Nature and Properties of Materials
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Lecture 27
Smart Materials 5

In this lecture I am going to talk about another smart material which is popularly known as shape memory alloy. So the shape memory alloy is one of the latest inclusions in the band of smart materials which has phenomenally dramatic properties in terms of the actuation strain, in terms of the force in fact, people actually compare it with something like an artificial muscle, so let us look into that what is there in this artificial muscle, what gives it such interesting properties.

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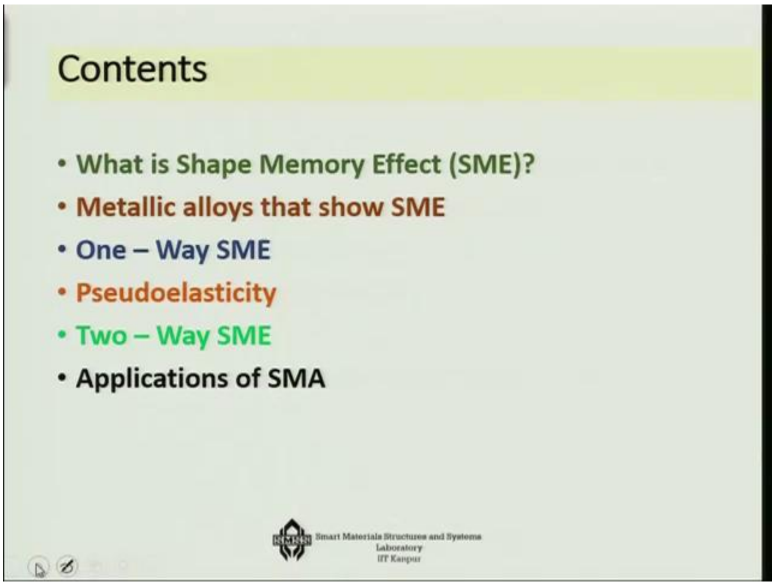

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- What is Shape Memory Effect (SME)?
- Metallic alloys that show SME
- One – Way SME
- Pseudoelasticity
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- Applications of SMA

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So I will 1st talk about what is shape memory effect, then I will say what are the metallic alloys that shows this shape memory effect. Then there are 3 modern properties of shape memory alloys, one is called One-way shape memory effect, another is called Two-way shape memory effect and the 3rd one is called Pseudo-elasticity, so these 3 things we will discuss. Finally, we will talk about the applications of the shape memory alloy. So let us 1st see what this shape memory effect is.

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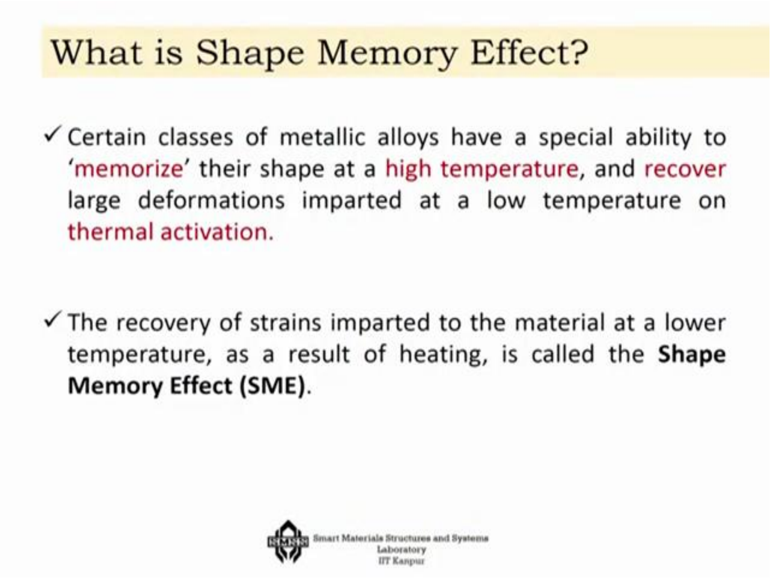

What is Shape Memory Effect?

- ✓ Certain classes of metallic alloys have a special ability to 'memorize' their shape at a high temperature, and recover large deformations imparted at a low temperature on thermal activation.
- ✓ The recovery of strains imparted to the material at a lower temperature, as a result of heating, is called the **Shape Memory Effect (SME)**.

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There are certain classes of metallic alloys which have a very special ability, the special ability is to memorize their shape at a particular temperature okay and then what you can do is that if you actually if it undergoes large deformation at a low temperature, the moment you thermally activate it then once again it will get back its shape. So I will rather say, generally it is to memorize the shape at a high temperature in fact, in case of a two way effect it is both low and high, but otherwise it is at high temperature and then you bring it to low temperature, do whatever you wish the large deformation.

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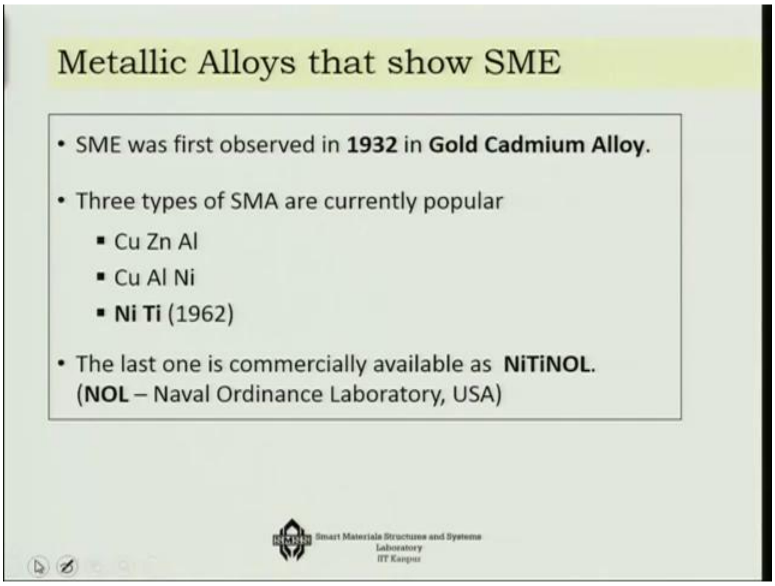

Metallic Alloys that show SME

- SME was first observed in **1932** in **Gold Cadmium Alloy**.
- Three types of SMA are currently popular
  - Cu Zn Al
  - Cu Al Ni
  - **Ni Ti** (1962)
- The last one is commercially available as **NiTiNOL**. (**NOL** – Naval Ordinance Laboratory, USA)

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Finally, as the thermoregulation takes place you will see that the same shape is back again. So this effect was 1st observed in 1932 in actually gold cadmium alloys. There are 3 types of

SMA that are currently popular, one is copper zinc aluminium, another is copper aluminium nickel and the other one is nickel titanium alloy um, so it is a binary alloy in comparison to the other 2 and since 1962 this was discovered, it is becoming more and more and more popular.

So the last one this NiTi is actually commercially available with a name called NiTiNOL that is Nickel Titanium Naval Ordinance Laboratory of USA, they actually discovered this particular shape memory effect in this particular material. Now let us see that what the competitive advantage of this shape memory alloy is. If you look at it that the maximum specific actuation stress wise SMA can give you something like 0.1 mega Newton meter per KG and the actuation strain is about 0.1.

On the other hand, if you look at PZT, it is capacity of 100 of this capacity of the SMA and actuation strain wise it is 1000; it is very-very low. Now, if you compare it with human muscle even then the SMA is actually quite high because human muscle is 0.005, so it is quite high and actuation strain wise however, the human muscle is much above the SMA.

So stress point of view if you compare SMA with an capability of SMA as an artificial muscle, then from stress point of view it is well above the human muscle, but from strain point of view it still has to improve a lot. On the other hand, with respect to any other smart material it is much far ahead.

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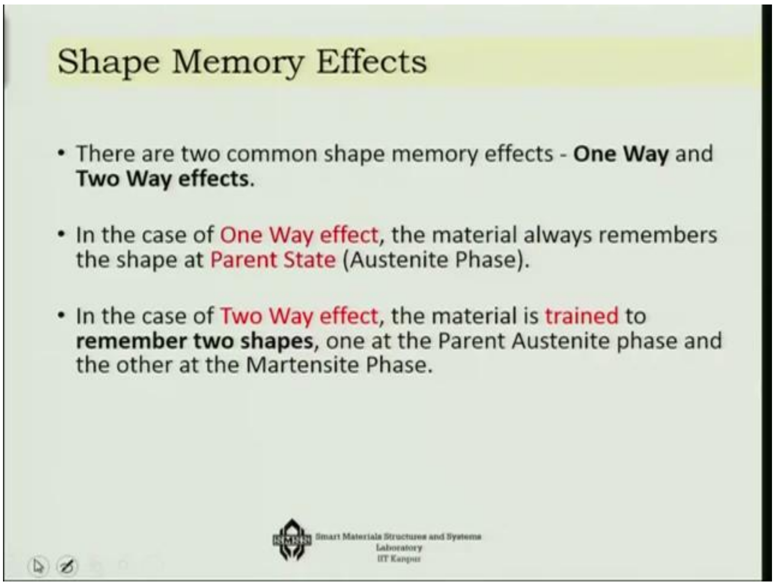

Shape Memory Effects

- There are two common shape memory effects - **One Way** and **Two Way effects.**
- In the case of One Way effect, the material always remembers the shape at Parent State (Austenite Phase).
- In the case of Two Way effect, the material is trained to **remember two shapes,** one at the Parent Austenite phase and the other at the Martensite Phase.

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Now, there are 2 common shape memory effects, one is called one-way effect and another is called two-way effect. In the case of one-way effect, the material always remembers the shape at Parent State and that is the Austenite phase between that is what I was telling that at the high temperature Austenite phase it remembers that in the case of one-way effect. However in the case of two-way effect, you can train the material in such a manner that it can remember two shapes, one at the parent Austenite phase and the other at the Martinsite phase, so this however you have to give a lot of training to the system.

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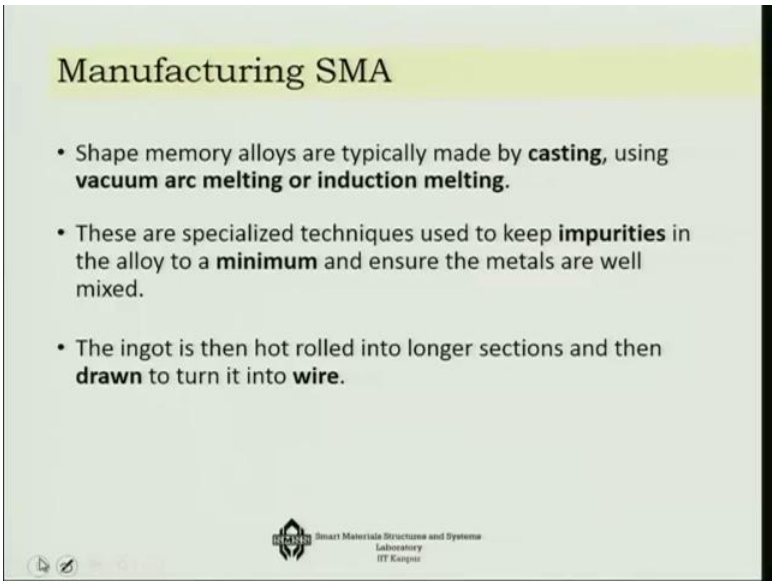

Manufacturing SMA

- Shape memory alloys are typically made by **casting**, using **vacuum arc melting or induction melting.**
- These are specialized techniques used to keep **impurities** in the alloy to a **minimum** and ensure the metals are well mixed.
- The ingot is then hot rolled into longer sections and then **drawn** to turn it into **wire**.

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How do we manufacture SMA particularly in the wire form? So SMA are typically 1st made by casting using vacuum arc melting or induction melting or similar processes, but both of these processes are highly specialized process and highly expensive process. However, these techniques are used to keep the impurities in the alloy to a minimum and insure that the metals are well mixed.

So once you are actually using this process and you are making these at a high temperature mixing this and then make the ingot, then you hot roll it into longer sections and finally you would draw it into wire form, so that is how we actually manufacture the SMA wire itself okay, this is just not simply SMA, but the SMA wire itself.

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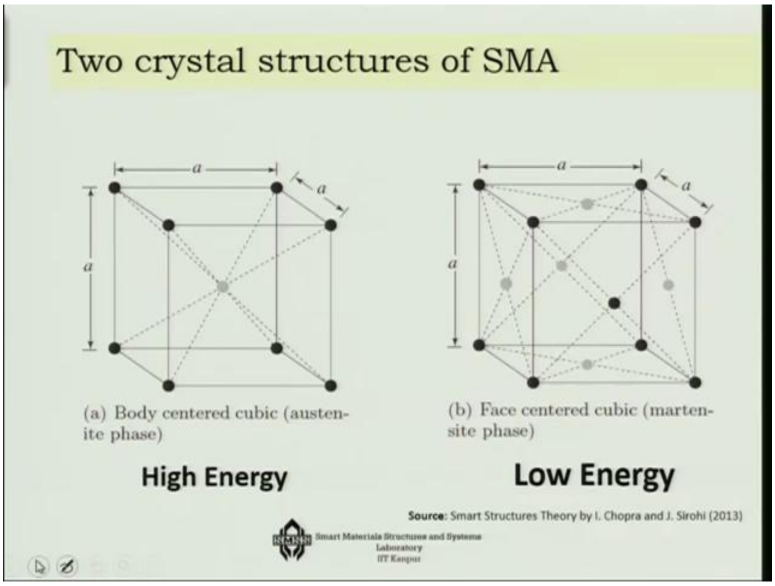

Two crystal structures of SMA

(a) Body centered cubic (austenite phase)

(b) Face centered cubic (martensite phase)

High Energy

Low Energy

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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Now the crystal structure point of view, there are 2 crystal structures in SMA one is that high energy or high temperature form and another is that low energy or low temperature form. So it high energy, the form that we encounter is called a Body centered cubic structure Austenite phase okay, so here nickel and titanium atoms as you can see in this system. And in the phase centre, you get it in the phase centered form of the system. Now these are 2 crystal structures, how does it behave?

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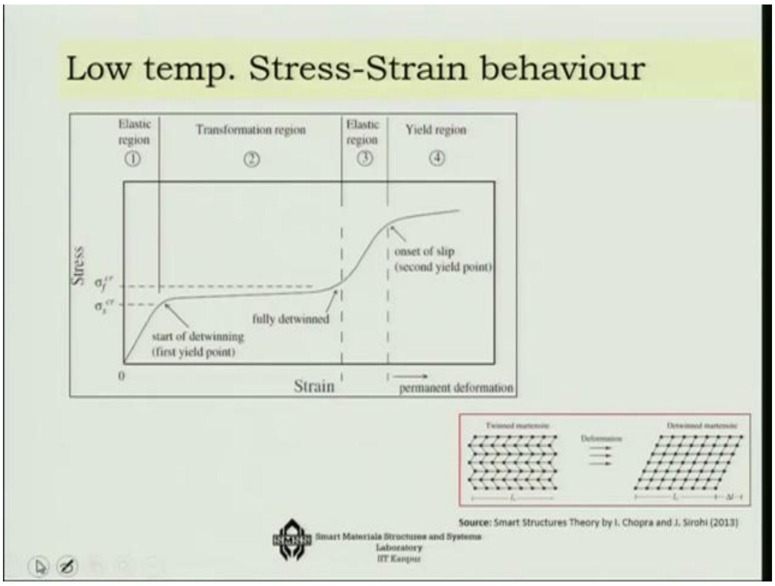

Low temp. Stress-Strain behaviour

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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Let us say 1st we consider the low temperature stress-strain behavior. So at the low temperature levels that means at it is at Martinsite, so this is at the Martinsite phase in fact, it is initially at detwinned Martinsite phase. Now as I am increasing the loading, after a certain point it will start to detwin that is the 1st yield point okay. So I have crossed the elastic region, now the transformation is happening from twinned to detwinned state. So beyond these detwinned state has been achieved as you can see.

And then once again it will be having and elastic manner, so that is the elastic region, after that twinned state if you do not change the temperature then you will see the yield region and the failure of the system, so this is the low temperature stress-strain behavior of the SMA wire and what about if I only change the temperature?

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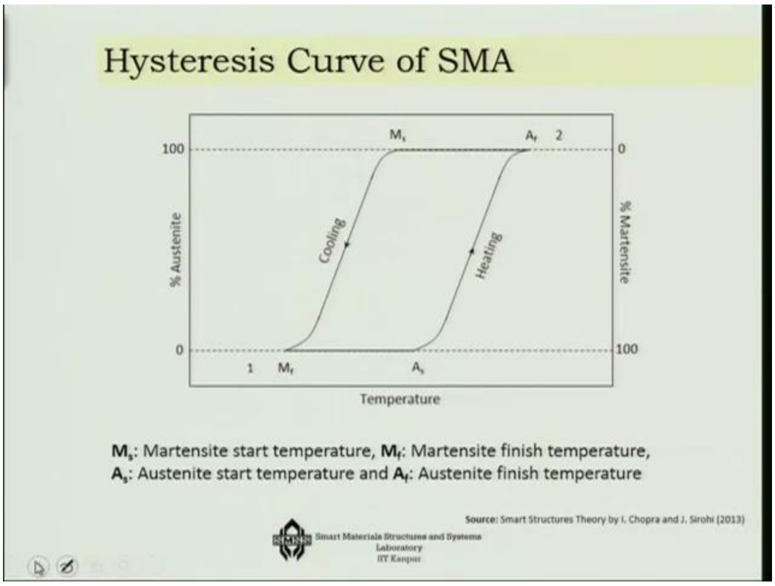

Hysteresis Curve of SMA

M_s: Martensite start temperature, **M_f**: Martensite finish temperature,
A_s: Austenite start temperature and **A_f**: Austenite finish temperature

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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So if I take a SMA wire and if I only change the temperature let us say, so what I will see if there is a way I can continuously monitor that what is happening to the internal material property change, I would see that initially till about say for example, Austenite start point, so I have to go up to this point I would see that the material is that Martinsite formation which is FCC formation.

And then as I am heating this Martinsite is now getting converted and it is now becoming Austenite okay, so it is taking the BCC form. So at A s this is starting and at A f this is over Austenite finished temperature. After that if I increase the temperature, it will be 100% austenite, so 0% Austenite initially and after A f it will become 100% austenite. Again, if I now reduce the temperature what will happen?

Initially nothing will happen, but then as I decrease the temperature at M s, suddenly it will start to cool and the Martinsite now will start to form, so Martinsite formation is happening more and more and more until we reach the point of M f. Here, the Martinsite formation is over, there is no Austenite left in the system provided that I have not touched the stress profile of the system. If I touch that, then of course the situation will be more complicated, but let us 1st talk about the one-way shape memory effect.

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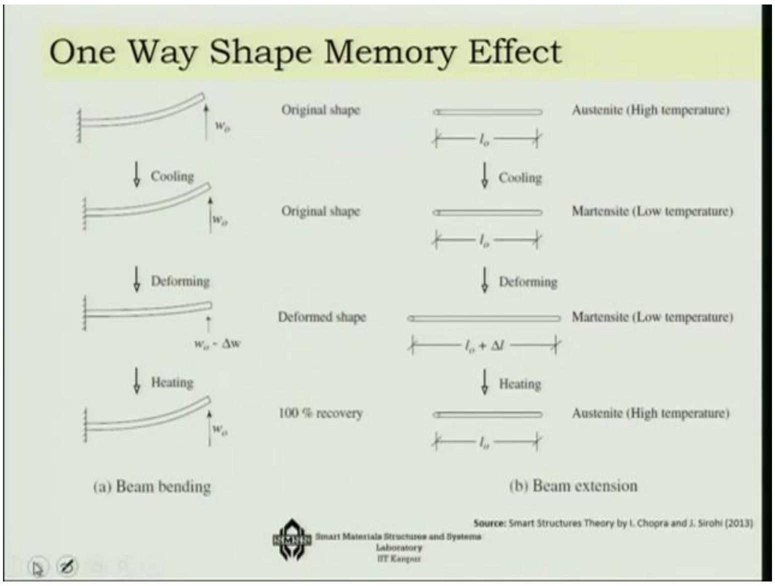

One Way Shape Memory Effect

(a) Beam bending

(b) Beam extension

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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So in the one-way shape memory effect there are 2 types, one is the beam extension, another is the beam bending, let us 1st discuss what happens in the beam extension. Suppose I take a SMA sample, which is at the Austenite high temperature phase, then I just cool it fine and then it goes to the Martinsite low-temperature phase, but there will be no change of length okay, so that means there is even though there is this twinned Martinsite formation that has taken place, but it is internally adjusted procedure, so there will be no change of length.

Now you deform it, as you deform the length got increased to L 0 plus Delta L, but here it is in the from the twinned to it has become detwinned Martinsite phase at low temperature. Now you heat it up, as you heat it up you are once again going to get back your L 0 at the Austenite high-temperature phase meaning thereby that every time you cool it, do whatever you wish and then once you heat it up, you come back to this Austenite high-temperature, you are going to get back that same length again and again and again that is what is the one-way shape memory effect.

What happens in terms of bending? Pretty much similar, suppose I have a particular beam here which is deformed due to some kind of an external loading? Now, it is at the Austenite phase so this is at the Austenite phase to begin with. Now I am cooling it, as I cool it there will be no change as I told you that this Martinsite is actually point Martinsite state, so there will be no change internal adjustment will be there, there will be no change, original shape will be there.

Now, suppose I change the load of then there will be a deformation the change of curvature immediately as you can see that is going to happen to the system. And now if I heat it up, what will happen? It will once again no matter whatever is the load, it has to go back to that original shape, so it will once again will gain that original shape that was there in the system, so that is the beam bending effect one-way shape memory effect in the beam bending.

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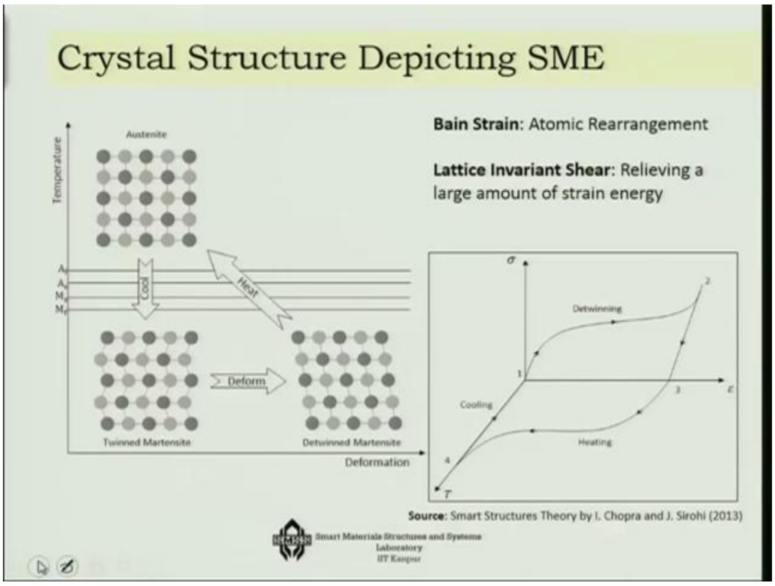

Crystal Structure Depicting SME

Bain Strain: Atomic Rearrangement

Lattice Invariant Shear: Relieving a large amount of strain energy

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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So, this is now in terms of 3-dimensional situation okay. Now there are 2 things that mean one is called the bend strain, which refers to the atomic rearrangement and another is a lattice invariant shear which refers to the release of a large amount of strain energy. Now if I have to follow that, I have to look into now the combined diagram of stress, strain and temperature. So far for all the materials we have only seen the stress strain behavior, but now temperature has also come into the picture.

So, let us say I have taken a material which is at its original point number 1 okay. And then I am loading it, as I am loading it from twinned Martinsite, so this is the twinned Martinsite state. As I am loading, I am detwinning it and then it is coming completely detwinned phase. Now, after that suppose I do not want to fail the material, so I will only reduce the load. If I reduce the load, it will come back to 0 point 3 in which there will be lot of plastic strain that will be there in the material.

At this stage, I leave the planner stress strain part and I start my new heat axis and I start to heat it up. As I heat it up, gradually you will see that this strain will vanish and this particular point of time, it has A f region, it has already gone back to its original shape. Now in that original shape if you cool it, it will remain in the original shape but if this is Austenite here, from Austenite stage will go to the twinned Martinsite stage, so this is the 3-dimensional change that happens to the system.

In the left side also we have shown you the same thing; Austenite BCC phase and then you cool it, you go to always twinned Martinsite, you deform it, the twinned Martinsite becomes detwinned Martinsite, you heat it and you are going to get back your Austenite shape or your memory shape.

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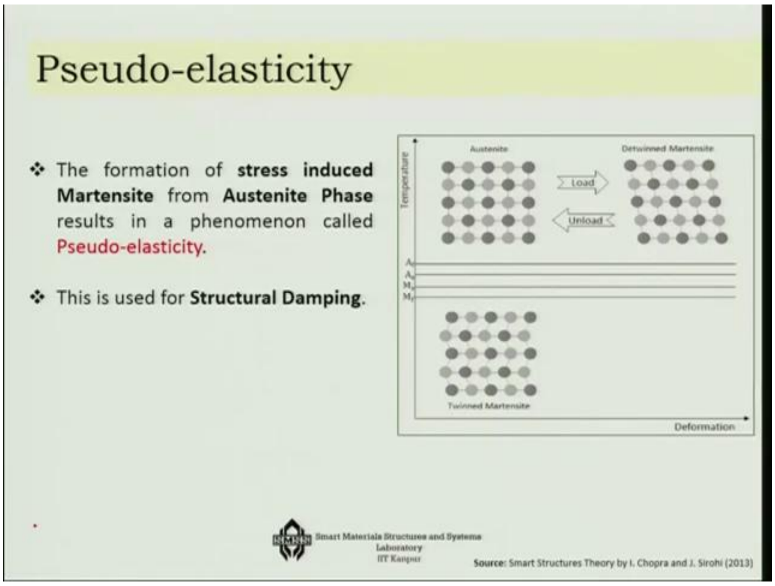

Pseudo-elasticity

- The formation of **stress induced Martensite** from **Austenite Phase** results in a phenomenon called Pseudo-elasticity.
- This is used for **Structural Damping**.

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Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

Now, if suppose I do not change the temperature um, I keep the temperature at high-temperature level this time, not at low temperature but at a high temperature level. And then that means to begin with I am at the Austenite level now at that level if I load it, what is going to happen? It will straight come down to the detwinned Martinsite phase and then if I unload it, it will straight come back to the Austenite phase.

So you are not coming via the twinned Martinsite state anymore. This kind of direct transformation from Austenite to detwinned Martinsite phase has something very peculiar in stress-strain relationship, which is known as Pseudo-elasticity and it is highly used in structural damping. Let us see how this will be useful.

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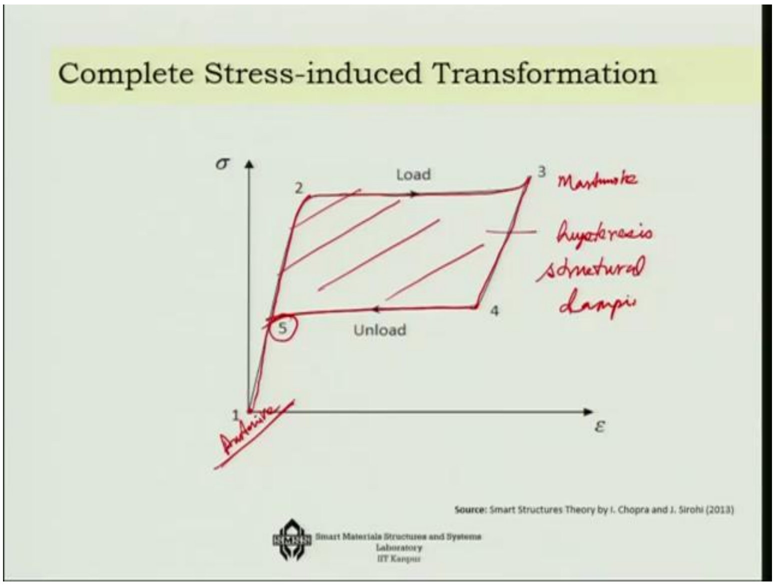

Complete Stress-induced Transformation

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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If I look at the pseudo-elastic behavior that means here I am at Austenite phase and then I am increasing the load okay up to 0 point 2, the elastic loading is over suddenly the phase transformation happens, this is stress induced phase transformation and I am going back to the Martinsite phase. And then from that phase I am reducing the load again and then if I reduce it 1st initially, it is once again elastic and then the huge change and it comes back to number 5.

And then if you further reduce it will be at that Austenite stage itself, so interesting thing is that this loading and unloading at a high temperature has this much of area covered by it and this area is responsible for the hysteresis or for that matter for structural damping. It is heavily being used today now for structural damping, so this is the pseudo-elastic effect. Now you need not always go through the full cycle of complete Austenite transformation.

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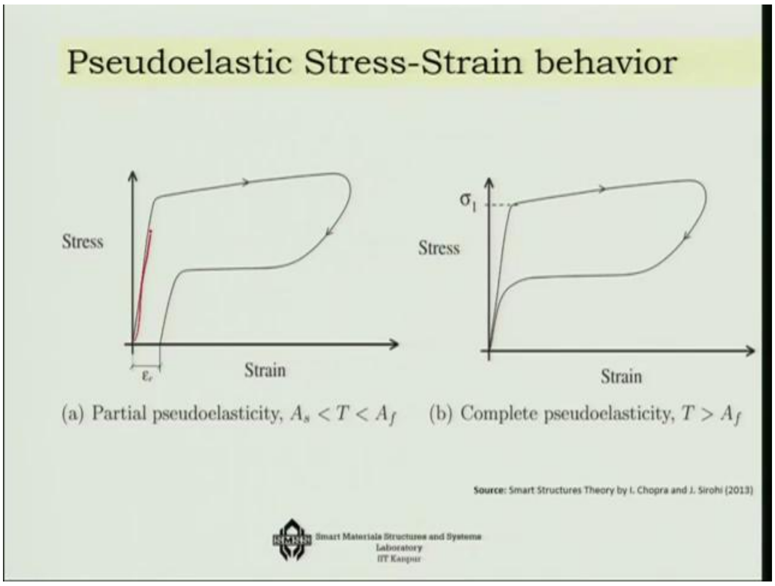

Pseudoelastic Stress-Strain behavior

(a) Partial pseudoelasticity, $A_s < T < A_f$ (b) Complete pseudoelasticity, $T > A_f$

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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In that it may happen that you increase the load, partial transformation has taken place, you unload it, and once again it is going back like this, so this is what partial pseudo-elasticity is. The difference between the 2 is that for complete pseudo-elasticity, you start from 0 and then you can come back to the 0 strain level almost itself that is complete pseudo-elasticity. If the temperature remains between A s and A f, then you get partial pseudo-elasticity, if the temperature is greater than A f then you get complete pseudo-elasticity in the system.

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Commercial Application of One Way SME

- The product is developed by Raychem Corp, USA and is known as Cryocon.
- It is a connector used for joining tubes in aerospace systems.
- It takes the form of a Oval ring of SMA set at Martensite Phase (Low temperature - cryo cooling)
- When cryo-cooling is removed, the ring gets circular and squeezes the tubes and joins them.

Cryofit & Cryocon

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Now, there are many commercial applications of one-way SME for example, this is a Raycherm Corporation product which is known as Cryocon, it is initially a connector which is used in joining tubes in aerospace applications and it takes the form of a Oval ring of SMA set at Martinsite phase at low temperature, so initially this is an Oval ring.

Now when Cryo-cooling is removed that means from low temperature when you are coming back to high temperature, the ring gets circular and squeezes the tubes and joined that 2 tubes, so it starts from Oval shape, you fit it and then you remove the Cryo-cooling and it fits the 2 connectors, so that is Cryo-fit and Cryocon system, this is the one of the effect of one-way shape memory effect.

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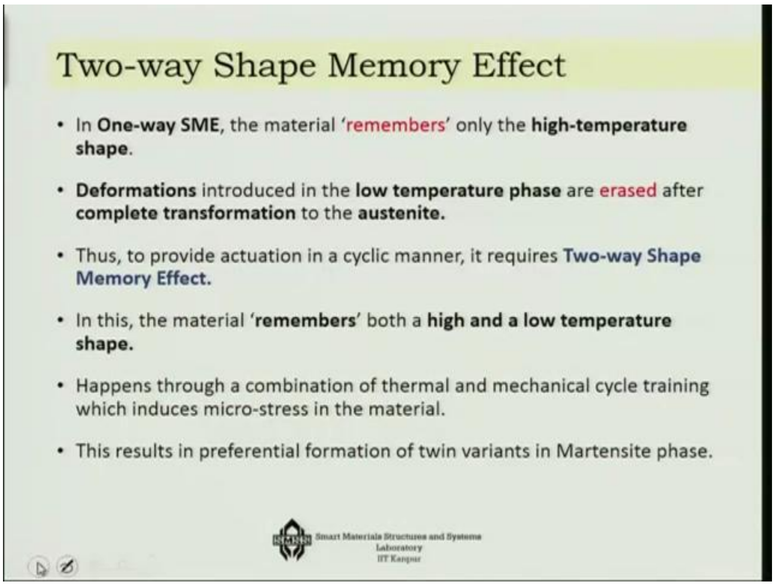

Two-way Shape Memory Effect

- In **One-way SME**, the material 'remembers' only the **high-temperature shape**.
- **Deformations** introduced in the **low temperature phase** are erased after **complete transformation** to the **austenite.**
- Thus, to provide actuation in a cyclic manner, it requires **Two-way Shape Memory Effect.**
- In this, the material **'remembers'** both a **high and a low temperature shape.**
- Happens through a combination of thermal and mechanical cycle training which induces micro-stress in the material.
- This results in preferential formation of twin variants in Martensite phase.

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Now in the two-way shape memory effect, it remembers both the high-temperature shape as well as the low temperature shape which is generally not erased in this particular case. The secret for this is that you need to have a combination of thermal and mechanical cycle training, so that it will induce the micro stresses in the material, then only at the low temperature phase it will be able to go back to the exact shape that you have craved it to have. So then this would result in preferential formation of twin variants in the Martinsite phase.

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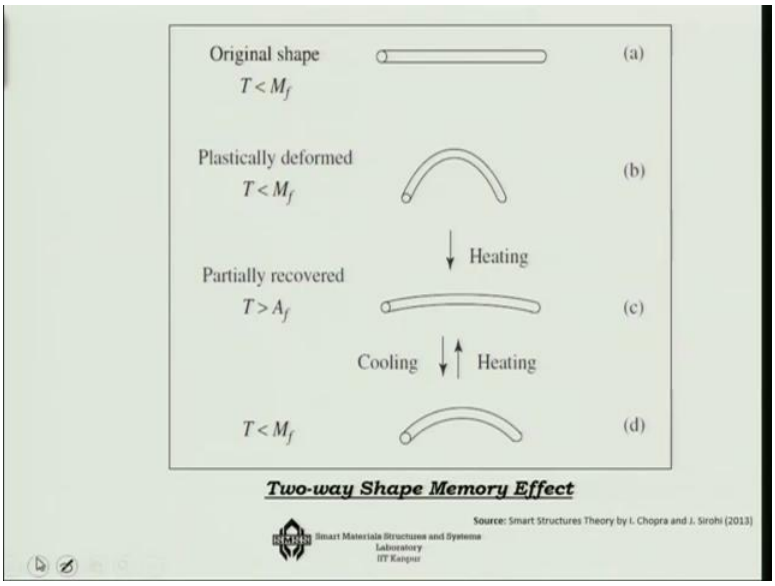

Two-way Shape Memory Effect

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

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So, how will be the two-way shape memory effect? This is where the original shape at the Martinsite level, you deform the whole thing and then you heat it up, you are going to get this particular shape. Now from this shape you cool it, you are going to go back to this particular shape, bent shape. So now you heat and cool, heat and cool you will be flipping between these 2 shapes, one is at a high temperature memory another is at a low-temperature memory shape.

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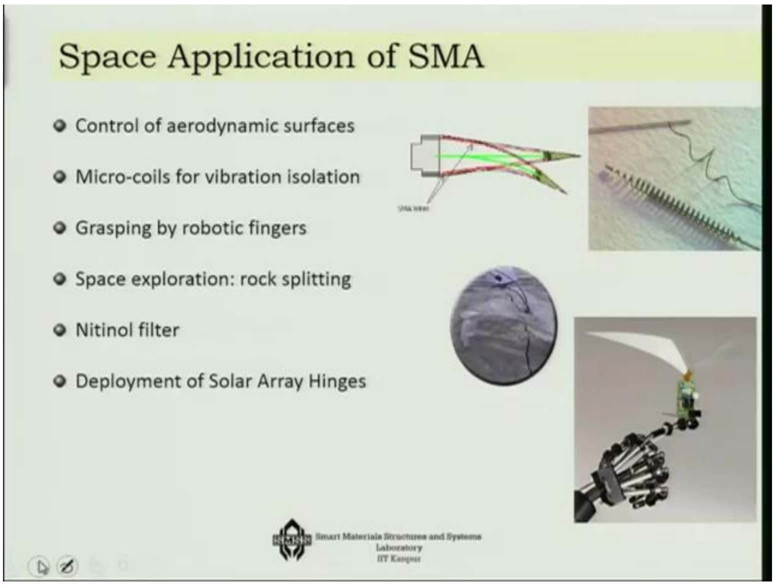

Space Application of SMA

- Control of aerodynamic surfaces
- Micro-coils for vibration isolation
- Grasping by robotic fingers
- Space exploration: rock splitting
- Nitinol filter
- Deployment of Solar Array Hinges

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Using this there are many interesting applications that have been developed for example, the control of aerodynamic surfaces like an aircraft wing control, et cetera. As you can see here that SMA wire is controlling this so called angle of aircraft, so that is one application. Micro-coils for vibration isolation or grasping by robotic fingers that is also done, space exploration or rock splitting, then development of Nitinol filters and deployment of solar array hinges, there are many applications particularly space applications of SMA.

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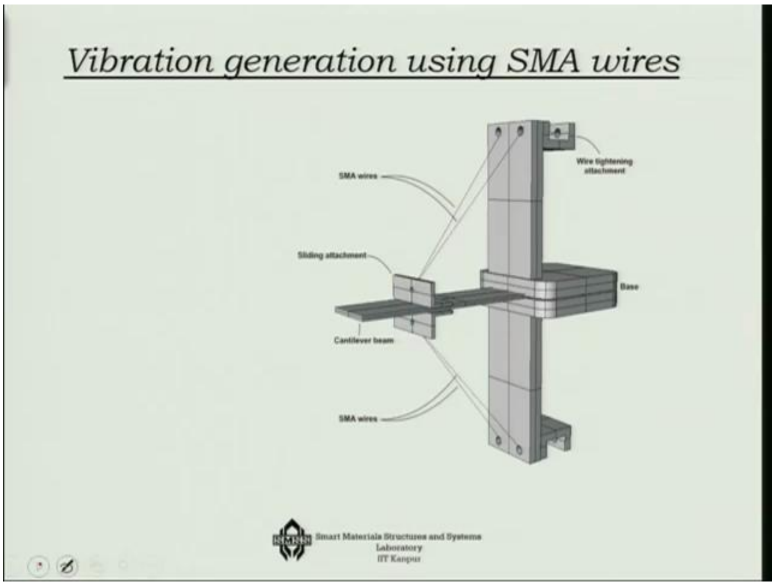

Vibration generation using SMA wires

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One such application is how to generate vibration. So what you do here is that suppose this is a cantilever beam that you have, on that beam you have 2 sets of SMA wires. Now, you actuate one of them suppose this one, so it gets shorten, so this whole beam gets deform downwards. And then you cool it and you start to heat the other one, so the whole beam will go to the other side, so then you do this process again and again and then you will see that there is a continuous vibration of course at a low frequency that is happening by the help of the SMA wire.

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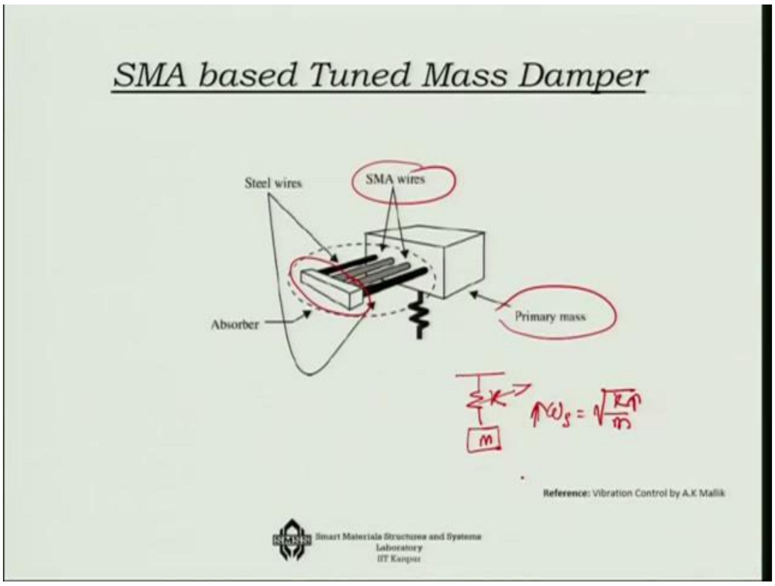

SMA based Tuned Mass Damper

Reference: Vibration Control by A.K Mallik

You can use this SMA wire for tuned mass dampers, where you have a primary mass and you have the SMA wires and then you have the absorber. The advantage is that for any tuned mass damper we know that there is a spring and mass that is attached to this system. Now this stiffness of the spring and the mass, these 2 remains invariant. But in the case of SMA, this K can vary and as the K varies, so the natural frequency of this secondary system square root of K by M, as K varies then the Omega s also varies and then thus you can actually tune it to different frequencies.

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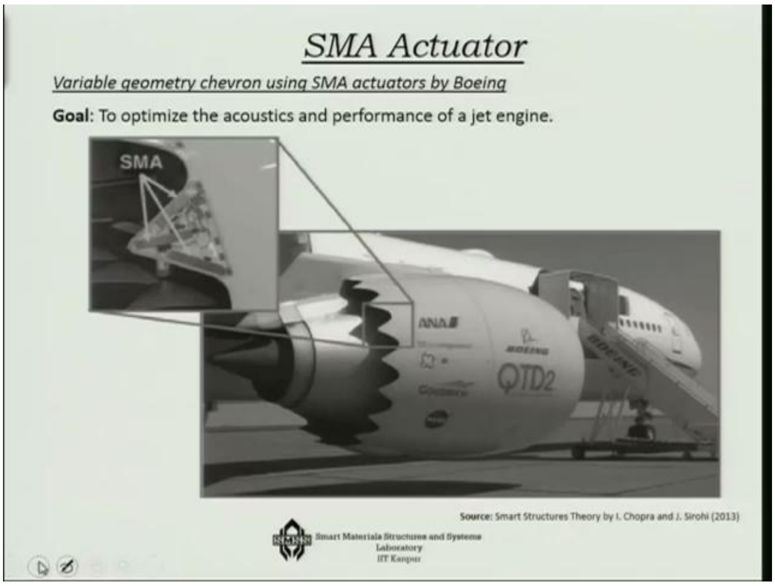

SMA Actuator

Variable geometry chevron using SMA actuators by Boeing

Goal: To optimize the acoustics and performance of a jet engine.

Source: Smart Structures Theory by I. Chopra and J. Sirohi (2013)

One of the fantastic applications of SMA is a variable geometry Chevron application, which is done by Boing dream liner aircraft. If you next time fly in dream liner, you will notice that its edges at the engine this is jagged. The reason being of this jagged shape is that initially at this phase when it is at say detwinned or twinned Martinsite, but it is mostly Martinsite phase, and this phase it has this jagged shape and this actually helps for vertices to make the keep the size of the vertices to low, so that it gets attenuated fast.

Now, as you are heating up, then this shape and you are going up, then this shape will go back to a flat shape which will increase fuel efficiency of the system, so thus you can play between the 2 shapes and then keep the aircraft really very less noisy.

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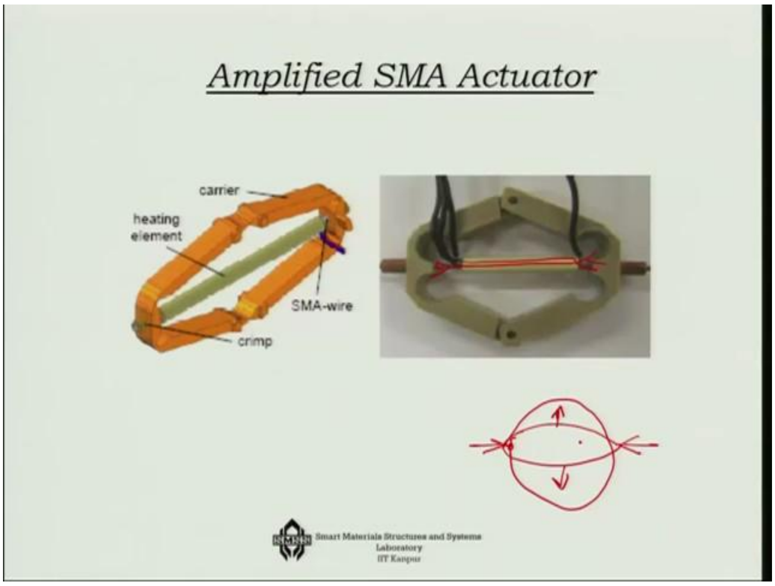

Amplified SMA Actuator

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Another example is in terms of amplifier SMA actuator, so here this is the SMA in the system and you apply heat. Now because SMA can give lot of force, so you can deform an egg shaped system, so if you try to deform an egg by the semi major axis, you will understand what I mean that it is very difficult, you need lot of force. But however, if there is a small deflection here, the deflection is going to definitely get amplified along this direction that is what actually is done in this particular case as well.

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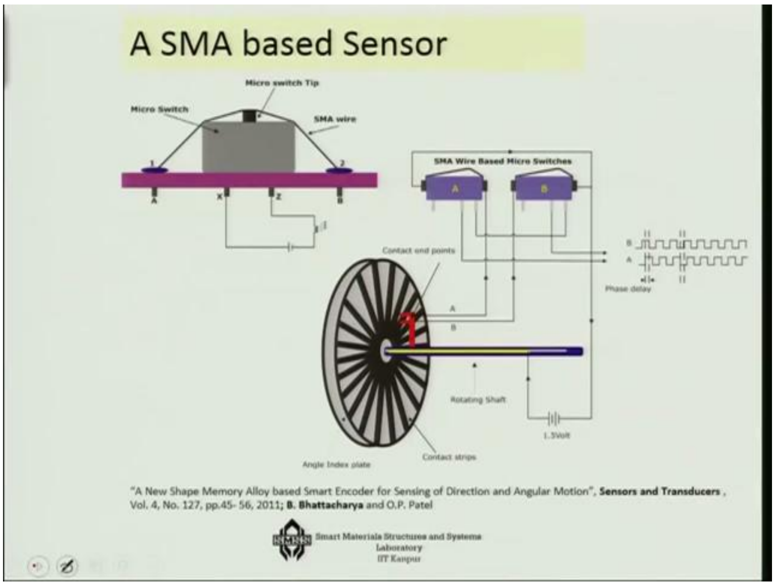

A SMA based Sensor

"A New Shape Memory Alloy based Smart Encoder for Sensing of Direction and Angular Motion", **Sensors and Transducers**, Vol. 4, No. 127, pp.45- 56, 2011; **B. Bhattacharya** and O.P. Patel

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One very interesting application of SMA is in the form of SMA wire based sensor that we have developed. So what you do here is that you take a kind of an angle encoder, where you have these contacts and then these are actually conductive things and these angles are drawn with known angle. Now, these 2 pins are touching are touching the system and you are passing the SMA wire based current. However, the catch is that whenever these 2 pins are touching this the SMA wire base system only than the current is flowing and then because of that resistance, you are going to get a signal.

The moment it is not or the velocity is changing; you are going to see there is a shift or a phase delay which you can use in terms of measuring the direction and the angular motion of the system. So this is where I will come to an end and in the next lecture we will talk about introduction to material selection and the Ashby approach. Thank you.