Smart Materials and Intelligent System Design
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Lecture – 05

Good morning everybody, welcome to the final lecture of module 1, on this book course Smart Materials and Intelligent System Design.

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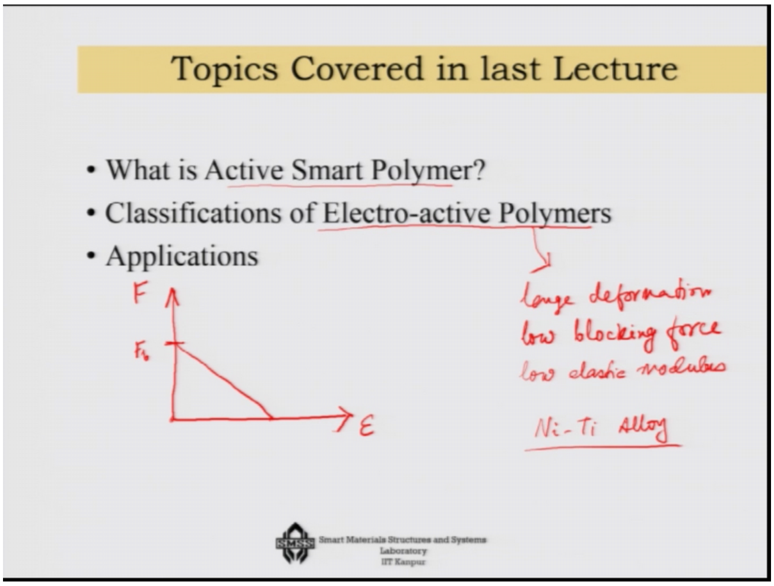

In the last particular you know lecture, we have talked about active smart polymers, and also I have test the issues on classifications of Electro-active Polymers which is a special group among this active smart polymer, and there if you remember we have mostly focus on IPMC, Ionic Polymer Matrix Composite. Now, the reason behind developing these kinds of you know active polymeric systems was I was telling that the inspiration was from the muscles ok, so that you can get a large deformation in the system.

However, also we have noted down that in polymers even though you can get large deformation, you are not going to get large force out of the system. So, this kind of active polymers will give you large deformation, but it will give you low blocking force. Now, already I have once told you about this concept of free strain and blocking force, if you remember that if we consider this you know as a strain versus force strain versus force of an actuator then when it is freely straining at that point, it is actually the maximum point, you know maximum strain that you can get from the system.

And on the other hand this is the point which we call it as the blocking force, where the strain is 0, but you are getting maximum force by stopping the actuator to defog at all; so that actuator will be giving you the force. Now, this force naturally depends on the you know one of the parameters is the modulus of elasticity. So, because these polymers are having low elastic modulus, so they will be giving us low blocking force.

Now, that is where we will see today that if we use not a this polymers, but a metallic alloys for example, nickel titanium alloys mostly used, then you will see that this modulus of elasticity will be much higher and as a result the locking force will be much higher, but of course, somewhere there is a compromise that the free strain for such cases will be lower. So, those are the group of materials that I will be discussing today and that is you know given a common name which is called shape memory alloys.

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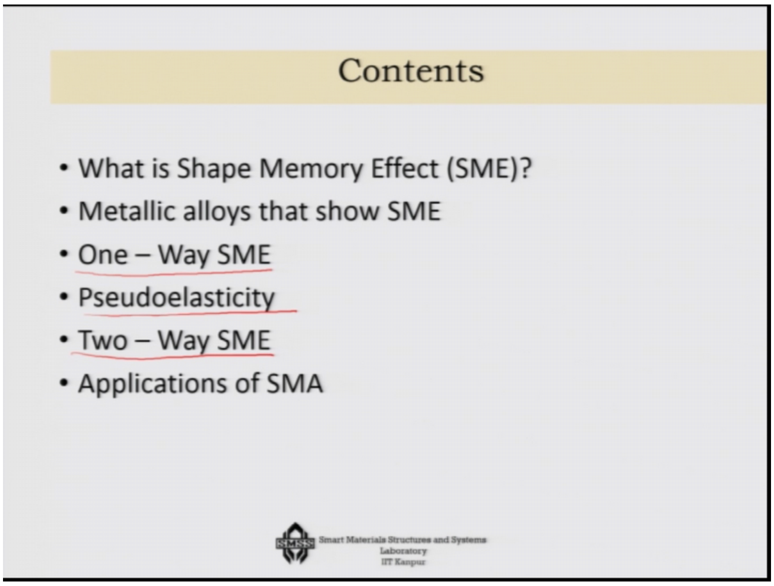

What I will be talking about is what is shape memory effect first of all and then the metallic alloys that show such shape memory effect. We will also talk about a couple of interesting properties like one-way shape memory effect, Pseudo-elasticity and two-way shape memory effect and finally, I will show you some applications of this shape memory alloy actuators.

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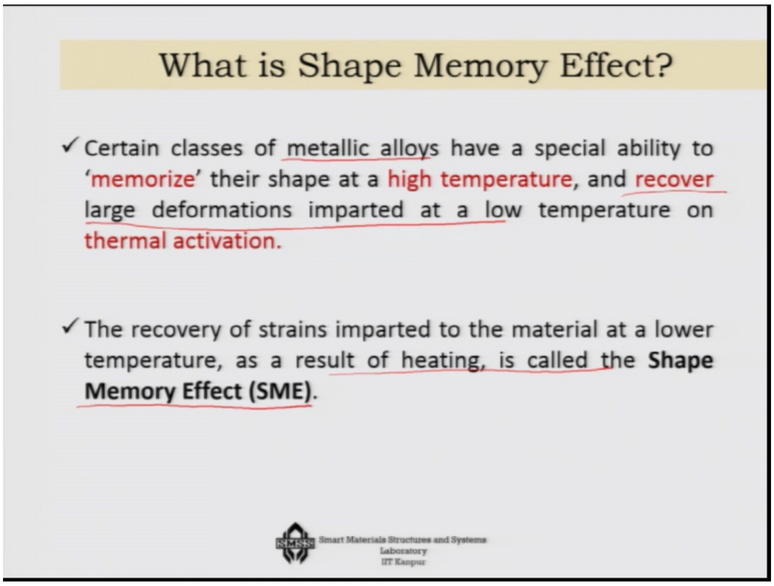

So, let us begin with that: what is this shape memory effect? Now, many of you might have seen this movie for example, Terminator 2 which actually you know amplifies the situation where the robot even if you melt it down the moment it is getting cold it actually gets backs its original shape. So, that is too much of a science friction, but indeed materials certain materials, it is found that they can actually remember their you know parent state shape and that is that happens particularly for certain group of metallic alloys ok.

So, this parent state is generally with respect to high temperature and whatever you do with this metallic alloy at the low temperature, the moment you take it back to the high temperature, it will get back to the parent shape because, it can recover the large deformations that are imparted at a low temperature. And, we will see later on that it actually happens because of a very regular crystal structure, most of the times it is a body centered BCC structure that it actually attains at a high temperature. This recovery strains imparted to the material at a lower temperature and which is you know actually later on regained by heating this entire phenomena is actually call the shape memory effect. So, we will see that how you know step by step we can carry out the deformation and then recovery of the material.

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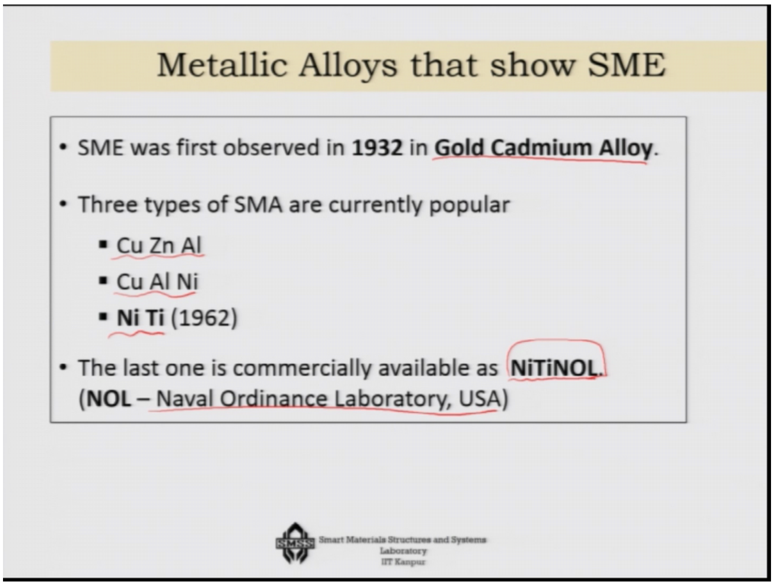

The effect was first observed in gold cadmium alloy in 1932, but gold cadmium is a very expensive alloy, so you cannot use it for day to day applications, neither it shows very large amount of this shape memory effect. It was found out later on that there are three candidates, the two ternary alloys copper, zinc, and aluminum and copper, aluminum, nickel, they show this effect and also one binary alloy that is nickel titanium, they also very interestingly show this effect of shape memory you know unit and once again this things are discovered particularly the nickel titanium.

So, on at the naval ordinance laboratory of USA and hence whenever we say this product it we actually refer it as NiTiNOL that NOL, part is the Naval Ordinance Laboratory abbreviation that is added with it.

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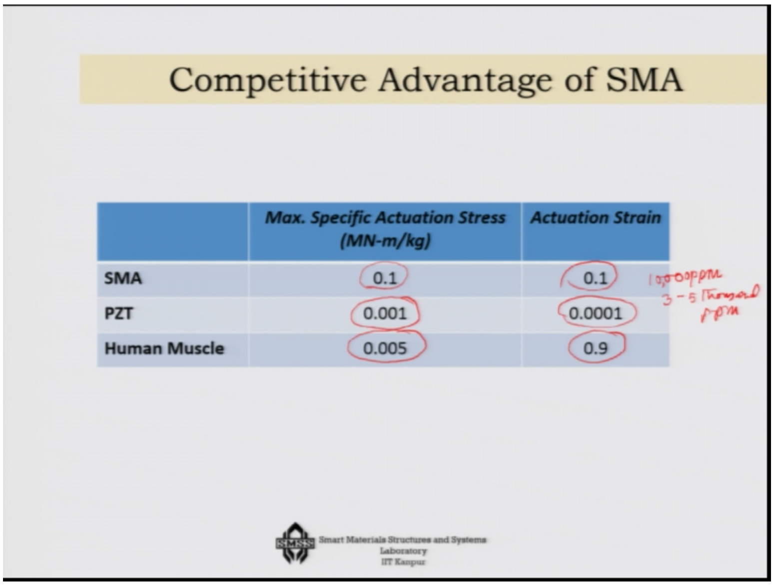

Now, what is the competitive advantage of SMA why should we go for this new material, if you look at it that from the you know actuation stress point of view piezoelectric material was having only about 0.001 mega Newton meter per kg you know specific actuation stress that in per unit weight in that same tone, if you actually check with the human muscle is slightly better means about 5 times better than PZT. However, this SMA is actually several orders of magnitude higher. So, with the same weight you can get much larger actuation stress from the SMA.

So, which means it is a you know it is possibly a much higher level something like you know 100 times more powerful than you know this other materials. So, that is how you know you can have a very good use of such materials in applications like robotic well, in terms of the strain also if you look at it piezoelectric material shows very very SMA ll strain, human muscle relatively shows a larger strain, but SMA shows a strain of around 0.1. So, it is not very high in terms of strain and the 0.1 also is maximum. We call it as you know 1000 parts per million 10000 parts per million, but this is maximum generally what we get is something at the range of 3-5000, 3-5000 PPM. So, actuation strain is not as I as a human muscle, but certainly it is higher than piezoelectric material.

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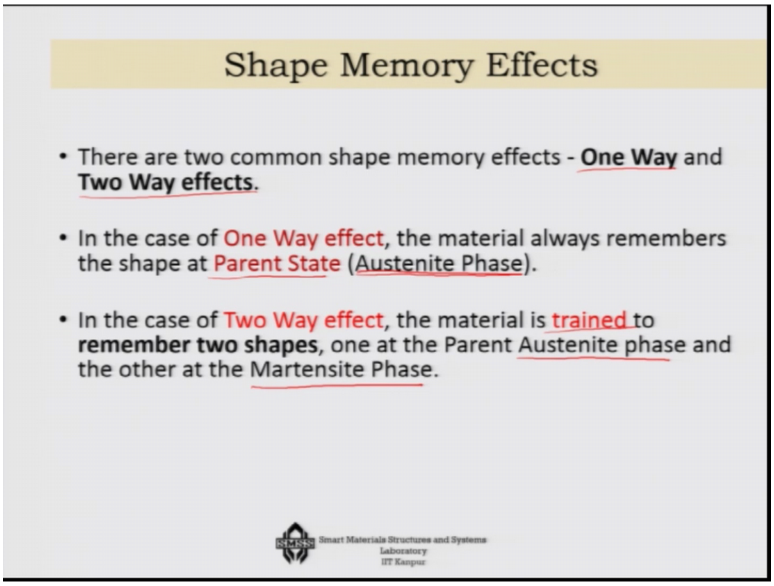

Now when we are talking about shape memory effects, there are two different types of shape memory effects, one is called one-way shape memory effect and another is called two-way effect. In fact, it is the one-way effect which is more you know related to the material property and two-way effect is something that comes through the training of the material. So, in the one-way effect what happens is that material remembers the shape only at its parents state and that parent state we would be referring it as Austenite phase, which is a high temperature.

But in the two-way effect the material will remember its shape both at Austenite phase that is high temperature phase as well as at low temperature phase that is Martensite phase. So, Austenite phase is high temperature and low temperature is Martensite phase and the material will remember both the shapes if it happens if you give proper training then only you will see the two-way effect.

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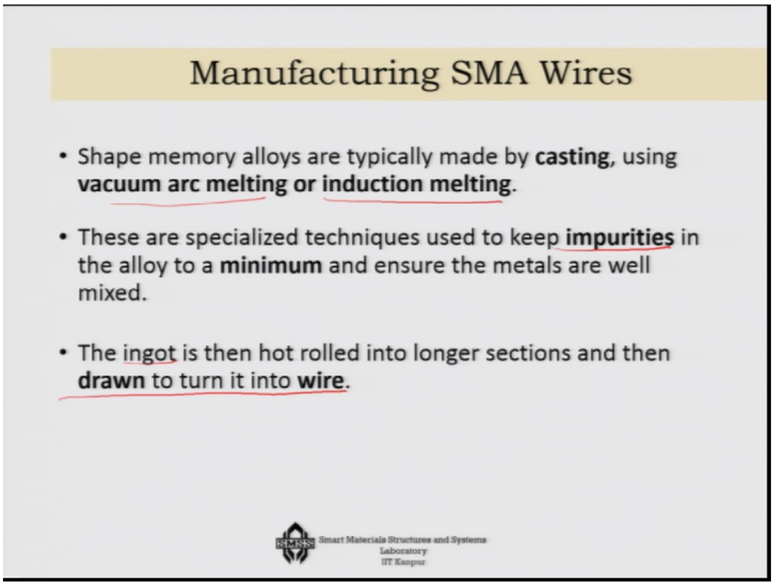

How do we manufacture such SMA wires with you can see that the basic composition is very simple nickel and titanium, but in order to have this crystal structure which will allow the twining it is to be very very pure. So, you know and also you have to do it at a high temperature mixing nickel and titanium. So, generally we use vacuum arc melting or induction melting process and we have to take this in vacuum is a, so that you know we can take care of impurities you can reduce it to a minimum oxides to a minimum.

So, at very high temperature in vacuum we melt nickel and titanium mix it together and then we get the ingot which we later on drawn into mostly wire forms, but today it is also available in thin strips and people are also talking about porous SMS which has some advantage in terms of quick temperature dissipation.

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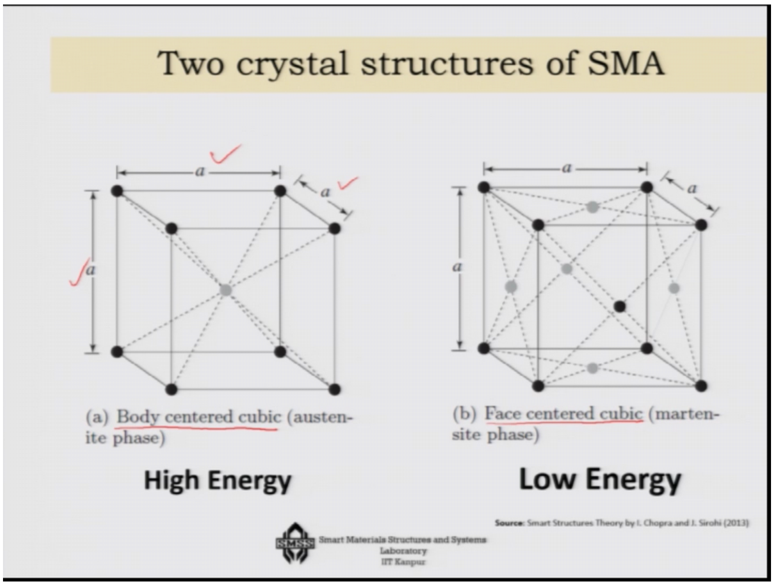

We were talking about the parent phase or the Austenite phase and the Martensite phase and each phase has its own typical crystal structure. At the Austenite phase that is at the high energy phase high temperature phase also there the crystal structure will be body centered cubic or BCC structure and it is a cubic crystal structure as you can see that in this unit cell the all these are of same size. So, it is perfectly cubic you know structure.

Now the moment I actually reduce the temperature then this changes to face centered cubic system and so you know from the body centered the crystal structure becomes face centered cubic and further many times it actually changes from cubic system to rhombic systems you know in terms of the crystal shape for example. Now so, these are the two. So, BCC at high temperature phase or Austenite phase and FCC at low temperature phase or Martensite phase we have to keep in mind.

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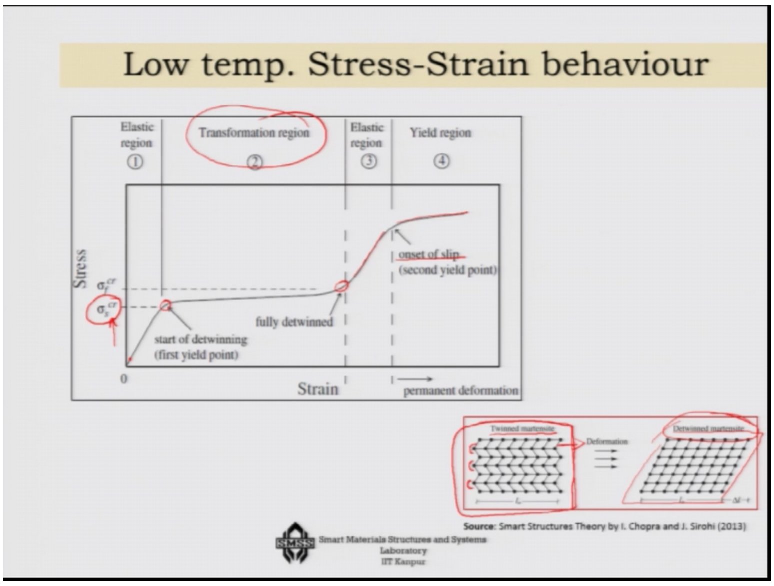

Now, let us see at the low temperature phase how it would behave, well if I reduce the temperature from BCC to FCC we generally do not see an appreciable change in terms of the original shape or the size of the system, why is it that we do not see it is because that even though it goes from BCC to FCC, but the crystals very nicely create a fold you can see a fold here, you can see a fold here a fold here. So, this folds actually take care of that you know expansion that could have happened in the or contractions that could have happened in the system.

So, that is why there is no shape change that you will see if you cool a system from Austenite phase to Martensite phase and this particular Martensite phase is called twinned Martensite phase. Now so when we are applying stress so far we are only applying temperature to bring it down to twinned Martensite phase. So, let us say at low temperature we are somewhere here where we are at the twinned Martensite phase. And, now I am increasing the stress, as I am increasing the stress there is a sigma stress critical beyond which the twinned Martensite state will actually this folds will vanish, the crystals will layered this layers will start to actually slide, each crystal layer will slide and then you are going to get this kind of a rhombic shape.

So, this is your detwinned Martensite phase. So, here sigma s cr here starting of the twinned Martensite phase and then sigma f cr here that is finishing stress at which complete you know detwinning has taken place. So, you have to you know even though this looks like a you know plastic deformation, but this is essentially crystal twining that is taking place in the system. Now once it is in the fully detwinned shape so, it is here, again if i increase the stress it will behave again like a elastic so region ok. So, the same way and finally, once the stress is beyond a certain level, there will be the onset of slips and then the plastic deformation and the failure will take place in the system.

So, the initial large deformation that you will see is not because of plastic deformation, but because of these twining you know detwinning to twinning this transformation that is happening in the system. So, twinning to detwinning or detwinning to twinning; so, that is: what is the low temperature stress strain behavior in the system when you are only in the Martensite region.

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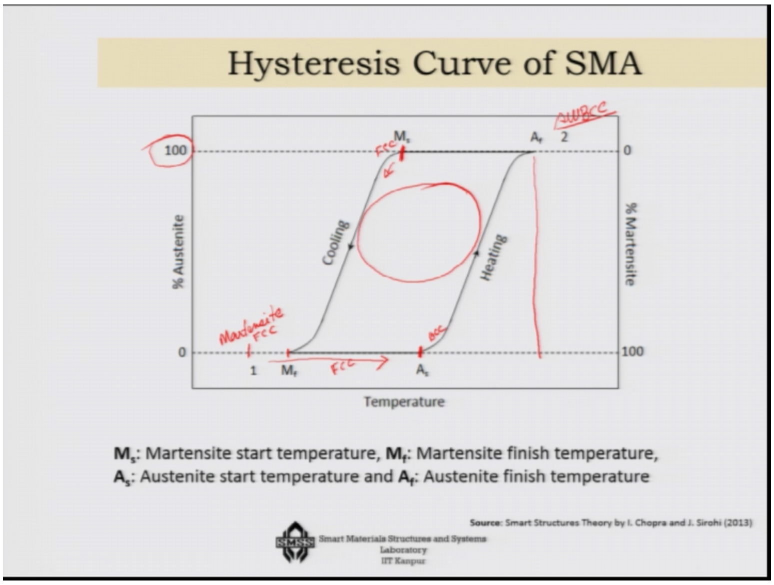

Now, what happens if I look at it with respect to temperature, well if you take a sample at a very low temperature let us say we expected to be here somewhere at a completely Martensite phase and what Martensite phase if there is no other stress etcetera then it is supposed to be at the twinned Martensite phase.

As I am increasing the temperature gradually ok. So, we will come to a point which is called Austenite start. So, far it is at the twinned Martensite state and also this is having FCC structure as we have already discussed. At, A s what will happen that some of these crystals will start to get transformed to BCC structure. So, now, this FCC to BCC transformation is happening, but not fully only some crystals, as I am increasing the heat further somewhere at A f I get full transformation to Austenite. So, all BCC I will be getting at this stage all BCC.

So, that is you know everything has been transformed from FCC to BCC Austenite finished I go to the parent shape of system. What happens if I again cool the system? So, this is 100 percent Austenite, if I cool it again at a particular temperature M s the bcc will start to get transform to FCC. So, now, BCC will start to get transformed not all of them, but just start the process and as I reduce the temperature further it will reach a point when Martensite finish will come and it will complete this and it will be completely Martensite and it will be having completely FCC structure. So, that is a temperature dependent behavior.

Now, look at it that when this is happening this M s and M f they are not actually coming at the same point neither A s and A f. So, there is a hysteresis that is always present in the system, now that hysteresis you know is something which you will see later on that in terms of stress we can actually exploit it as pseudo-elasticity, in terms of temperature this hysteresis for an actuator is not very good the naval it is the better is the system.

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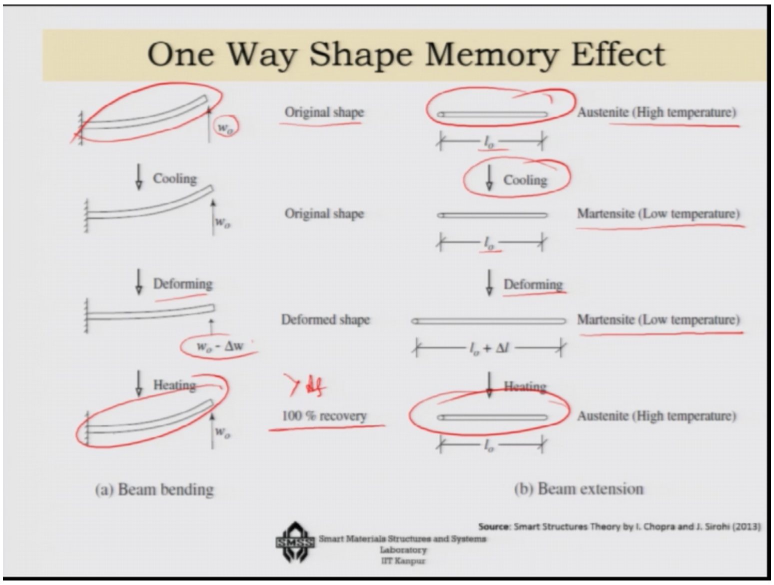

Now, let us look into the one way shape memory effect just once again because it is little bit complex. So, let us see that I have taken a beam here and I am bending the beam here I am giving a deformation bending the beam and this is at its original shape that is at Austenite high temperature. Now, I am simply cooling this system what will happen I told you that there will be no change of shape. So, if I cool it there will be no change of shape length is in the same which means here also in the bent case there is no change of shape, but only it will get converted from Austenite to twinned Martensite phase. Now if I apply load, so I am deforming I am applying load and then if I apply the load what will happen is that there will be a change of shape that will happen to the system and; that means, this you know twinned Martensites is going in the Martensite phase in the detwinned shape.

Now, again if I heat it up beyond a certain Austenite finish of course, beyond Austenite finish we will get 100 percent recovery. So, you will get back the original shape just like this shape. In this case also it get back the original shape just like this shape ok. So, that is the one way shape memory effect and how people got excited about it, its phenomenal that you know the first thought of NASA that let us make an antenna out of this shape memory alloy wires and then let us you know at the Mertensite stage low temperature stage you know let us deform it because at the Martensite stage you can deform it ok.

So, you squeeze it that whole antenna you can make it at the Austenite pahse and then you squeeze it and you can make a SMA ll roll out of it. Now the moment you deployed in the space you increase the temperature it goes to Austenite phase and you get the full antenna back. So, that was how you know first applications were actually and we said of this one way shape memory effect. Now, what if so far we have not done two things together what if I do both the things together temperature and stress ok. So, there are three parameters here in this system stress, and temperature and strain ok.

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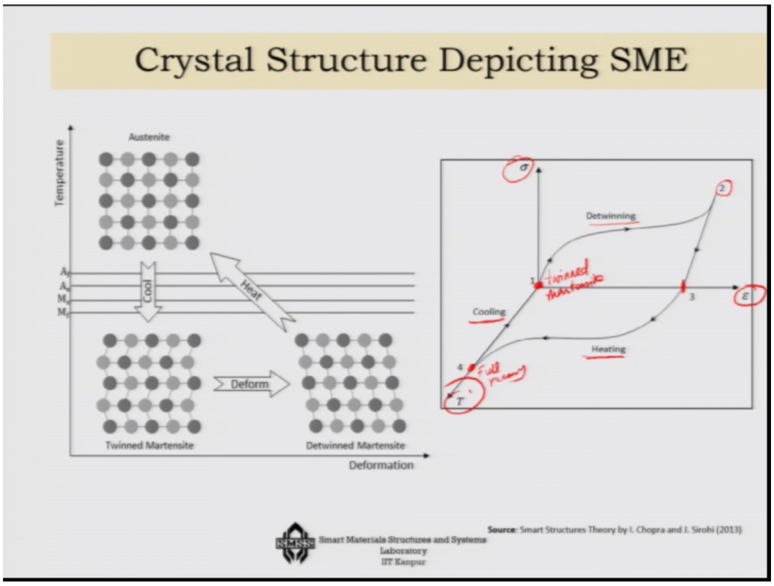

Let us say we start from a situation one and where you know this whole thing is supposed to be at the twinned Martensite pahse. I am increasing the load, so detwinning is happening and I will be reaching two if I increase the load further the material would have failed, but I do not want to do it I am reducing the load now if I reduce the load it will not actually get back to its original shape, because there is this detwinning to twining.

You know that load release will only bring it back to the partial the elastic part of the recovery then I heat it up, as I heat it up it actually goes to point four and here full recovery has taken place full recovery of the shape. And, then if I cool it up then what will happen it will go back to its you know Martensite state that is here we shall should say that the twinned Martensite state here and that would not mean there will be any more change of strain, strain is 0 ok, but only that it will get converted from the Austenite to the twinned Martensite phase. So, that is the whole diagram we have to keep in our mind.

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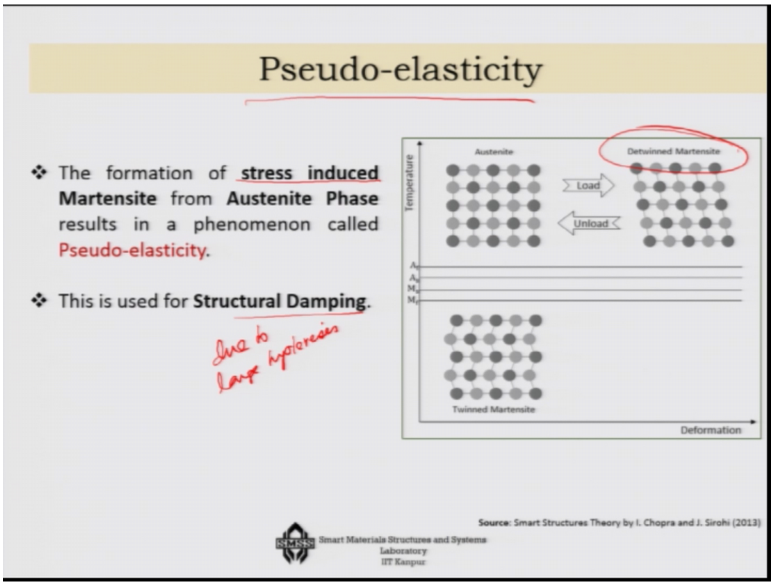

Now, there is something which is called pseudo-elasticity now the way the whole thing happens is that in the Austenite phase that is at the high temperature phase, if without changing the temperature if I only applies stress then what happens is that this Austenite phase can get converted to the detwinned Martensite phase and this procedure ok. So, you know directly; that means, you know you are not coming to twinned Martensite phase, but directly between Austenite to detwinned Martensite phase transformation this has lot of hysteresisily and that is why the pseudo-elasticity; that means, it is not perfectly elastic, but it is because of a stress induced phase transformation and neither it is plastic.

So, that is why it is pseudo-elastic and this involves large hysteresis and that is used for structural damping due to large hysteresis in the in this particular transformation process. So, that is pseudo-elasticity which we will show later on that can be used in structural damping.

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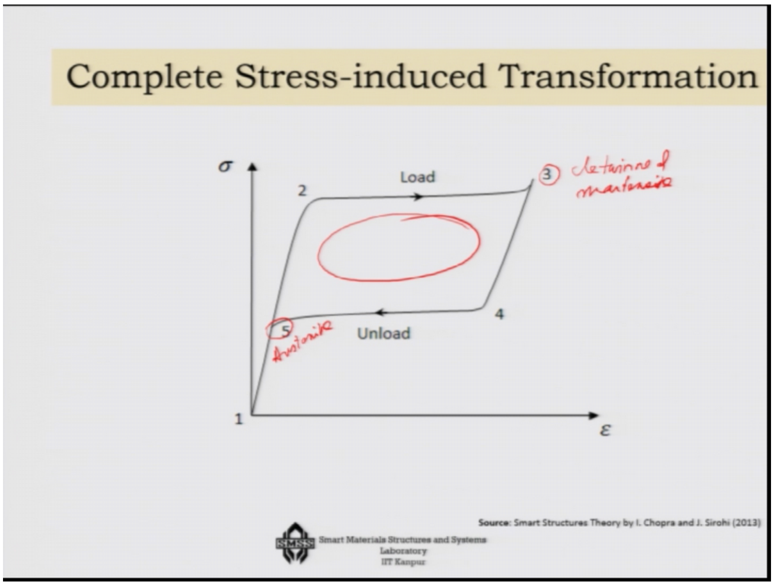

In fact, this is: what is this stress induced transformation diagram, you can see that you are at the Austenite phase increasing the stress and it is going to directly to the detwinned Martensite phase. So, here this detwinning is complete detwinned Martensite phase. There is no change of temperature remember and then as I am reducing the load ok, I will come back to the Austenite state here and this process has a full hysteresis that you can see.

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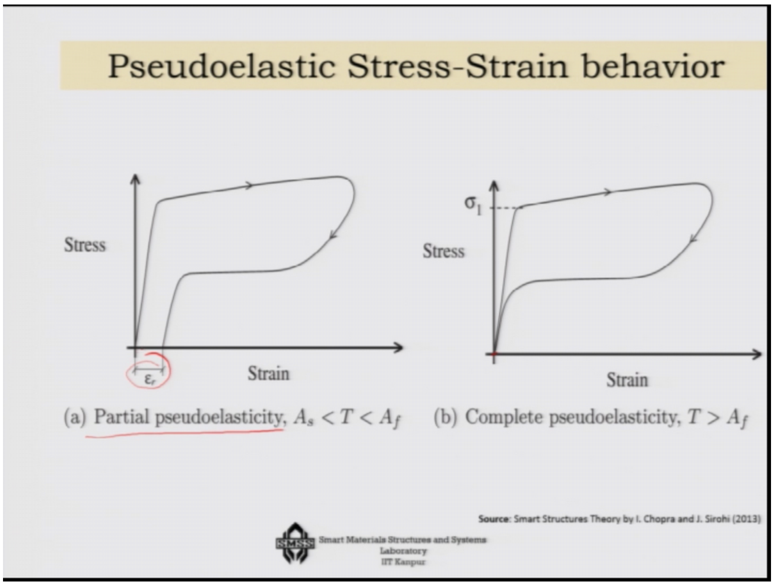

Now, what if I do not take it to complete detwinned Martensite phase that is possible in this case it will be partial pseudo-elasticity as you can see that you are going partially and coming back and there will be some amount of recovery strain that will be there in the system. So, complete pseudo-elasticity will bring it can bring it back to the 0 strain condition, but partial pseudo-elasticity will have some amount of remnant strain in the system.

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Now, what are the commercial applications of this you know effect, first effect actually came from you know one of the aircraft applications in by Raychem Corporation and this is known as Cryocon. So, what they have done in this case is that this is used for joining tubes in aerospace systems. So, initially the shape will be oval ring of SMA and that will be set at the Martensite phase oval ring ok.

And then you can easily join the two submit at that shape let us you design it in that manner and this is happening when it is cryo cooled which means it is fully at the Martensite phase. Now, you remove that cryogenic condition. So, it will go back to its memorized shape and the memorized shape is actually a circular you know ring ok. So, the moment that happens then there is a tightening because it is squeezing inside the tube and joints the system. So, as a result you know you can fit it at the cryogenic condition and get a complete beautiful connectivity between the system that was the first effect using one-way SMA.

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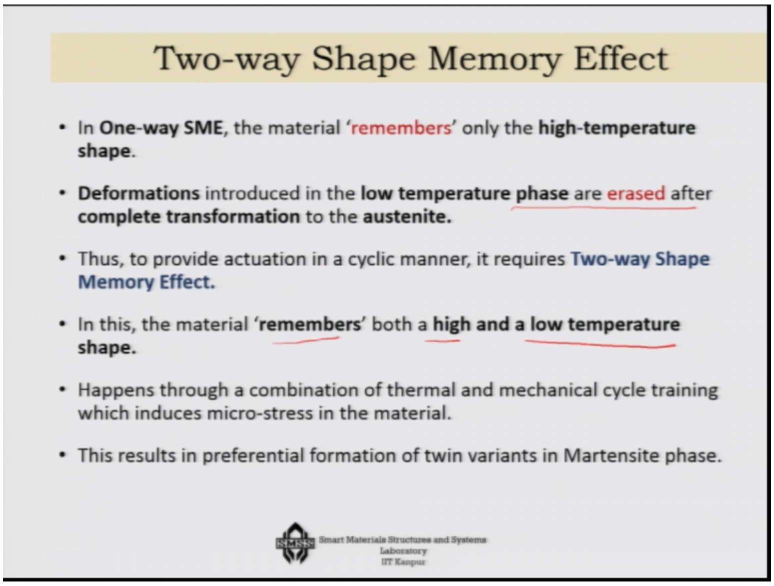

Now, one way SMA remembers only one shape that is the high temperature shape, but if you actually you know reduce the temperature then this memory gets erased. However, if you do it in a cyclic manner then what will happen that is what call the training then it will remember both the high and the low temperature shape and that is in some applications very much useful that you get both high as well as the low temperature shape. Say for example, you have this as the original shape when temperature is less than Martensite finish you are plastically deforming the system ok.

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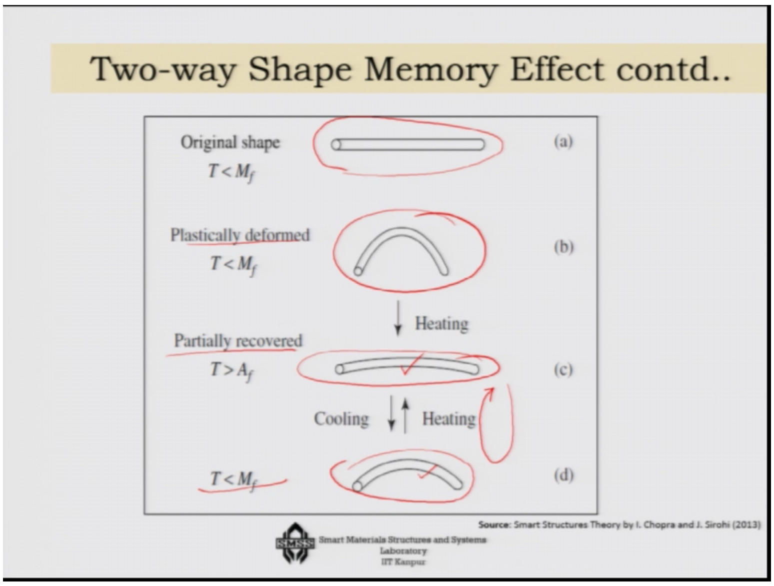

So, you are in that bend shape now you are heating it up, but only partially you are recovering ok. So, you are coming back to the Austenite phase and then from this stage if I cool it temperature is now less than M f ok. I am getting this particular shape and I have to repeat in this cycle continuously, if I do it then it will be trained and in that case whenever every time you will actually you know cool it, it will you will get this shape. So, not only you will get the Austenite shape, but also you will get the Martensite save every time and that is: what is the two-way shape memory effect that you will get in the system.

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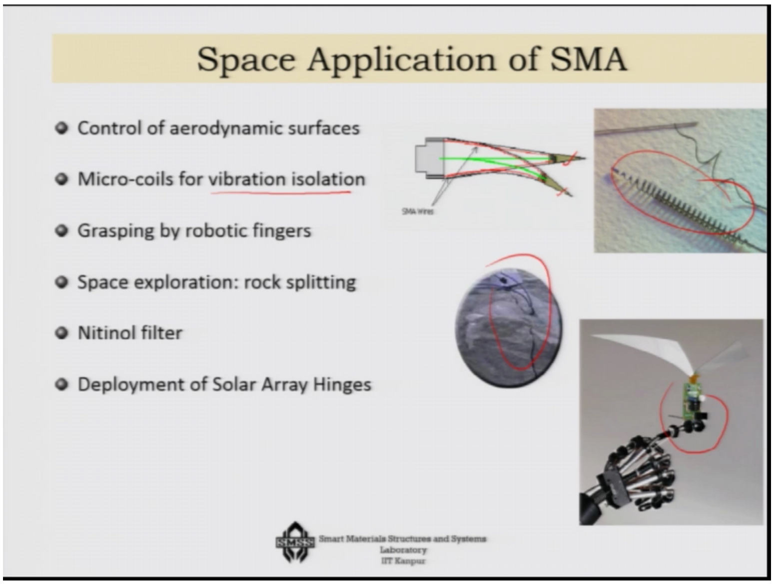

Now, there are lots of applications of these for example, the two-way effects can be used for control of aerodynamic surfaces; so, that you can bend it in a manner that it goes from one shape to another shape. So, you can use it for flapping of wings for example, then you can use it for as micro coils for vibration isolation you can use this system, grasping by robotic fingers people have tried it, space exploration like a rock splitting, NiTiNOL filters deployment of solar array hinges there are many such space applications that are thought of my using this effect.

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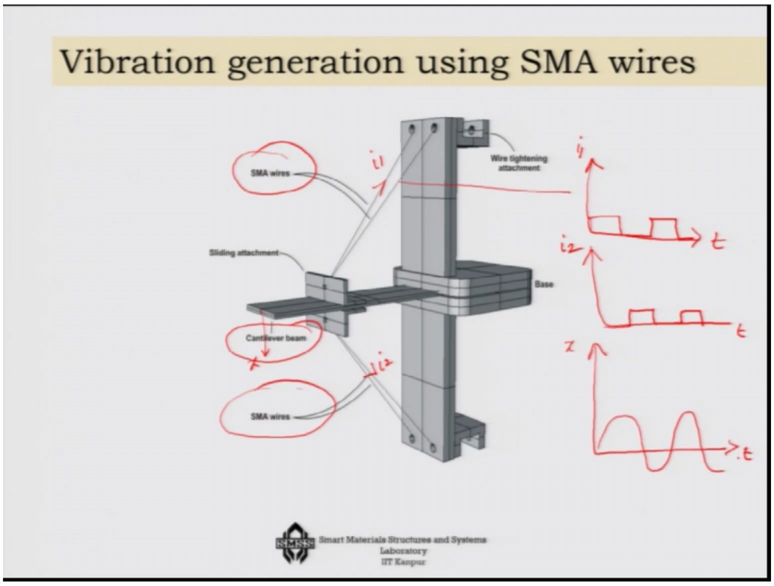

Some of the very specific effect that we are doing in laboratories are for example, we have 2 series of SMA where is one below and 1 you know 1 top one below of a cantilever beam and then by actuating each one of them. So, like you know if you consider that this one you just have time versus current you pass it in a manner that it is like this. So, at a repeated cycle you are doing it and so this is i1 let us say for this one i1 and let us say for this one current is i2. So, if I plot i2 versus t I just do it just the reverse manner; that means, like this.

So, by repeatedly you know periodically heating up at the top and the bottom you can actually generate if you look at time versus displacement of any particular point. Let us say I am trying to plot the x the displacement of this point I will be actually getting this kind of a deflection in the system. So, that is how you can generate vibration in a system.

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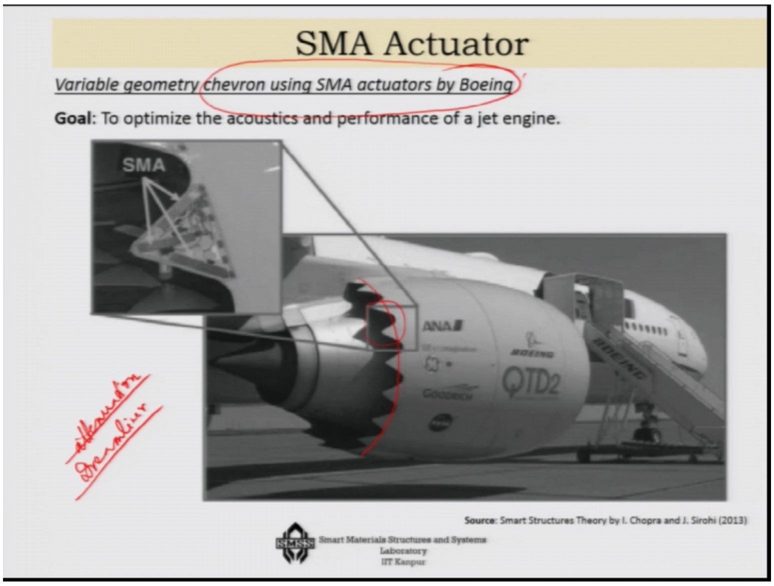

People have used for the chevron using SMA actuators by Boeing and what they have done is that if you look at it that this part is actually Jagat ok. So, at the you know beginning when you are the taking off is happening at that time this part is Jagat and as the heat increases, so this Jagatless actually helps in terms of attenuation ok. So, the sound will be much less this you will see in dream liner all dream liners if you look at it you will see the this technology there.

Now as the temperature is increasing the aircraft is going at the you know high altitude you do not is the sound does not matter anymore and this that temperature will make it actually flat. So, this will become flatter. So, that you get more fuel efficiency from the system. So, that how this particular system is very cleverly designed.

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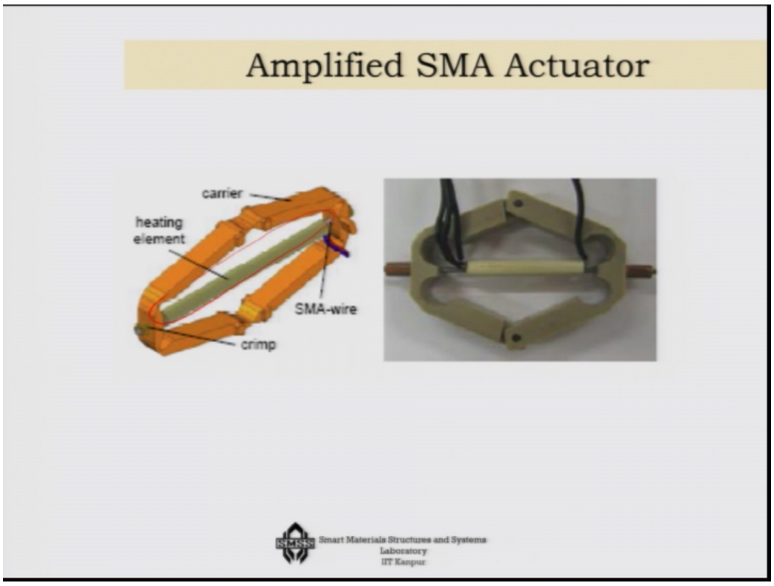

Then you know there is also another example of amplified SMA actuator to further amplify. So, let us say this is the SMA you know at this core and as you are shortening it is like these 2 points where you are getting a mechanical amplification of the system by using arch type of a mechanism. So, thus you can actually further amplify the deformation.

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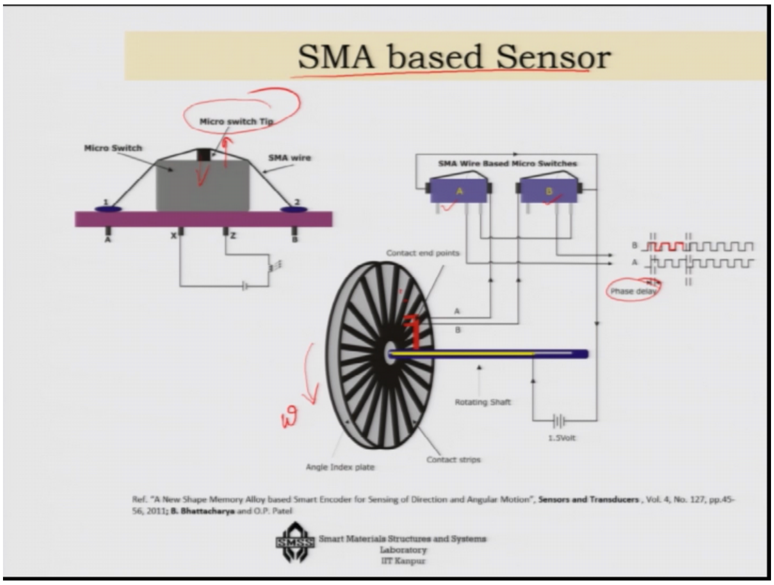

One last use that I want to talk about is actually. So, far I am only talked about SMS based actuators, but now I want to just show one last slide or SMA based sensor. So, in this case what you can do is that that suppose you have a micro switch tip and you have a SMA wires and tell you have a system which is actually having two such micro switches.

As you can see A and B and you have 2 point touching two parts of the conductive strips. Now if this system rotates what happens that there are certain times when the, these two style as will be over 2 of these conductive strips. So, whenever there will be at the 2 conduct strips there will be current which will be flowing and as the current will be flowing then you will be getting the heating here and this switch that we have here that switch will be actually pressed. So; that means, the current flowing on the next momentum one of them goes here; that means, the current is not there. So, it will once again lift up. So, you will be able to see this kind of a you know current flowing and again no current, current flowing, no current situation.

If you have two switches with a phase lag between them then there is a phase difference that you are getting between 2 adjacent switches. So, by measuring this phase delay you should be able to say that how fast the angular rotation omega is taking place in this disk and by integrating that you should be also able to say how much of angular deformation has taken place. So, this can be used for sensing of you know angular sensing by using SMS. So, a briefly I have told you that what is the shape memory effect I have told you about 3 shape memory effects one-way, two-way and pseudo-elasticity and I have talked about the shape memory actuators and the shape memory based sensors in this particular overview.

In the next lecture I will talk about introduction to composites.

Thank you.