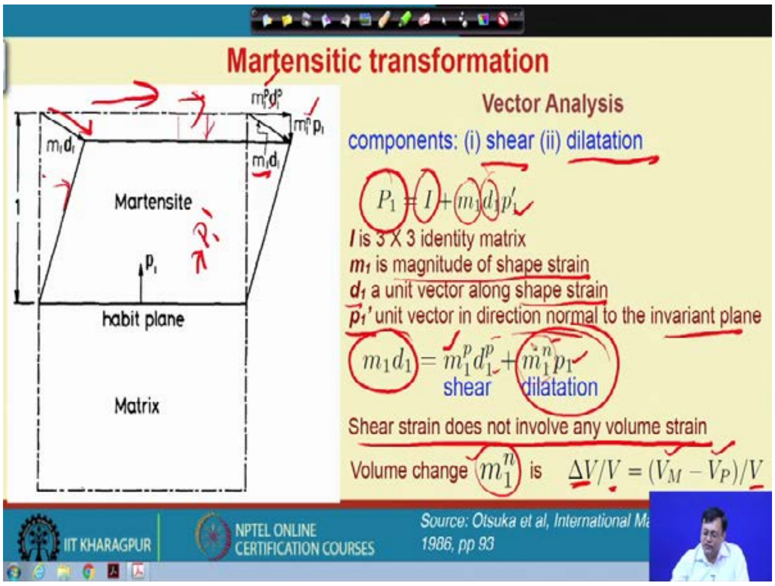

And if we look at very carefully, then you will be able to see that there is a dilation involve and there is a shear involve. So, martensitic transformation has two components; one is the shear, another one is the dilatation. So, this P_1 is basically a summation of an identity matrix I plus $m_1 d_1 p'_1$. What are they? m_1 actually stands for the magnitude of the shape strain. This is the magnitude of the shape strain. So, here is the m_1 and now it is in which direction that gives you basically the superscript; d_1 is a unit vector along the shape strain.

So, that shape has change in this direction it has distorted there is a shear you can see this. So, this along this direction they are it comes the unit vector d and p'_1. p'_1 is a unit vector in direction normal to the invariant plane. So, here we considered there is a unit vector that is p'_1. And, so the $m_1 d_1$ which is represented with this vector, which is the summation of a shear component and a dilation component.

What are they? Here, this is the $m_1^p d_1^p$ and m_1^n this is to the normal direction here and the p_1 and one thing is very much involved and we must considered that the shear strain does not involve any of the volume strain. So, when we know that there is a shear goes on in the austenite parent lattice. So, it does not basically involved in any kind of volume change; but volume change is given by this particular component.

So, we could easily understand that the volume change which is represented with the magnitude here m_1^n is equal to ΔV which is the volume change which could be positive or negative due to martensitic transformation and the parent net volume which is equal to the volume of the martensite minus volume of the parent austenite divided by the net volume.

So, from here we can measure this particular component and this is very important actually. We will see later on why these consideration are very much critical? So, now, in a martensitic transformation we learn that there are two different component are involved; one is a shear, another one is the dilatation.

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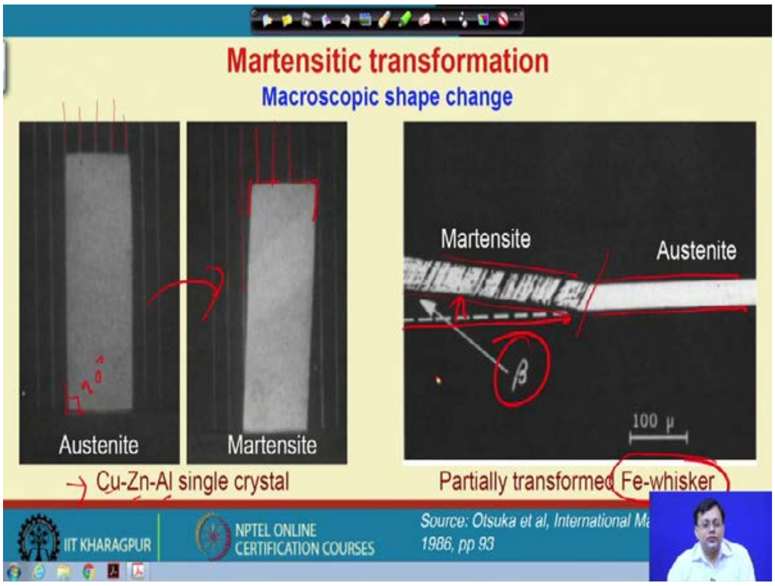

Now, we must look at the real changes that occur, where there is really a shape change in the austenite during transformation. So, here one example I show you in the left hand side. This is a copper-zinc-aluminum single crystal and some lines are drawn here. So, that you can see and monitor this angle is basically 90° and after phase transformation, the same single crystal has change this angle, you can see these are the line you can see that and how the shape has changed. How the shape of the martensite changed from the parent austenite due to the martensitic transformation.

Very similarly, we can also see that some iron whisker, the change of the austenite from the martensite. So, it is actually this is the austenite sample and this is the interface which is the habit plane and here the martensite; from this particular orientation it has change at an angle due to the shear involve in this process. So, even if you take a single crystal or a whisker, then you can directly see how these shape strain involve a macroscopic shape change in a single crystal. So, that gives us an idea about the net change of the volume as well as in the shear direction.

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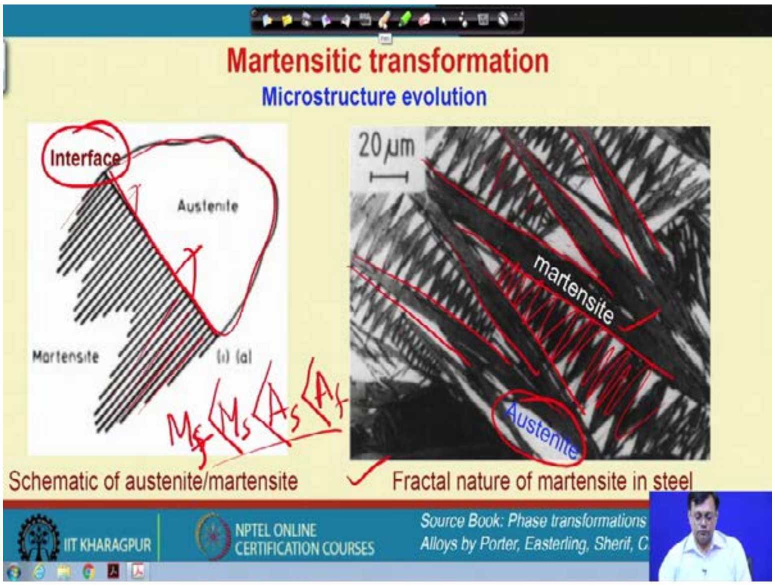

Now, we must look at how the microstructure evolves in a polycrystalline sample? So, schematically I have shown you here that this is like a austenite grain and this is the interface which is unrotated and undistorted, which is a lattice invariant plane and these are the martensite that basically transforming from the parent austenite.

So, interface will move along this direction and consume the whole austenite grain. In the right hand side, we can see this is an example of a fractal nature of a martensite in a steel. So, the whole grain was austenite initially and after martensite forms and they consume those austenite and after this transformation, the new martensite nuclei appear and they basically consume this part of the austenite.

So, once this particular martensite has formed, then the new martensite nuclei again will appear and they will grow and in this process, the whole transformation will be completed until and unless there is the complete austenite consumed by the martensite. However, it has been observed that 1% to 2% residual austenite which never completed it is transformation because of some sort of stabilization that may be discuss later on.

So, along this aspect and topic we also have learnt that martensitic transformation involve 4 very important temperatures, when a martensite is heated then austenite will form and that temperature of start is called as A_s austenite start and when the complete transformation will occur it is called as austenite finish.

On the other hand, when austenite is cooled, then martensite will start to form the temperature is denoted at the M_s and it will finish at M_f. So, if you look at the temperatures, then they lie somewhat here. So, austenite finish is higher than austenite start which is higher than Ms than M_f. This is the usual sequence.

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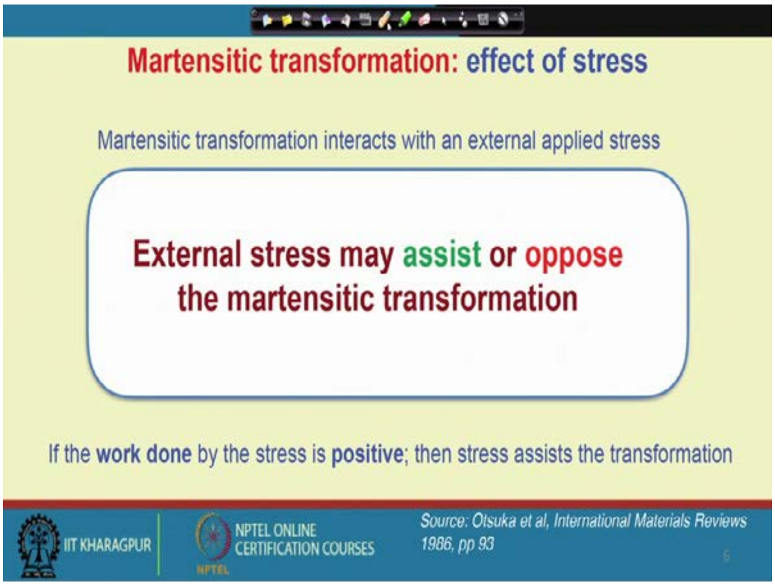

Now, we learn about this 4 temperatures. So, this basically means that if you change the temperature of austenite or martensite; then we may reach to the other phase. However, the question arises whether there is any effect on the external stresses that may be involved in this martensitic transformation. The answer is yes.

So, the martensitic transformation interact with the external applied stress field and this external stress field, there is another question we will arise whether if I apply stress to a martensitic transformation, whether it will assist or it will not assist? Yes, it depends on some other factors. So, external stress may assist or it may also oppose a martensitic transformation. And how to know that if I apply stress, the martensitic transformation will be assisted by the stress or it will be oppose by the stress? So, for that particular thing we have to see and calculate the work done by the external stress.

If the work done by the applied stress is positive, then it will simply assist the phase transformation. However, if the work done is negative, then we will see that it will oppose the transformation. So, this is something very much interesting. So, it means that whatever temperature characteristics temperature I talked to you about like a characteristics temperature like M_s, where when you cool austenite the martensite start forming. So, if I apply stress then Ms can be tuned depending on the applied stress and that could be very much interesting.

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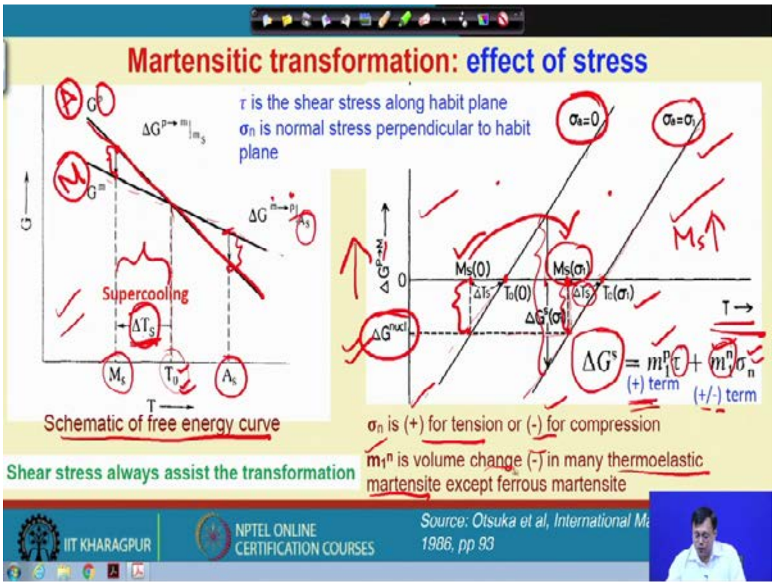

Now, let us have a look at this particular plot. So, here a schematic I have shown you which shows the free energy curve of this martensitic transformation. So, the first carve this one is stands for the parent phase; parent means austenite and this is the free energy curve of the martensite. And you see here that the transformation temperature is T_0. T_0 means that below the temperature martensite is stable; above the temperature austenite is stable.

But in reality, it does not happens; means that for any phase transformation you have to cross or the system has to cross the activation barrier of the transformation. So, in that particular phase, we have to give some sort of under cooling and how these under cooling or super cooling affect the start temperature you can see here.

So, ΔT_s represent the actual transformation temperature and the difference between the martensite start temperature. So, this difference gives us that the ΔT_s is required in order to transform from austenite to martensite. So, here is a net decrease of the free energy. On the other hand, if you start with a martensite and if you keep on heating at T_0 it should be austenite; but you need some extra activation or extra energy or activation energy so that there will be a net free energy change. So, here this is from martensite to parent austenite transformation which start at A_s. A_s stands for austenite start temperature.

So, now how to know that shear stress will assess the transformation or not because I said that shear stress may also oppose the transformation. So, let us have a look at this particular diagram which I have presented here, we take axis of ΔG. ΔG here stands for from parent to martensite phase; parent austenite to martensite and here X-axis is the temperature. And so in the X-axis of the temperature, we know here where the T_0 lies in this case, in this plot T_0 lies here and we need some super-cooling from austenite to martensite transformation and we consider this point because here the applied stress is 0.

So, definitely the free energy will follow this line and we need ΔT_s. So, ΔT_s is here. It basically means that martensitic start temperature is somehow lying here because there is an activation energy that is required for the nucleation of the martensitic phase. Clear? So, if that is the case then we see that both this diagrams are clearly understandable to us.

And now, a stress will assist the transformation. What does it mean? It means if I provide some stress then the free energy will decrease; is not it? So, now, whether this side we should go or that side? If I apply stress, then the curve will shift here. So, this means I will always have at any given temperature; I will always have decrease in the free energy by the application of stress.

Now if that is the case then, we again need the activation energy and please try to remember that these free energy required for nucleation or the activation barrier does not depend on whether it is thermally activated martensitic transformation or stress induced, they are the same because the activation barrier you have to reach to that particular point of transformation.

So, if that is the case then we can see here this gives us the T_0 for applied stress. However, you need a ΔT_s here. So, in that particular case because you need this activation energy; so, M_s has moved from here to here. This means M_s has raised, right. So, if I apply stress, if I apply stress and this applied stress will assist the martensitic transformation; then M_s temperature will rise, otherwise if it oppose, then M_s will go down.

So, that is the case actually. Now here, you see that ΔG_s which stands for net free energy change. There are two components; one component is the shear stress which gives you a positive term and here is the normal stress, it could be positive or negative. Why? That is very simple if it is tension, then it is positive, when it is compression then it is negative. And now the m_1^n is the volume change. So, it is negative m_1^n. So, this one is negative. So, in most of the thermo-elastic stress driven change in the transformation and most of the martensite except ferrous martensite involves a volume change which is the negative.

And now, the stress which we apply along the habit plane is the shear stress which I have written here and this shear stress will always assist this particular transformation and σ_n stands for the normal stress perpendicular to the habit plane if you remember the earlier diagram. So, here we have seen that the shear stress assist the transformation; whereas, this normal stress plays the role whether the transformation will be assisted by the stress or not because shear stress always the assist. This part is always in favor of martensitic transformation. However, this part may or may not.

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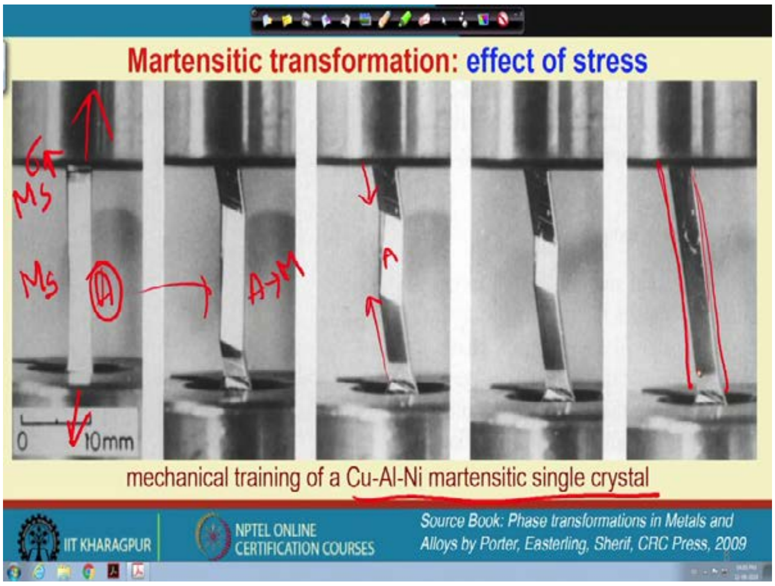

And now I show you one of the example of such martensitic transformation under stress. So, I have taken a copper-aluminum-nickel martensite single crystal and put it on a tensile test machine and stressed it. So, initially the microstructure was austenite and then, the austenite should be stable at zero stress and martensitic M_s temperature has raised up because of the stress assisted transformation.

So, initially the martensite start temperature was lower and now martensite starts temperature has increased due to application of the stress. So, austenite is now transforming into martensite. So, in that particular case you see the martensitic transformation is occurring from both the ends and this is the austenite and then finally, the whole martensite has form from austenite and that basically bend the geometry of the specimen. So, there is a net shear you can see and so on.

So, there is a definite effect of stress on martensitic transformation; even though the shear stress applied along the habit plane assist the transformation. However, the normal stress it basically depends whether it is positive or negative. There is a volume change is positive or negative that basically dictate whether the transformation will be favor or it will be opposed and next day we will continue this discussion.

Thank you very much.