

## **Microrobotics**

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**Week- 05**

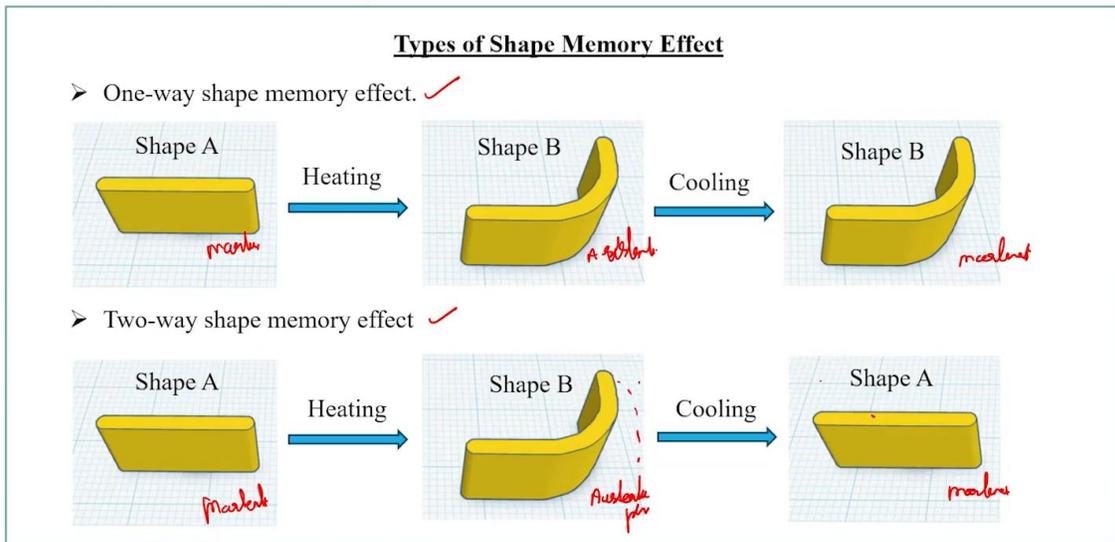
**Lecture No- 22**

### **Micro-actuation and Micromanipulation - Module 07**

In the last class, we discussed the overall family of smart materials, how these smart materials can be selected for a particular application, and what the different process parameters are that are involved with reference to smart materials. In fact, we discussed shape memory alloys, the family of shape memory alloys, and the different parameters involved with reference to shape memory alloys. This video will give you better clarity on how a shape memory alloy works, where there is a spring tied to a weight; because of the weight, it gets deformed. When I try to apply an electrical bias to it, it returns to its original shape. Similar responses are happening here; for example, when we try to elongate the Shape-Memory alloy spring and put it in hot water, it returns to its original shape. Now the mechanism behind this, which we had seen, is a kind of austenite to martensite shift, and with reference to the austenite to martensite transformation, we get a kind of actuation that is exhibited in these shape-memory alloy structures.

That's how we are involved in the micromanipulation of shape memory alloy structures for different applications. The overall types of shape memory alloy that exhibit based on the type of shape memory effect appropriately design an actuator for micro-robotic applications. To classify the type of shape memory effect, two types of shape memory effects are demonstrated. One is called the one-way shape memory effect, and the other is called the two-way shape memory effect.

# Shape Memory Alloy



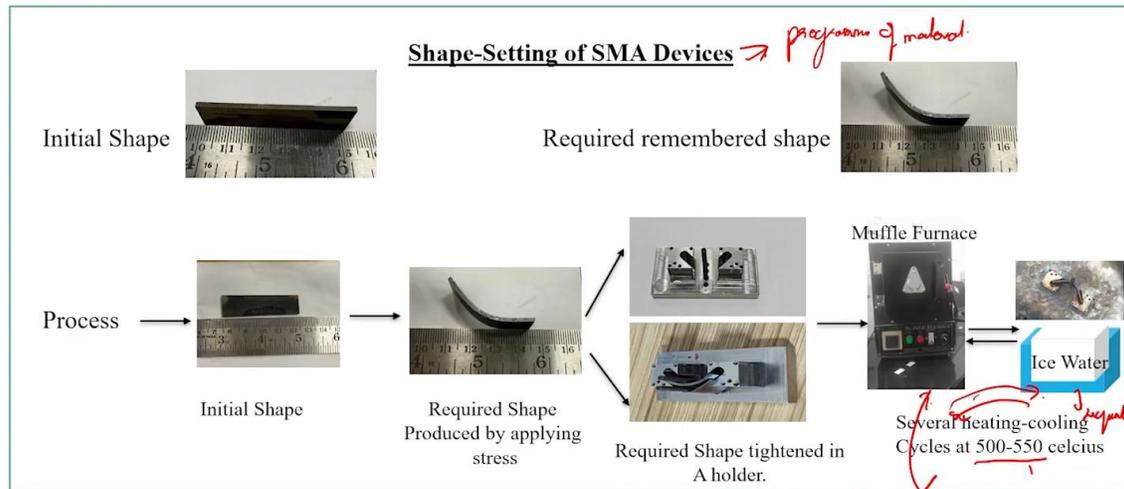
In the case of a one-way shape memory effect, let us consider a shape A that is straight. When trying to supply heat to it, it takes the shape B. However, when trying to quench it, it will be in the same state, that is martensite austenite martensite memory. That is, it won't come back to its original shape, so it's a kind of one-time deformation that happens. However, in the case of a two-way shape memory effect, let us consider a shape A, which is initially in the martensite phase.

Now when we try to heat it, it takes up a shape B, which is a form of the austenite phase. On cooling, it comes back to its shape, which is again a kind of martensite phase. This happens without any kind of external loading. So this effect is called a two-way effect. That is, let us consider a cantilever; the cantilever is loaded and deformed.

When we try to supply heat to it, it remembers its shape and returns to its state. This is called one-way actuation. In the case of a two-way actuation, it is in shape A, shape B, and shape A. This happens due to a two-way effect, that is, from position A to position B and from position B to position A. This is called a two-way shape memory effect.

# Shape Memory Alloy

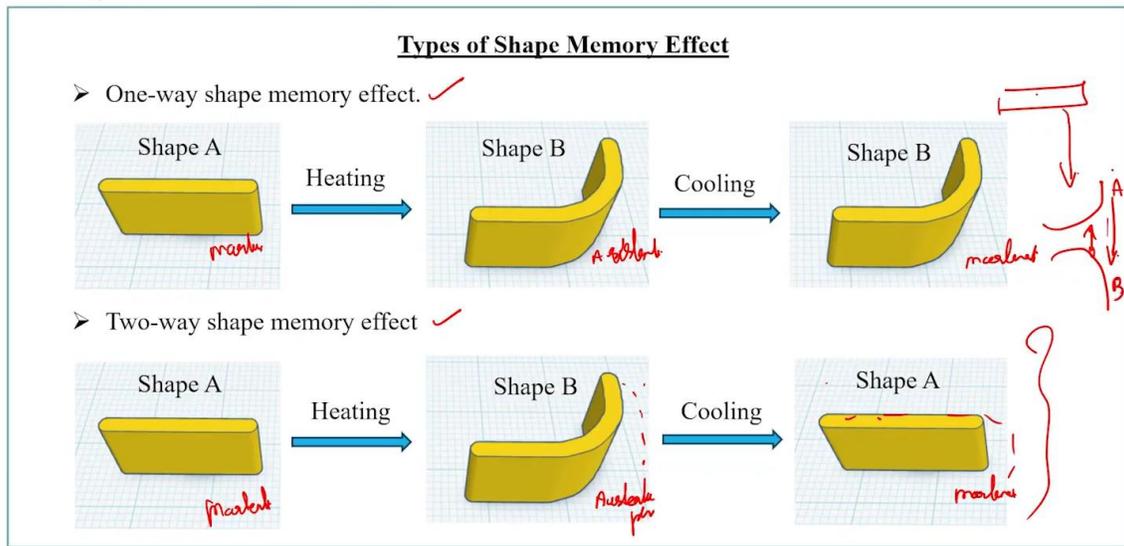
(Module-3)Micro actuation and Micromanipulation -2



Now, how can we program this material for this particular shape memory effect, train the material, or make this material remember its shape? For that, there are different types of mechanism which exist. However, for that we need to have a fundamental understanding of the phase transformation which is getting exhibited over here. If you closely observe the case of a shape memory alloy, you will see that there is a switching behavior between the austenite phase and the martensite phase. The main device here is that I have a shape memory alloy plate that is approximately 0.25 mm thick.

Initially, the shape memory alloy plate is in its initial shape. Now it needs to remember this particular shape. So what we are trying to do is, this is an initial shape. If I want to train it to a particular shape, I prepare a fixture in such a way that inside this fixture, I apply a load to it. Then, in order to make the shape remember, this is basically called programming the material.

# Shape Memory Alloy



What we try to do is go through several heating cycles. That is, we deform it into this shape. Put it inside a muffle furnace, heated to 500 to 550 degrees Celsius, which is almost close to the martensite phase, and then quench it in ice water or liquid nitrogen conditions so that it comes back to the austenite phase. This switching between the martensite and the austenite happens in such a way that you get a kind of closed structure or a kind of deformed structure; this process is called shape setting. However, with reference to the robotic perspective point of view, we call it programming of material.

So, why do we call it programming? Because we are giving a shape or setting the shape based on the requirement so that it gets actuated appropriately. In case this is a kind of one-way training, what happens to the two-way training? First, I need to get new material; then, I need to train for one-way training. After training it for one-way training with reference to a particular shape setting, I now need to deform it to the next level, and I need to repeat the cycles. So, what happens is that the initial new training will be completely eradicated from the memory of the material, and then the switching between the one-way actuation and the two-way actuation occurs. So that is something like, if this is like this with a particular angle and suppose this is like this.

So, I need to switch between here and here from the material that is flat. So, first I try to train with geometry A, then from geometry A I train the material to geometry B. I will be loading and unloading, that is, I will be switching these two mechanisms to create a kind of structure. In fact, I would like to show you a video here that talks about its actuation. This is a simple actuation of nickel titanium; that is why it is being actuated even with a lighter.

The estimated temperature is around 80 to 110 degrees Celsius, which we call the actuation temperature and is sufficient for actuating shape memory alloys for different functional applications. For example, in this case, these kinds of systems can be efficiently used for some types of bimetallic contacts. However, if I want to go for continuous actuation, then there is a possibility that I can use joule heating to create such structures. These types of shape memory alloys are concerned, so we have already seen that they are either Nitinol-based. These nitinol-based shape memory alloy structures are of concern; they have a high recovery strain of up to around 8%.

The most important point is that, as far as the shape memory alloy structures are concerned, these shape memory alloy structures have excellent biocompatibility. So that is the reason it has a potential application in biomimicking-related robots, and it can be efficiently used for biomedical devices like stents, orthodontic wires, etc. As far as these stent-related applications are concerned, it has the capability to immerse and can then be actuated. Then we have copper-based shape memory alloys. So as far as these copper-based shape memory alloys are concerned, the Cu-Al-Ni combination and the Cu-Zn-Al combination are some of the types of shape memory alloy structures that are being exhibited here effectively for actuation-related applications.

## Shape Memory Alloy

(Module-3)Micro actuation and Micromanipulation -2

### Types of SMAs

- **Nickel-Titanium (NiTi or Nitinol)** ✓
  - High recovery strain (up to **8%**).
  - Excellent **biocompatibility**.
  - Biomedical devices (**stents, orthodontic wires**).
- **Copper-based Alloys**
  - **Cu-Al-Ni, Cu-Zn-Al**.
  - Cost-effective, lower transformation temperatures.
  - Used in **actuators, dampers**.
- **Iron-based Alloys**
  - **Fe-Mn-Si, Fe-Ni-Co-Ti**.
  - Magnetic **shape memory** properties.
  - Lower cost compared to NiTi.
  - **Structural applications** in engineering.

One of the key points is that it has a lower transformation, and since the lower transformation behavior is considered to be one of the advantages of using copper-based shape-memory alloy structures. Whenever we are developing a micro robot for lower temperature transformation, this combination is considered to be a promising option for cryogenic-related applications. Next, we have the Fe–Mn–Si or Fe–Ni–Co–Ti iron-based alloys. So, as far as these iron-based alloys are concerned, they are called magnetic if they have a magnetic shape memory property, and in fact, they are of low cost compared to nickel titanium. They have potential applications related to structural characteristics.

## Characteristics of SMAs

- **Mechanical Properties:**
  - High recovery stress.
  - Large recoverable strain.
  - Good fatigue resistance.
  
- **Biocompatibility:**
  - NiTi is widely used in medical applications.

In fact, in technical terms, we call these shape memory alloys a kind of passive shape memory alloy. These passive shape memory alloys are capable enough for pseudoelastic-related applications. However, from an actuator's point of view, it has its own limitations because of the response time. Now, when I try to talk about the characteristics of shape memory alloy, this shape memory alloy has good mechanical properties; basically, it has a high recovery stress, a large recoverable strain, and good fatigue resistance. As discussed with respect to the biocompatibility point of view, NiTi is widely used in medical applications.

Now, one of the major aspects that comes into the picture is the manufacturing of shape memory alloys. These shape memory alloys are highly responsive to heat, or I would say that they are highly sensitive to heat. Even a slight variation in the structure will result in a different kind of material. For example, if I have a combination of Ni-Ti-Cu, considered a ternary alloy, with nickel close to 45%, titanium around 45%, and 10% of copper. Even if there is a minor variation, this may result in the shifting of the shape memory alloy to a different level.

The second thing is, let us consider that I have a shape memory alloy rod and a shape memory alloy sheet. So, if I want to machine the shape memory alloy sheet, I will, of course, be going for a drilling process. It will be very difficult for me to drill using a drilling process because the heat that is generated causes it to deform, which may have its own impact. That is why we normally prefer to use wire EDM-based machining so that there is less heat transfer and we can appropriately create the features. Now, when you try to buy these shape memory alloy structures commercially, they are available in the form of wire, powder, sheets, plates, or rods.

# Shape Memory Alloy

(Module-3)Micro actuation and Micromanipulation -2

Manufacturing of SMAs → ~~to~~ ~~separate~~ to heat ←

- **Traditional Methods:**
  - **Melting** in a vacuum to prevent oxidation.
  - **Casting** into ingots and **heat treatment** to set transformation temperatures.
  - Forming processes like **rolling**.
- **Advanced Methods:**
  - **Wire Arc Additive Manufacturing (WAAM):** Uses wire as feedstock for 3D printing.
  - **Powder Metallurgy:** Sintering powdered metals to form the alloy.
  - Enables complex shapes and cost-effective production.

wire form  
powder  
sheet  
plates  
rods  
↓  
[3D printing]

So in the wire form, of course, it can be in different diameters. From a powder form perspective, many cases like Ni are taken separately, Ti is taken separately, and they are being appropriately ball milled to achieve the structure. Then, in the form of sheets, we can get thin sheets from 0.1 mm to a higher order. For plates, we can also go for thick plates.

In certain cases, we also receive it in the form of a rod. Which means that, in most commercially available structures, these kinds of shape memory alloys, which have a higher performance, are appropriately taken wherever there are bulk manufacturing requirements. In fact, sometimes we get shape memory alloys in the form of springs as well. So this has a potential application towards actuator development, and in certain cases, it is also used for a certain amount of sensor development. Now, as far as the traditional perspective point of view is concerned, these structures are basically melted in a vacuum to prevent oxidation, and after melting, what happens is that it either goes for casting in the form of an ingot or, in certain cases, it also goes for heat treatment to set the transformation process.

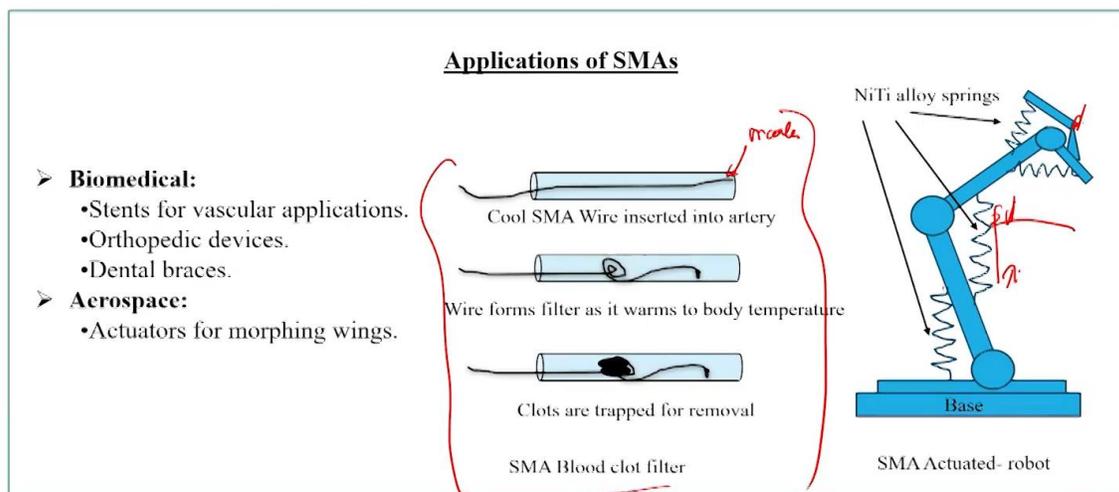
Like forming the shape memory alloy is a challenging task, the forming process, such as rolling, can be employed. However, recently there has been a wide variety of research focusing on taking the additive manufacturing route as one of the promising methods for this shape memory alloy fabrication. In fact, a wire arc-based additive manufacturing route is one of the promising routes since we have a wire form; thus, the wire form is suitable in case you need to add intermetallic. Appropriately, you can use a separate wire feeder, and then we can feed the powder to create the structure based on our requirements. The second way is similar; since it is in the form of a sheet, we can use a type of friction stir-based additive manufacturing to prepare such structures for thicker sections, etc.

And then a powder metallurgical route is one way through which people are developing bulk structures. However, a DED process, directed energy deposition-based techniques, can also be deployed through either a powder bed or a nozzle base. So, through which we can have multiple powders. These multiple powders coagulate and then create a structure based on our requirements. Of course, additive manufacturing is promising for creating such complex shapes based on our requirements with shape memory alloys.

However, one of the major challenges that exist here is training the shape memory alloys based on our capability. So, what people used to do is whenever they tried to go for the additive route, whatever shape setting had been made initially was the original shape of the material. Now a kind of fixture can be deployed to have a series of training so that with this training we can have adaptable structures. Now, as far as the shape memory alloy perspective point of view, this is a good example where a shape memory alloy wire is initially in the martensite phase. This is inserted inside the artery, and the wire forms a filter; when the wire gets this one, the body gets warm, and because of that, a certain amount of clots or trapped material is completely removed from this process.

## Shape Memory Alloy

(Module-3)Micro actuation and Micromanipulation -2



So this is a kind of mechanism which is being deployed to remove a kind of SMA clot-based structure. In fact, a similar technology is deployed for inserting an SMA-based stent, and when we try to actuate it, this stent enlarges and can be used appropriately. Like this, we can use NiTi springs to develop an SMA actuated robot. So, the loading can be done through the concerned link and then by applying a kind of actuation by connecting it with the appropriate wires and providing joule heating to this system. Thus, we can have a form of manipulation.

Recently, there have been some reports of people using a laser to heat such kinds of shape memory alloy structures. By selectively heating this, a kind of actuation occurs; these

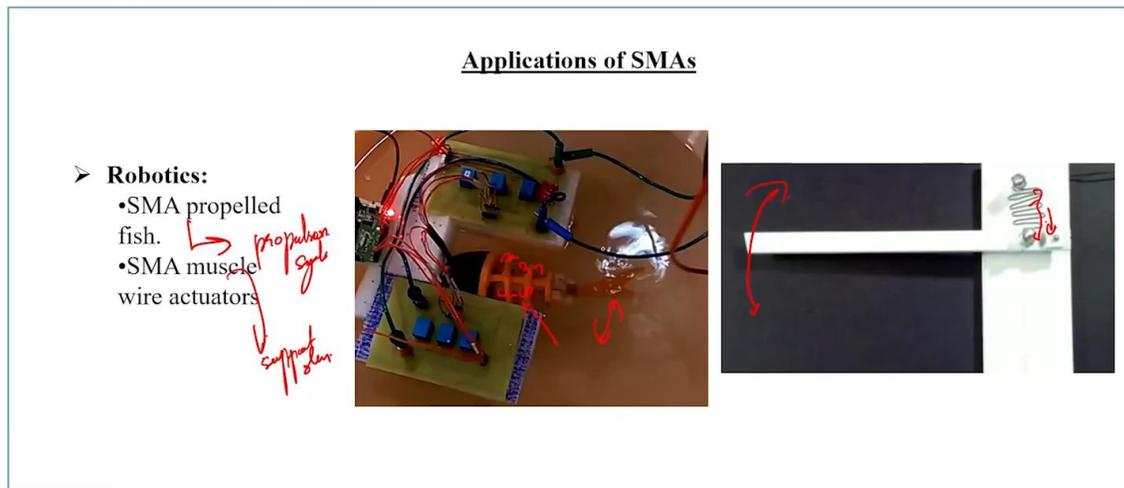
actuators are capable of being used to actuate the shape memory alloy based on its characteristics. Now, let us see some of the key applications of shape memory alloys from a micro-robotic perspective. From a micro-robotic perspective, shape memory alloys are used as a type of propulsion system or as a supporting structure. Like this is a kind of supporting structure.

By actuating it, we can have a displacement that is exhibited over here. And this is a kind of propulsion mechanism; in this propulsion mechanism, a shape memory alloy spring is integrated into it. By actuating it, we can have a kind of actuation that almost gives a bio-mimicking capability to the structure. Now, this is a kind of bio-inspired SMA bimorph and a bio-inspired origami robot. In this aspect, to develop it in the form of a micron level, we need to develop it on a micron level.

One of the key aspects is that, since we have a shape memory alloy in the form of wire, we can integrate the shape memory alloy wires with a type of composite structure or a polyamide structure based on our requirements. For instance, let us take a composite structure. This composite structure is integrated with the shape memory alloy wire. So, to provide an appropriate program for it, for example, if I am looking for an actuation, something like this. One option I have is to give a kind of training to the SMA wire by straining it by two to four percent.

## Shape Memory Alloy

(Module-3)Micro actuation and Micromanipulation -2

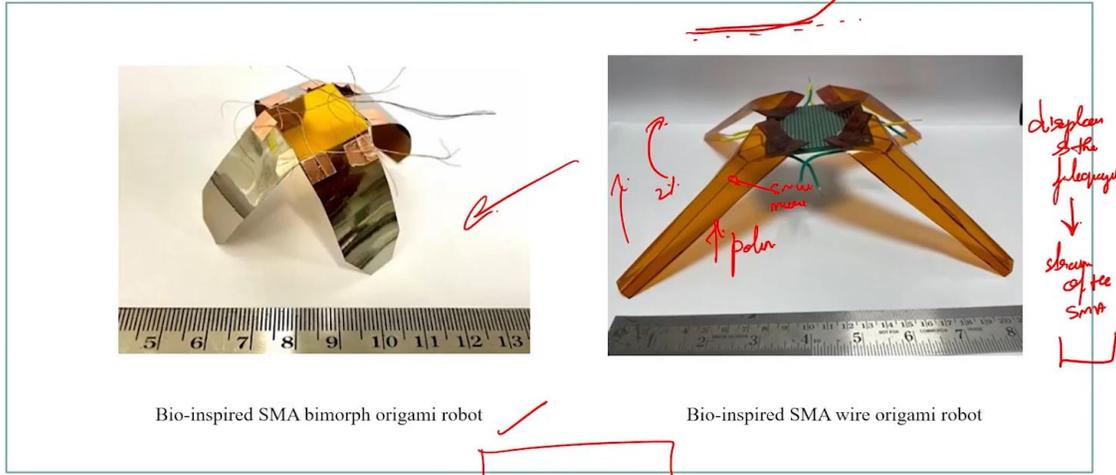


So what happens is that when I am straining a wire up to 4%, appropriately, over these strained wires, we have a kind of PDMS structure and a composite structure that is being integrated into it. So what happens is, when you try to actuate this shape memory layer structure, these composite structures will try to deflect and then they try to come back. In this particular case, we have a polyamide that is integrated with a micron SMA wire. So these SMA wires are integrated with this polyamide composite structure, and these SMA

wires are strained up to 2% so that this 2% will be the kind of programming for this shape memory alloy. So that the shape memory alloy gets actuated, there will be a kind of displacement exhibited here.

## Shape Memory Alloy

Trans. strain by strain  $\Rightarrow 2 \Rightarrow 4\%$   
 (Module-3) Micro actuation and Micromanipulation -2



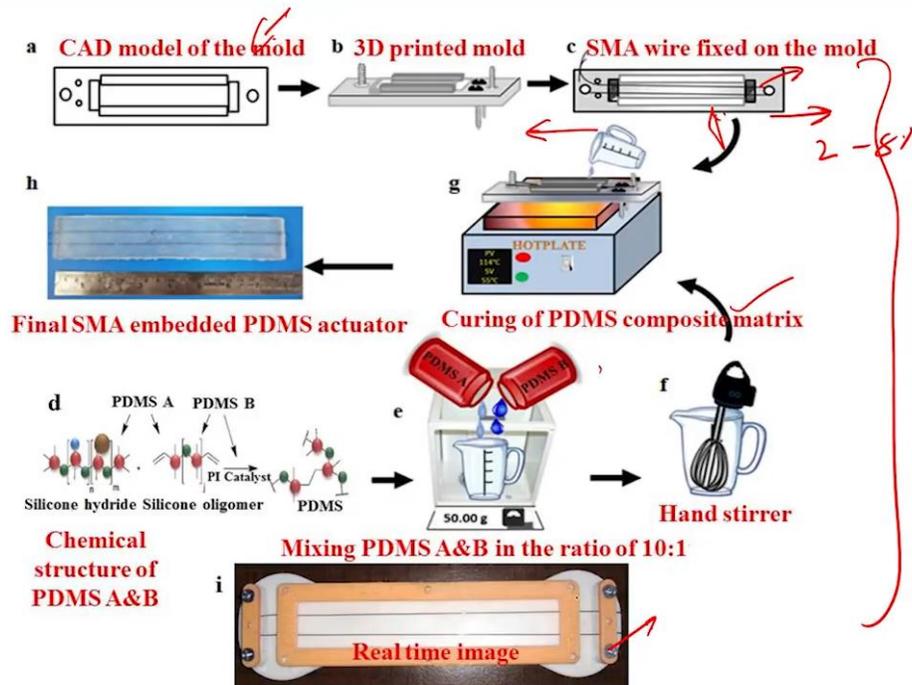
So, based on the displacement or based on the frequency, ideally, your displacement and the frequencies are correlated to the straining of the SMA wire. Once the SMA wires are strained appropriately, composite is encapsulated on this, or in certain cases, what people do is strain the SMA wire and then try to encapsulate it. Now let us discuss these SMA-based composite structures, which are being incorporated. So, it's a kind of SMA-based origami robot that is activated using an underwater application. Of course, we will discuss more about this in the biomimicking module.

Now, let me take a simple example or a simple case study where an SMA-embedded structure is fabricated with PDMS. So PDMS is a kind of jelly-like structure. It's a soft structure that is used for biomimicking-related applications, and it is also used for soft robotic applications, etc. So, the first thing is that we are trying to print the mold using CAD, and then these molds are 3D printed, and inside this 3D printed structure, we are trying to integrate an SMA wire. So, over this SMA wire, there is a mold that is being kept, and these SMA wires are strained from 2 to 5 percent.

So, over this 2 to 5 percent, the PDMS structure is being laid, and then the PDMS is skewed for an appropriate composition matrix. So, what we are trying to do is, there is a mixing of a PDMS structure, and finally, it's a kind of SMA integrated PDMS layer that you can observe over here. Now, it is a kind of study that has evolved to investigate the actuation behavior of these shape memory alloy structures. So basically, this is a kind of structure where the SMA wires are integrated into it, and the actuation is done through electrical biasing.

So it's a kind of joule heating that is done. So we could see that there is a kind of temperature rise that increases with reference to the applied current. So, as and when the current increases appropriately, the temperature will increase, which will result in the actuation. Now let us see a small gripper that is fabricated using a kind of SMA-based biomorph. So in this, this is a kind of PDMS structure. This is a kind of SMA, which is integrated into this PDMS structure.

## FABRICATION OF SMA EMBEDDED PDMS STRUCTURE



So, where we could see, these structures are trained with different percentages, such as 2%, 4%, and 6% strength. So, based on the straining impact, it appropriately has a capability for load carrying capacity. And the most important thing is that since it is being strained, it has an actuation in this direction. And when you try to fit it up, it appropriately holds it and retains it for a particular time.

So, you could keenly observe a load of up to 2.5 grams. And this is up to 3.5 grams with a 4% strain, which is embedded over here, and up to 7 grams, where a kind of load can be actuated in it. Now, based on the gripping arrangement appropriately we can use this system for different applications. So, to summarize, we had discussed the shape-setting characteristics in a shape-memory alloy. So, in the case of shape-setting characteristics, we have discussed the one-way shape memory effect and the two-way shape memory effect.

How a one-way, that is, which is more required for programming the shape memory alloys for different robotic as well as micro-robotic related applications. If we need to program it

appropriately, we may need to have a kind of manipulation in the memory of the material; for that, certain methodologies are followed. Since it works on the austenite to martensite transformation, a die can be prepared and appropriately deployed in both hot and cold conditions, and then we can observe or train the material shape setting that can evolve from it. So as far as the one-way shape memory effect is concerned, it is switching from the nave to the shape. As far as two-way shape memory is concerned, it is switching between two shape-setting domains so that it can be used as a kind of actuator, and you can also use it for a frequency-based system.

This is a kind of shape-setting procedure that is being followed here, and this is the actual actuation of a shape memory alloy thin sheet that is being actuated at a temperature of around 80 to 110 degrees Celsius. We discussed the different types of shape memory alloy structures and their properties. We also discussed the manufacturing of these shape memory alloys. As mentioned, it is highly sensitive to temperature, and appropriate manufacturing routes should be deployed. By deploying these manufacturing routes, we can employ them for different applications.

This is a practical application where shape memory alloy structures are used to remove blood clots in a structure. So, there is a kind of tube structure through which shape memory alloy wires are incorporated. By giving an appropriate actuation to it, you can manipulate the beam for our requirements, and this is a kind of SMA-actuated robot. So, where there is a base with nickel titanium springs being deployed into it. By actuating it under different conditions, we can observe a kind of actuation that persists here and these actuations are capable enough to be used for holding or manipulating structures for different applications. Now, since these materials have a capability for biomimicking, they have potential applications for different robotic structures related to biomimicking. So, it takes care of the structure, and it takes care of the propulsion. And these are some kinds of biomimicking-based robots. So, I had given you an idea about how SMA-integrated composite structures are fabricated, how SMA-integrated polyamide structures are fabricated, and how these structures are being incorporated into the system and this is the overview of the performance of this shape memory law integrated PDMS structure, which is used as a gripper over here. So, a kind of manipulation exists that takes care of the loading and unloading of the systems. Now we will discuss one of the important case studies where shape memory alloy-based Microactuators have been developed for a kind of optomechatronic application. Basically, we have developed a small shape memory alloy thin film-based steered platform, a parallel manipulator for beam steering-related applications. So we will discuss that case study in the upcoming class.