Materials Chemistry
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Module - 5
Lecture - 1
Shape Memory Materials

In the earlier lectures, we have seen how magnetic materials can be used in a different applications. Whenever we talk about magnetic materials, the most important feature that comes to our mind is magnets and the fundamental applications that govern magnets and how the magnetic induction can be used in variety of applications. As we have seen in the previous lectures, magnetic materials also play a decisive role in controlling other properties.

For example, in the case of manganites, we said magnetic property of manganites controls the electrical conductivity and two dual properties go hand in hand, which we call it as a dual property of magneto resistance, where magnetism governs the resistivity of that material. And we have also seen, how this effect is pronounced in multi layers and we were talking about a tunneling magneto resistance.

Also as another example we shown, how we can translate a insulating or a semi conducting material by carefully doping some magnetic impurity, how you can transform even with low level of doping say 1 or 2 percent, you can still transform that material to go magnetic. Today, I am going to isolate another important group of materials called magnetic materials that retains shape. So, no matter what happens to this material, because of it is intrinsic property of this magnetic material to get deformed from a elastic to a super elastic behavior.

They have a special tendency to retain it is memory, so when a particular stimuli is given, it can come back to its original shape. So, this is pronounced in a rather few materials, predominantly they are called alloys and these alloys are materials sandwiched between few 3 D and 4 D metals. And there are also non metallic materials called polymers, which show the same property that is, to retain it is shape. So, I would take you through some issues and more so I will also highlight specially one aspect of this magnetic material that is, magnetic alloys, which is finding lot of applications in today's life.

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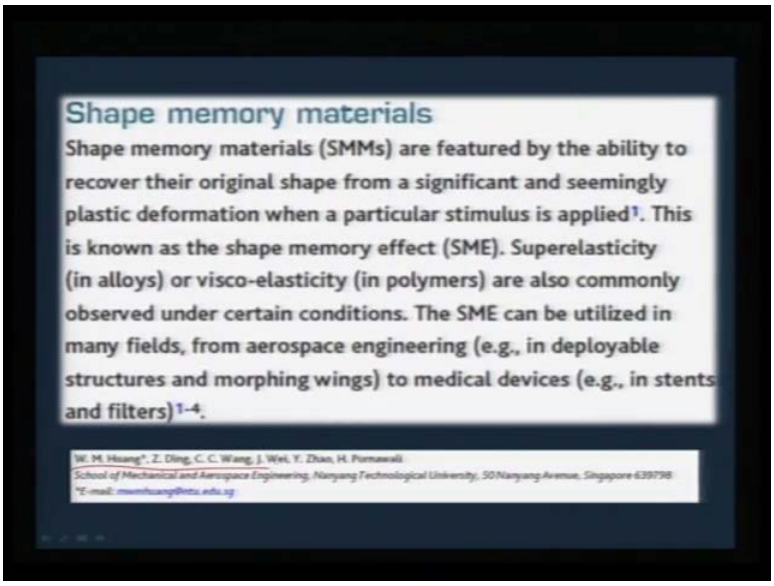

To start with, let us go with some of basic definitions, shape memory materials, they are classified as SMMs. So, shape memory materials are featured by their ability to recover their original shape from a significant and seemingly plastic deformation. You can just pull it and after a particular stimuli, it can come back to its same shape and this stimuli can be either pressure or it can be temperature or it can be light and so on, this is known as shape memory effect, which we call it as SME.

In alloys, it is usually super plasticity that is happening, even in some oxides you can actually pull, such oxides had a particular temperature and it almost behaves like a rubber and it can even go through a plastic deformation. So, they are called super elasticity and this is more pronounced in metals or alloys and in polymers, it is called viscoelasticity, it can go beyond it is blending temperature and these are observed at certain conditions.

The SME can be utilized in many fields, for example in aerospace engineering, in deployable structures and morphing wings, mainly to arrest the vibrations in aerodynamics, these alloys are specially used. And if you go to medical devices, as a extreme case you even see, instance that are deployed in our cardiovascular system, you can see these are finding enormous application.

Recent article in materials world, which was written by Huang and coworkers, they have specially covered some of the essential features of these alloys. I would like to emphasize more with respect to this article and pick out some of the examples, which they have listed out. So, I will be essentially dealing with this article written by Huang.

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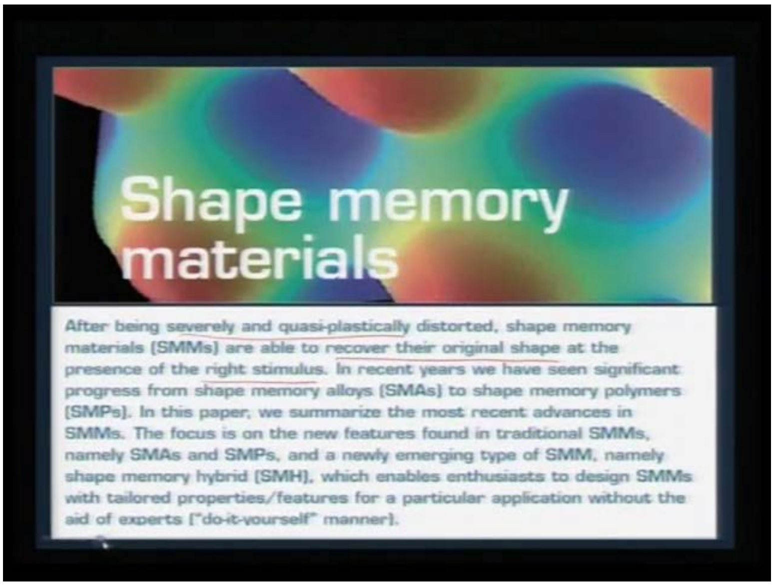

And this is the article that featured in materials world, so as I told you, the severely and quasi plastically distorted materials, they recover to their original shape at the presence of right stimulus. So, there are two, three group of compounds, which we will be studying in today's lecture. One is super plastic or shape memory alloys, the next one is shape memory polymers and we will also show some example of shape memory hybrids, that has both the polymer and the alloys impregnated in each other. Therefore, we can see how the properties can be understood.

As I told you in the beginning, shape memory alloys are thermo responsive, so at low temperature, suppose you try to make a particular shape like a spring or a hook using alloy then at high temperature, you can actually remove that shape at the transition temperature or at the temperature, where there is a martensitic transformation of this alloy. And once you cool it down, again the same shape that you formed for this alloy can be retained, so this is called a thermo responsive. The shape recovery is heat, some shape memory alloys also show magneto response. In other words, applying a field, you can try to revert it back to the same shape.

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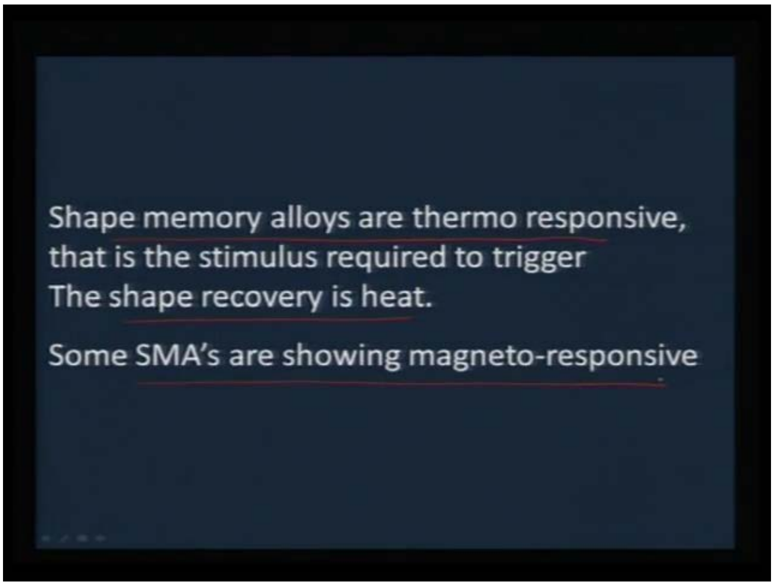

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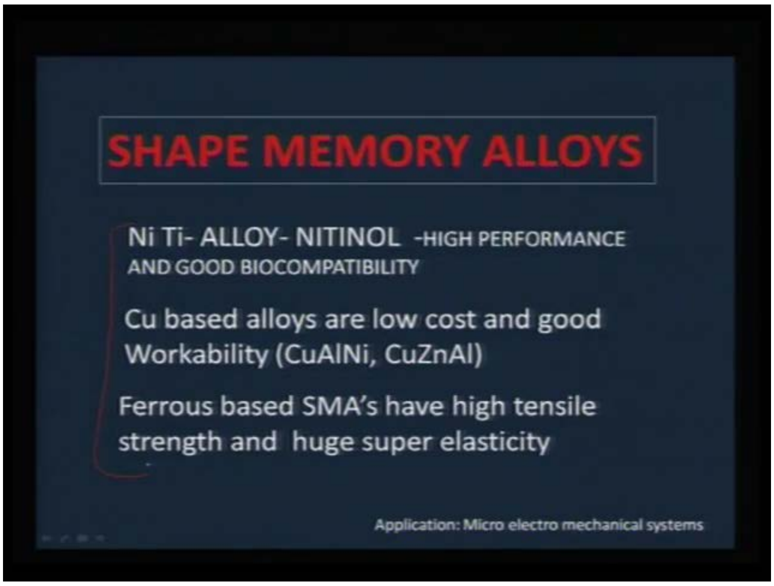

Shape memory alloys can be categorized into many compounds, just single out some of the widely used ones in today's application. Nickel titanium alloy is one of the predominantly used one and this was a part breaking discovery by US defense lab in the late part of last century and it is also nick named as nitinol, nickel titanium alloy. And the essential feature is, it has very high performance in terms of elasticity, mechanical strength and also it has a very good biocompatibility.

Closely followed by copper based alloys and for example, copper based alloys are Cu, Al, Ni and Cu, Zn, Al these are very good compounds, which are cost effective. Because, unlike nickel and titanium, copper based alloys are much more cheaper and processing is easier, because they are more malleable. So, the workability into different shapes is achieved much better for copper based alloys. We also have ferrous based SMA's that is, shape memory alloys, which have very high tensile strength and huge super elasticity.

So, in today's application, you see almost either of this group of alloys competing for the market and one of the most recent application of this shape memory alloys is, in the field of MEMS, Micro Electro Mechanical Systems, which is a used for device applications, it is one of the emerging field and it is called MEMS technology. Lot of groups are actually converging into this area, chemists, physicist and mechanical engineers are particularly interested in MEMS technology.

Because, you can actually transcend from micron based devices into nano based devices, specially in constructing new MEMS device structures. One of the thing that is very important in a shape memory alloy is the transition that take place.

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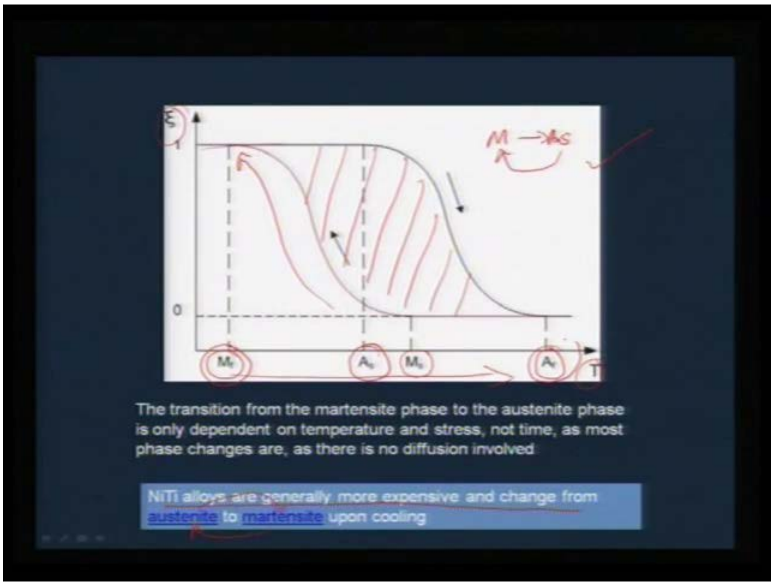

In nickel titanium alloys, they are more expensive but then they have a very good transformation to show this shape memory behavior, specially in the conversion of martensite to austenite or austenite to martensite transformation. And this figure shows the transformation ratio eta in terms of temperature, so as you start heating from the martensite, which is stable at low temperature, the material actually transforms and the transformation starts somewhere here, which we call it the starting point of austenite.

And then at a particular temperature, there is a complete conversion of this austenite, from martensite to austenite. And once you are here, you can actually cool this to the martensite by a periodic cooling and you can see here, the martensite starts appearing again at temperature somewhere here. And then again the conversion is completely through, when you go to M f that is, final state of martensite. So, in this transformation from martensite to austenite and austenite to martensite, you essentially evolve with a hysteresis.

And this is the hysteresis, which makes this a useful shape memory alloy which means, at low temperature you stabilize the martensite phase, at high temperature you stabilize the austenite phase and this is a plastic deformation that occurs in this alloy. So, this is a very important and these alloys can also go through this martensite to austenite transformation not necessarily in with respect to temperature, but also with respect to stress that is, pressure. So, you can also apply just pressure without temperature, at a particular isothermal condition you can bring about this phase transformation.

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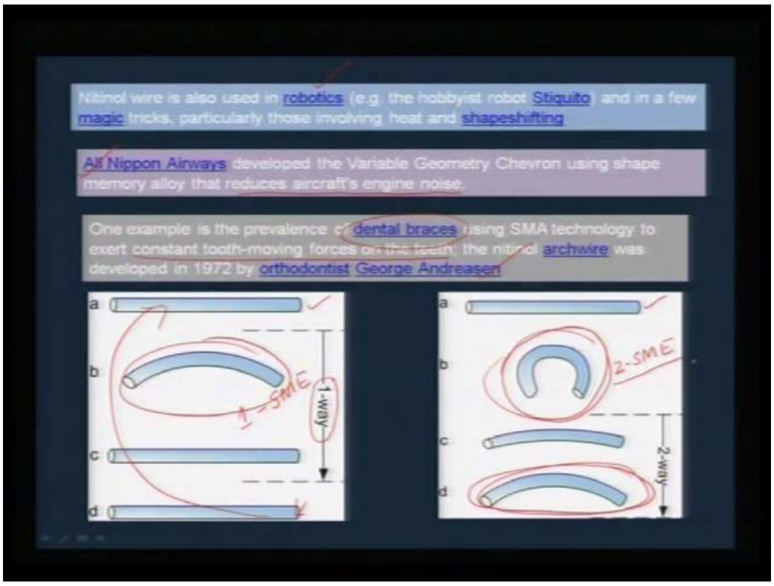

So, nitinol wire in terms of application is used in robotics, because of the shape memory property, you can actually design robotic instruments using nitinol wire, that is why it is very costly, because you can actually use it for many functional applications. For example, the hobbyist robot stiquito is particularly made of nitinol wire and in few magic tricks and particularly, those involving heat and shape shifting. So, for a laymen, it appears like it is a magic, but actually the property that is used is a shape memory alloy.

Therefore, it is used in toys and in robotics, but this is not as cheap as that, this finds very sophisticated application. For example, Japanese airlines Nippon developed this shape memory alloy, that actually reduces aircraft's engine noise. Therefore, in several application in today's airline fabrication, nitinol is quite widely used. Another example is the prevalence of dental braces, which we use to restructure our teeth using shape memory technology, because it will exert constant tooth moving forces on the teeth.

And therefore, it always keeps the shape intact, and therefore this can be used as a dental braces and also this has been used for several other dental applications. Now, there are two ways these shape memory alloys can be used, they exhibit two sort of properties, number 1 it is a one way shape memory effect I can call it. I can abbreviate this as SME, one ways shape memory effect or it can be a two way shape memory effect, what does it mean, suppose this is the initial state and then I try to cool it.

On cooling, I want to bend this a stuff, so it retains this shape and I can play around with that, but once I do not want this shape, I can actually heat it back and then I recover back the original shape, which is nothing but your A. So, this is one way effect, which means, whenever I go back then at low temperature it will recognize this shape and it will form to this particular shape. So, it is a one way, but at high temperature, it again comes back to its original shape.

But, whenever I cool it at to low temperature then it recognizes this shape that it was initially taken to, so it will bend when it goes to that particular temperature. 2 SME is something different, you start with this structure, and then in cold condition, probably you have twisted it like this and in hot condition you have actually twisted it like this. So, it will actually display both this property, whenever you are in the cold temperature regime then it will recognize this shape, when you come back to high temperature regime, it will recognize this shape.

So, it is called a 2 SME, Space Shape Memory, so both these effects are seen in a variety of compounds. Some show only one way, some show two way shape memory effect, so we have a list of alloys, which have been used.

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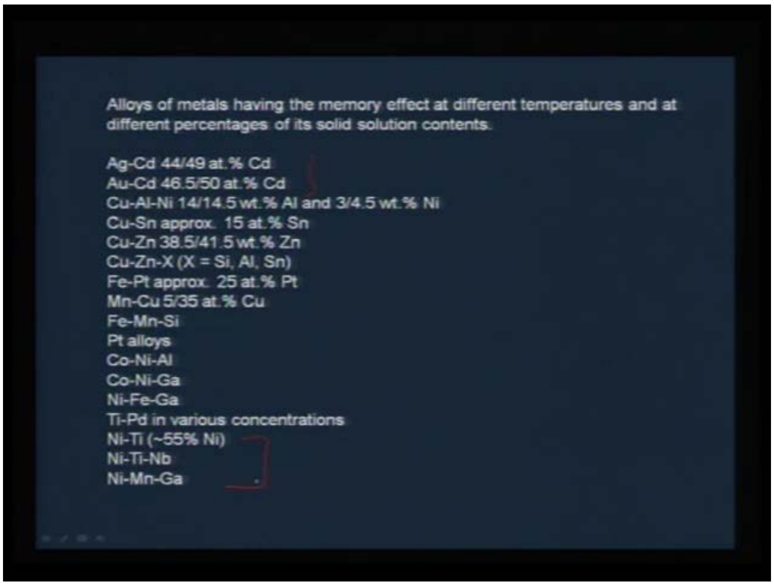

In the initial days of discovery, actually in the previous century, it was actually silver and gold based ones, which have shown such shape memory effect. But, what we see now is predominantly the titanium nickel based one, which is nitinol and the copper based ones and the iron based compounds. So, these have taken more limelight in the recent past, because of it is extraordinary stress strain characteristics. And also, the way you can man over or you can make different value added products out of this alloys, I will show some of the examples in this talk.

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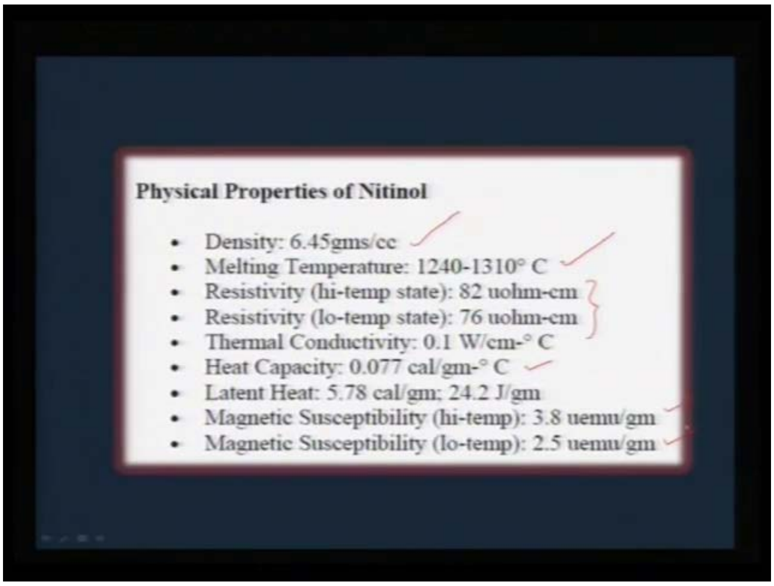

Let us take for example, nitinol as a case study and see, why nitinol can be used and if nitinol is a shape memory alloy then what are the characteristics of this. So, physical properties of nitinol, it has a density of 6.5 grams per cc, melting point is very high, therefore you can actually use this in variety of applications including aircraft, because the melting temperature is quite high. And it does not change much over a white spectrum of application, whether it is high temperature or low temperature, the resistivity is of the order of micro Ohms and it does not change much.

Therefore, that serves as a advantage, that you can use this for applications for joule heating. For example, I will show some examples, how this super shape memory alloys can be used to regain it is shape in using temperature. So, for joule heating, if you have resistivity along the same region at different temperature regimes then it becomes very advantageous and heat capacity is of 0.077 cals per gram. And then magnetic susceptibility, although it is low, but they are quite comparable again, at high temperature and low temperature, they show magnetic property of the order of micro EME per gram.

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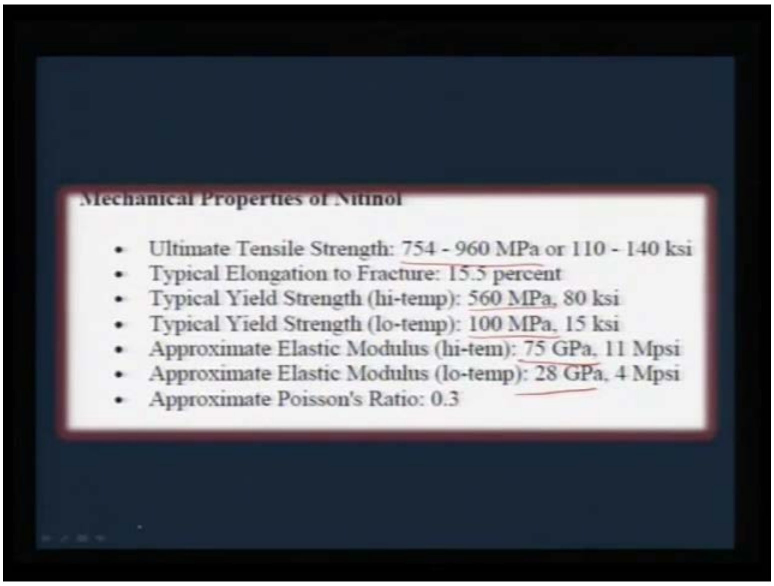

Mechanical properties are also equally important when we are considering applications, therefore some of the values that we can have in mind. Typical yield strength is 550 mega Pascal and 100 mega Pascal at low temperature then tensile strength ranges from 754 to 960 mega Pascal. Because, when you are trying to use pressure to induce shape then you need to know what is the tensile strength that it can take otherwise, if we exceed this strength tensile strength then it will break, it will get totally deformed.

Therefore, you should know under what tensile strength this shape memory alloy effect can be used. And similarly, you have the elastic modulus at low temperature and high temperature, which is 75 and 28 giga Pascal. So, this is quite a good amount of details, which can help us device nitinol for several device applications.

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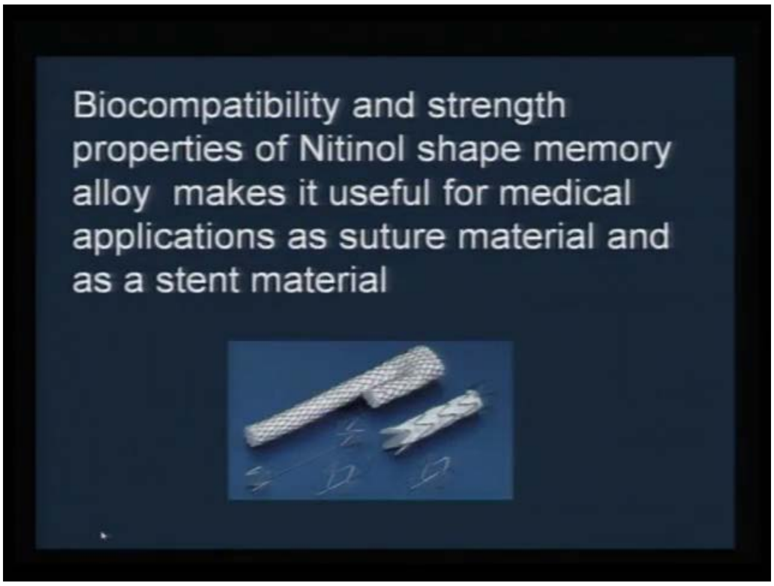

The most important property of this shape memory alloy is biocompatibility, if we want to think about biological applications. One of the usefulness is the biocompatibility and strength properties of nitinol, is to use this in sutures and also as a stent material. Now a days we have sutures, suture materials which are both bio dissolvable, so you do not go back to the physician and try to cut open your sutures. After your wound is healed, you try to take this suture out, you do not do that, because now a days you have bio dissolvable, it just dissolves over a period of time.

So, you do not have the pain of going and removing your suture through a physician, but nitinol is now used more so in as a stent material. Stent is nothing but a coiled wire like this, you can see the shape of this wire and this is predominantly used in your cardiovascular applications. Also, this sort of stents can be used in the neck region if there is a clot, in brain if there is a clot then you can try to put a stent and then relieve the blood clot.

You can also put this in kidney, suppose there is a stone formation then you can actually dilate that place by putting a stent then the tract can be released. So, there are variety of applications for using stent, not just for coronary artery applications. But, I will try to show you just one compound, which has a good compromise on biocompatibility mechanical strength, chemical properties, how this can be used for a very invasive procedure that is happening routinely in today's life.

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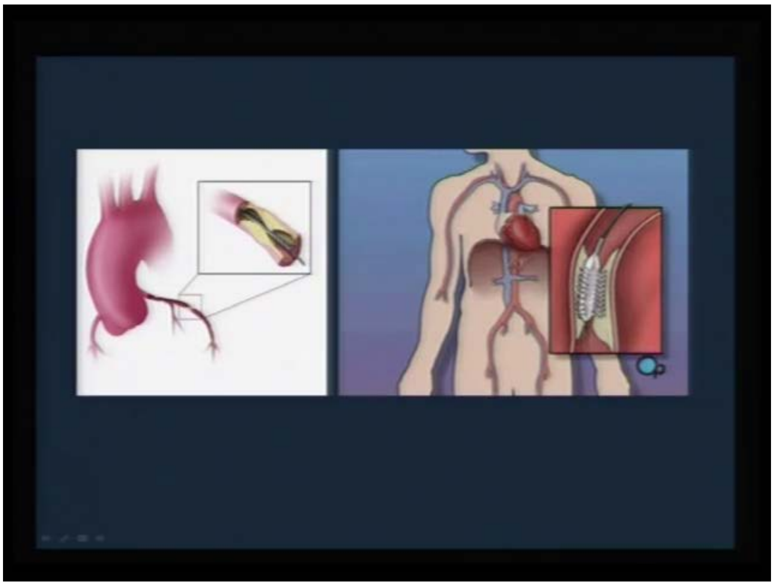

This is a cartoon that shows before and after how this nitinol based stent is employed, this is the one of the artery of our human heart. And this is a coronary artery, where this yellow region what you see, is nothing but your cholesterol deposit, which we call it as plaque and this plaque can actually hinder the lumen flow, as a result you get into myocardial infarction, which is your heart attack in other words. So, if you go through this anginal problem, the best solution is to put a stent material inside to relieve this strain and also to keep this plaque away, so that the blood flow can be restored.

So, this is the situation, when you just insert the stent and you can actually deploy this stent and try to restrain this by blowing it with a balloon and that is what you see here. It is now stationed in the place, where the blockage is and once you station this stent then the normal recovery of blood flow is established, as a result a patient recovers from anginal problem. Now, the material that is placed here is nothing but a nitinol stent, it can also be replaced by several other stents, I will show you some example of that.

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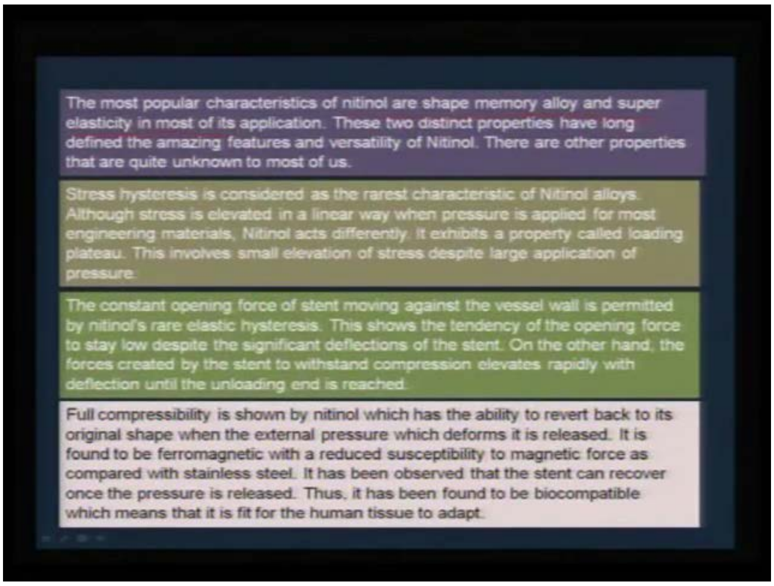

What makes this nitinol more special, apart from the shape memory effect and the super elasticity, there are other features, which makes nitinol more versatile. And they have amazing features, one is the stress hysteresis, which is considered to be a rarest of the nitinol alloys. What it means is, although stress is elevated in a linear fashion, whenever pressure is applied for most of the materials that is the way, a stress increases with pressure.

But, what happens in nitinol is something different, it actually exhibits a property called loading plateau. Meaning, a very small elevation of stress, despite large application of pressure is achieved. So, even when you are pumping lot of pressure, the stress loading is very very gradual, in other words it does not go linearly, it rather tappers down, there is a loading plateau. As a result, suppose you insert your nitinol stent into the cardiovascular stuff, it does not really blow the coronary artery, because it has a loading plateau.

So, this is called a stress hysteresis, which is a very important feature of nitinol and the second important feature is the elastic hysteresis. Elastic hysteresis is nothing but the tendency of the opening force to stay low, despite the significant deflections of the stent. So, when you are trying to open the stent there, the opening force is actually very very slow, you know if it is very sensitive and just deploys on it is own. Then you cannot even station your stent at the right position, because it would have got deployed somewhere else, other than the place where you want.

So, this is called elastic hysteresis, which is very useful and makes it more selective for housing your stent at the right position. So, another useful thing is the full compressibility that is shown by nitinol, meaning it has the ability to revert back to it is original shape when external pressure, which deforms it is released. So, this can also be a useful feature, full compressibility is possible like in some of the shape memory alloys, when you try to bring it back to the original shape, it will actually collapse only 90 percent or 80 percent.

So, in such cases, the usefulness of that material is lost, because you do not regain the shape fully, but full compressibility is possible with nitinol. Meaning, by mistake a physician has deployed the stent for some purpose and he wants to collapse it back, it should actually go back 100 percent, otherwise that stent becomes useless. So, nitinol has full compressibility factor, so it is observed that, stent can recover once the pressure is released and it is also ferromagnetic with a reduced susceptibility to magnetic force.

See, suppose the stent is deployed in the heart, the person will be very sensitive to magnetic field. So, if it is too sensitive then that also can really bring about damage to the stent at the cardiovascular system, therefore it has to be ferromagnetic, but with the reduced susceptibility, which can help the patient from getting exposed to severe magnetic fields. So, these are some of the main characteristics of the nitinol, which makes it special. So, in essence, shape memory alloys are super elastic in it is application, but added to that comes two advantages. One is stress hysteresis and elastic hysteresis, and this along with the full compressibility factor makes nitinol one of the best ones.

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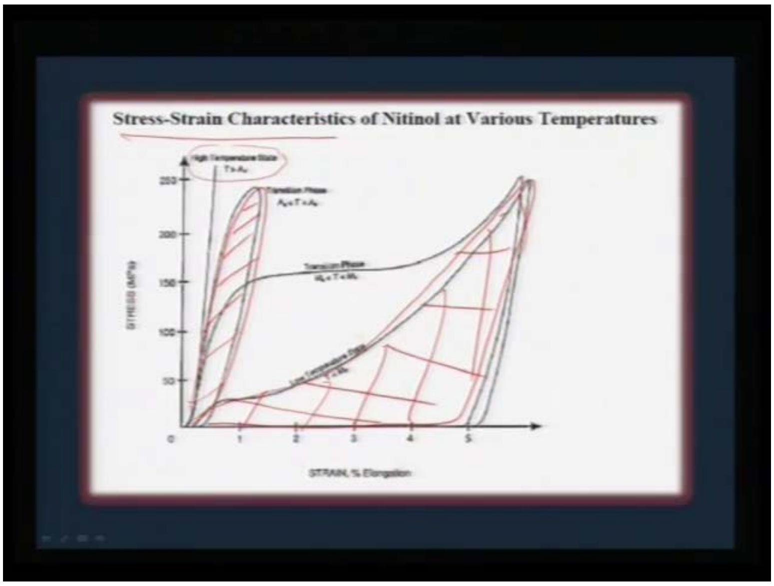

So, just to sum up why nitinol is good, if you look at the stress strain characteristics, you plot stress versus strain and in different regime, this is how it works. In the high temperature state you can see that, if you take it beyond the transformation temperature, it does not come back, it is irreversible. Otherwise, within the transition phases, you see a clear hysteresis that is produced at high temperature and similarly, at low temperature you can see another hysteresis proceeding here.

So, this is the way the stress strain curve applies for nitinol in the high temperature and low temperature regime, plus you also have the transition, which is very clearly seen. A transition from the martensite to austenite phase is clearly seen in this in this regime and this is also reversible which is highly selective. So, you can clearly make out the difference between the austenite to martensite transformation, which gives you the allowance to play with the different applications depending on, whether it is needed in high temperature phase or in low temperature. Now, we need to understand, how this deformation works.

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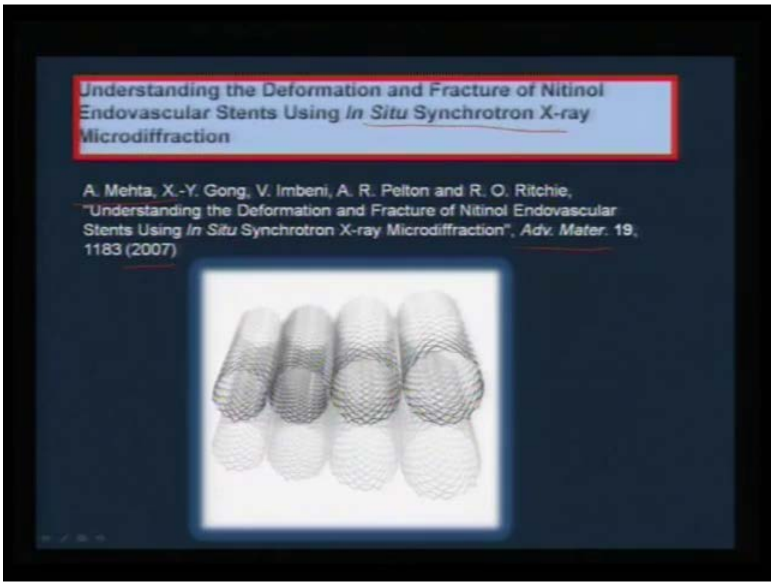

And this is another useful article, that came out in 2007 in advanced materials published by Mehta and co workers. When you try to deploy this stents in cardiovascular devices, you need to see, how the deformation and fracture occurs in nitinol stents. And this can be done using in situ synchrotron x-ray micro diffraction, that clearly tells you the sort of transformation that happens when pressure is employed. So, this is one study, which is useful to understand, how the transformation occurs inside the heart when you are applying pressure.

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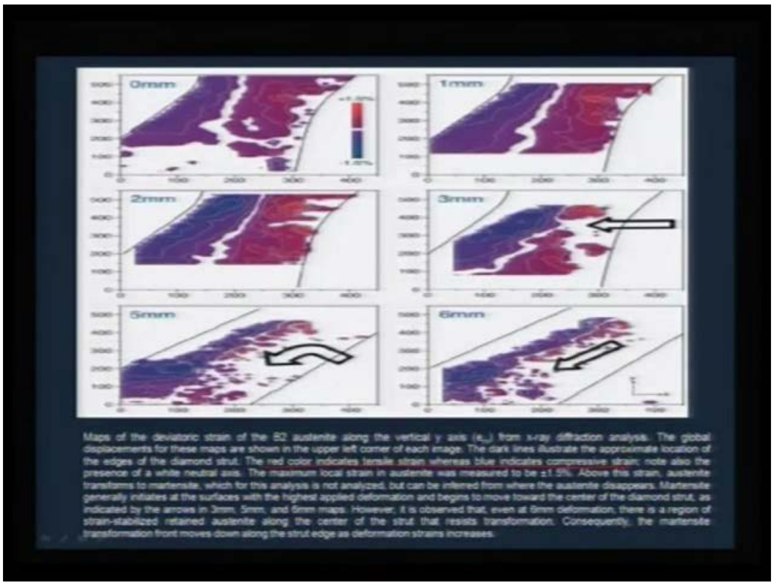

And this view graph gives the mapping, for example before deployment when the stent is actually placed, this is the mapping which shows, how the tensile strength is. The red color indicates that tensile strength, whereas the blue color in this contour explains the compressive strain. And if you see here, the maximum local strain in austenite can vary between minus 1.5 percent to plus 1.5 percent. So, before deployment, you can see the compressive strain and the tensile strain, which is mapped in this extreme and you also have a neutral axis here.

Now, if you start deploying this stent, you can see how the transformation occurs, at 1 millimeter you do not see much of changes, but when you go to 2 millimeters and then 3 millimeters and 5 and 6 millimeter, you can clearly see the change between the compressive strain and the tensile strain. And specially, when you are deploying the stent beyond 3 millimeter and go all the way up to 6 millimeter, you can see there is a complete transformation of your austenite to martensite.

So, we can clearly map, what sort of a phase transformation is occurring, when you are applying pressure inside your cardiovascular system. So, this is a useful way to understand, how much of loading this stent can take and how much centimeter that you can deploy this strength and what is the risk factor involved. Beyond a particular condition, it cannot be brought back to it is original state, in other words it loses it is super elasticity. Therefore, this contour gives you a idea about the transformation limit that is happening and that is what is mentioned here.

However, it is observed, even at 6 millimeter deformation, there is a region of strain stabilized retained austenite along the center of the stent, that resist transformation. Consequently, the martensite transformation front moves down along the strut edge, as deformation strain increases, this is what we see here.

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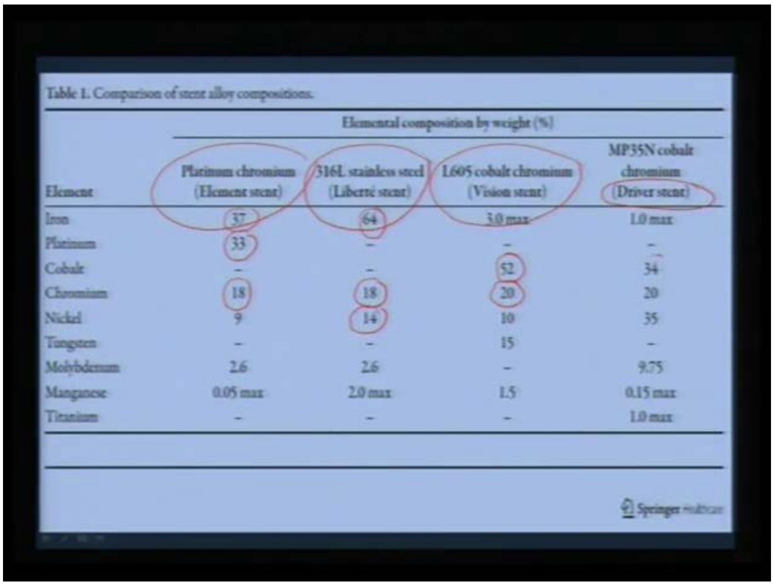

Table 1. Comparison of stent alloy compositions.

Element	Elemental composition by weight (%)			
	Platinum chromium (Element stent)	316L stainless steel (Liberté stent)	L605 cobalt chromium (Vision stent)	MP35N cobalt chromium (Driver stent)
Iron	37	64	3.0 max	1.0 max
Platinum	33	–	–	–
Cobalt	–	–	52	34
Chromium	18	18	20	20
Nickel	9	14	10	35
Tungsten	–	–	15	–
Molybdenum	2.6	2.6	–	9.75
Manganese	0.05 max	2.0 max	1.5	0.15 max
Titanium	–	–	–	1.0 max

Nitinol is not the only player, there are several other ones, specially in stent applications we have many alloys, which find usefulness in cardiovascular biomedical applications. For example, platinum chromium is one alloy, which is now being used, now the first question that might arise to us is, why nitinol is replaced. Nitinol is replaced, because it is of great demand, because of it is application in a aerospace engineering, it is highly expensive, so one can go for alternate ones with better features.

Now, if you look at the market of stent technology, in 2003 nitinol was very popular, but now you would see, there are other alloys which are performing, doing the same performance and they are costing much much less. One is platinum chromium alloy and the other one is stainless steel alloy and the other one is cobalt chromium alloy, all these are being presently used in human heart. Therefore, it is good to take a look at, what this compositions are and how they vary from each other.

Now, we should also understand that, merely getting a cheaper alloy is not important, we need to know whether it can really satisfy all the conditions that are needed when you put that in the coronary artery. So, when you take a platinum chromium, when you say platinum chromium stent then you are talking about platinum 33 percent chromium 18 percent, but still you have a larger proportion of iron in this stent. Similarly, when you say stainless steel, the greater proportion here is iron, whereas you still have chromium and nickel involved.

So, it does not really go by the nomenclature, but principally the shape memory effect is actually coming from this alloy composition. Cobalt chromium is one of the most widely used now, specially in India lot of application based on cobalt chromium and here, cobalt is maximum 52 percent and chromium is 20 percent and then you would also see lot other metals are being used. And there is another driver stent, which is also from another company, where they use 34 percent and 20 percent, and more of nickel is used, but still this is also referred to as cobalt chromium alloy.

Apart from nitinol, we have several other shape memory alloys, which can also do the job. Now, when we think about stent for example, as a useful application, why we are looking for different kind of alloys, why we need to drag many issues into this stent technology.

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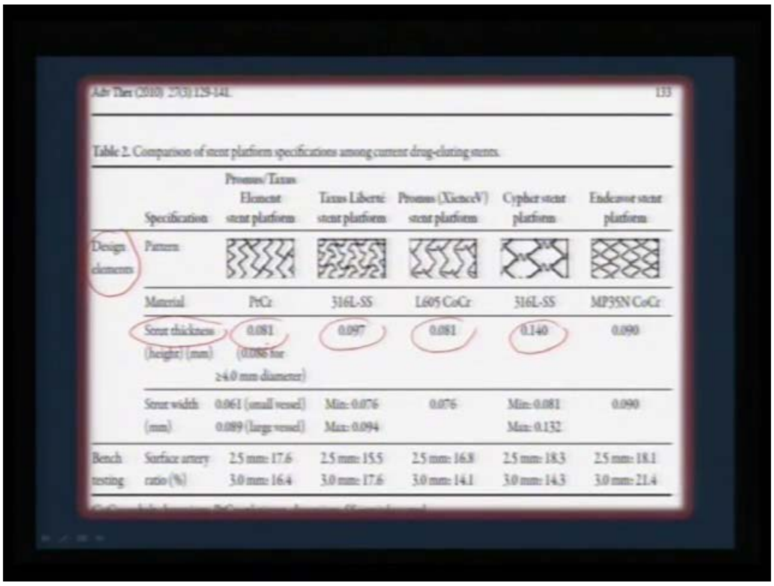

One is the design pattern, these are very thin wires of the order of 2, 3 millimeter and they have to be deployed. Therefore, the stent pattern becomes very important, because stent pattern can also relieve the anginal problem to a greater extent or it can complicate the matter once it is put inside the artery. Now, these are several patterns, which have emerged from different companies, you can see one is like a zebra crossing, this is one such stuff and then you have several models.

These are all a real marvel of mechanical design, it is not just to the constitute these models in using a CAD CAM but then to execute this is a mechanical proficiency. So, it is not just the chemistry that is important in choosing the material, but it goes all the way into a technology, where you need to transcend beyond this, but keeping in effect the properties of the material and try to design several stuff. One issue that is very important is the strut thickness, strut thickness is nothing but the gauge.

Usually when we talk about a wire, we call about gauge, gauge is nothing but the thickness. So, strut thickness means, thinner it is better, because if it is thicker what will happen, it is rubbing with the walls of your artery walls and it is constantly in contact with your lumen flow. Therefore, thinner, it is better, otherwise if it is thicker, it is going to create more damage to the walls of your artery. So, strut thickness is important and if you carefully look at it, look at platinum chromium, look at cobalt chromium and make a comparison with the stainless steel.

You can clearly see, that stainless steel ones are actually more thicker, and therefore it is not very easy to bring down the strut thickness, because that is the property of this material. So, in case of platinum, you can go down to 0.081 millimeters which means, you can make a very thin stent and those are also easily deployable. So, the different sort of alloys have the privilege of controlling the size, we will continue with the other information.

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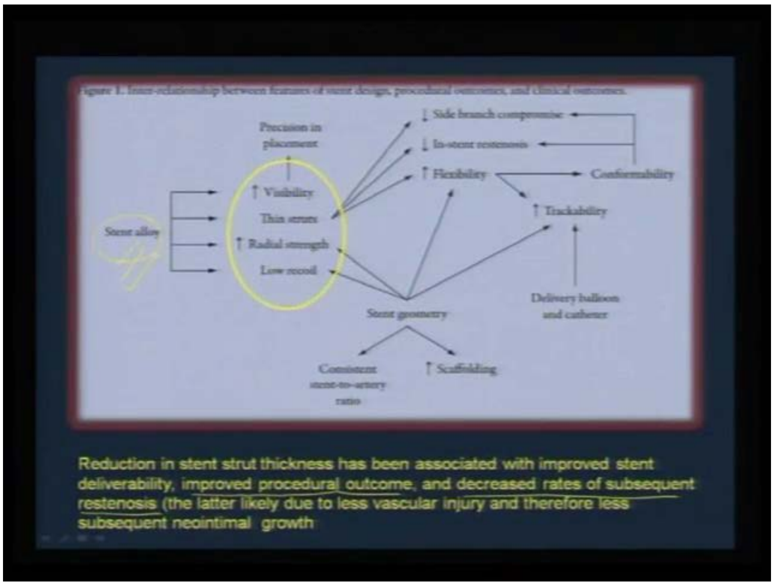

So, the strut thickness plays a very important role in deciding, which sort of alloy can be widely used. Reduction in strut thickness, therefore can improve the stent deliverability and improved procedural outcome and decreased rate of subsequent restenosis. We will come to this in the next few slides and show, how these things can be controlled. So, when you think about a stent alloy, there are four things that we need to have in mind.

One is visibility, visibility is nothing but as the cardiologist is trying to deploy this stent in the particular place of blockage, he needs to see it visibly so that, he can easily position the stent in the right place. And this need not be done with the dye, because usually during the angiogram, you try to pump it with a dye, to see where the blockage is. But, when you are actually employing the stent, the patient may be running at risk, if you are going to take so much time.

Therefore, you need to quickly place the stent, even without the help of a dye, you should be able to map, whether you are in the right place. So, I will show this in one of the cartoons, so visibility is a important stuff, as I told you thin struts can bring down side branch compromise, because when actually you are going to deploy this in a side branch, you should know whether it is going to damage the other wall. So, that will help us and also bring down the instant restenosis risk and increase the flexibility radial strength, which is indirectly dependent on the stent geometry.

And low recoil, once you position it and deploy it, you should not recoil back, which is disastrous. Therefore, all this are very important when you are choosing the stent alloy and these are all some of the prime factors that you would look for, when you are applying.

Here is two groups of element stent, which is actually a platinum based stent and liberty stent is nothing but a stainless steel based stent, this is stainless steel and this is platinum based stent. Now, if you see here, the element visibility is much much better in the element stent, because of the presence of platinum. Whereas, the liberty stent is predominantly a stainless steel stent and you can see, for a physician, he would rather go with a element stent, mainly because without the dye he can easily map it.

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In other words, these are the X-ray images taken when the stent is deployed inside the heart. So, the element visibility plays a very important role, when you are looking at a proper alloy. So, whether it is a 2 millimeter diameter or 4 millimeter diameter, we see proportionally, the visibility is much more pronounced in platinum alloys.

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This is another real time image, which was taken while the stent is actually placed, here in the coronary artery, they have placed one element stent and one liberty stent. You can clearly see, that the liberty stent is not to be seen at all, it is not easy to map it, whereas even without a dye, you can see the element stent is traceable, you can easily see the position. But, during contrast when you pump it with dye, you can see that the flow is restored, irrespective of which alloy was used.

But, for a physician to take the right decision while he is deploying the stent, what he looks for is the visibility. So, when he takes a random X-ray photograph, he should be able to see that, this is in the right place, but people have also used many other coatings on this devices. For example, gold coated devices have been tried, but it looks to be, although gold is a safer metal biocompatible, it seems to be that they restenosis is appearing at a higher rate when it is gold coated. So, gold coating is actually not prevalent these days, specially on this stent alloys.

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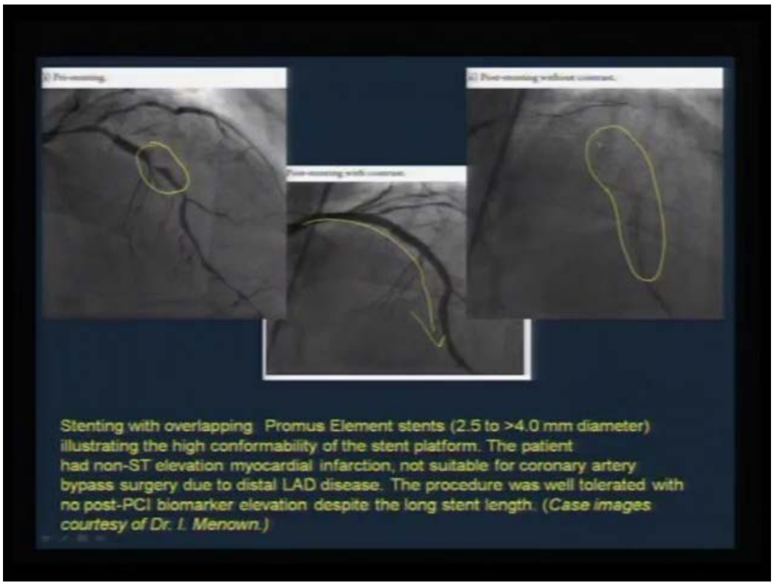

Here is another example, where you can see the visibility factor and not only visibility factor you can see, actually the stent is placed here and you can see the visibility of the stent very clearly here and why it is important is, this is done in the branching area. Therefore, it is very sensitive, that it should not actually rupture this junction, so the choice of your stent is very important. In other words, you have to use a thin strut instead of a thick strut, otherwise it will induce more loading at this interface, which may be detrimental for the patient. Also it is found that, cobalt chromium alloy, although it has higher elastic properties and it is associated with greater recoil strength, it is because of it is recoil property, it is clinically a bit disadvantageous when you compared to platinum chromium stent.

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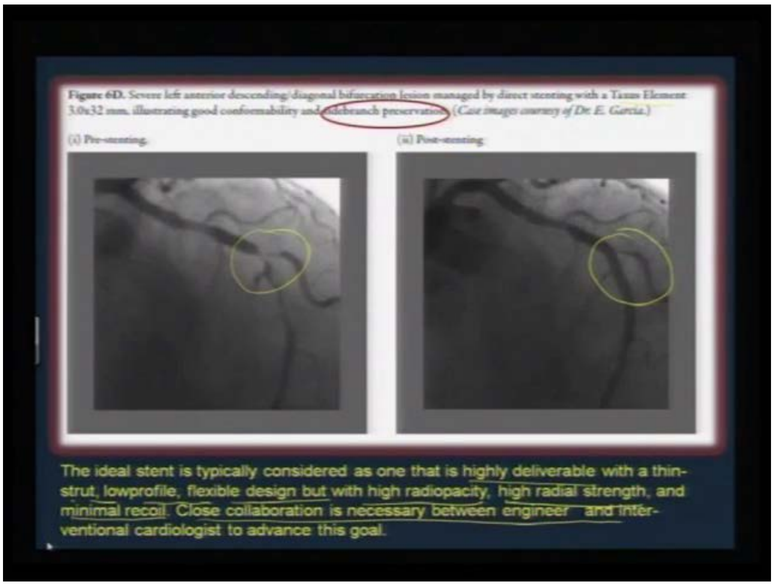

Here is another view graph real time, view graph of angioplasty, where you can see this is the region, where there is a blockage in the heart and how the platinum alloy has been used to map even without contrast, this is with contrast after the stent is deployed. So, you can see a normal flow of blood, but you can see the abstraction very clearly, it is a very severely abstracted patient. And one can find out that, even without the biomarkers, you can easily map the deployment of the stent here.

And similarly, a side branch is preserved, in this case you can see the blockage is here and very carefully, because this side branching is very, very intricate. So, if you are going to employ, you should not rupture this branch and you can see, using taxes element, which is nothing but your platinum chromium alloy, using that you can do the side branch preservation. The ideal stent is therefore, typically considered to be highly deliverable with a thin strut, low profile, flexible design and radiopacity.

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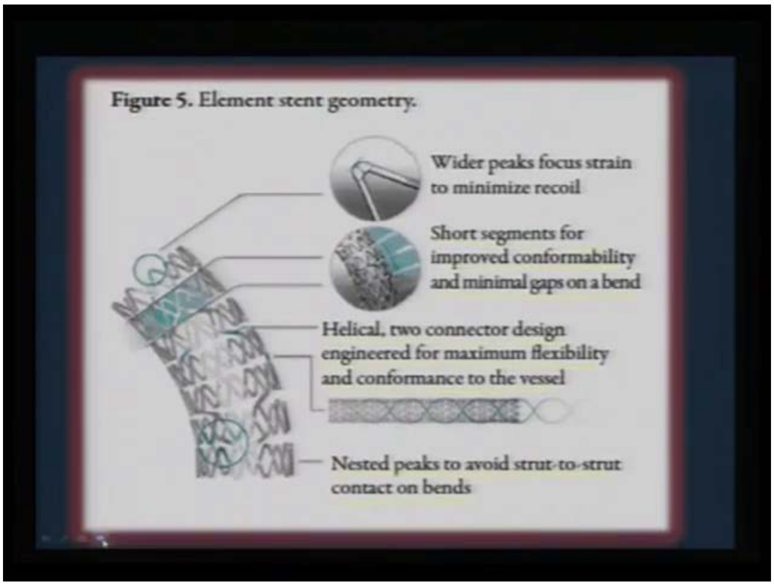

Radiopacity is nothing but visibility, because it should give the contrast when you put it under X-ray machine and high radial strength and minimum recoil. Therefore, close collaboration is needed between the engineers and cardiologists to advance this technology. So, depending on the demands of a cardiologist, technologies should be able to remap the alloy composition and give the best. So, in essense, when you look at a stent geometry, the whole thing is about the material that you are choosing, which alloy you are choosing and you can clearly see this stib.

For example, this stib design is a marvel, which is a mechanical prudency, why this stib is used, because it will restrain the recoil of the stent and that is actually done using lot of simulations. When you go for short segments for improved conformability and minimal gaps on a bend, you need a design like this. Because, when you are trying to flip it, you should not see, that the strut to strut contact is made, because you are actually mapping it through several regions.

Therefore, when bending occurs, you should make sure that, there is no contact between and only this sort of a helical contour will help you. And we also see this two connector design here, which is engineered for maximum flexibility and conformance to the vessel. So, the design of the stent and the choice of the alloy goes hand in hand, therefore the property of your shape memory alloy is very essential.

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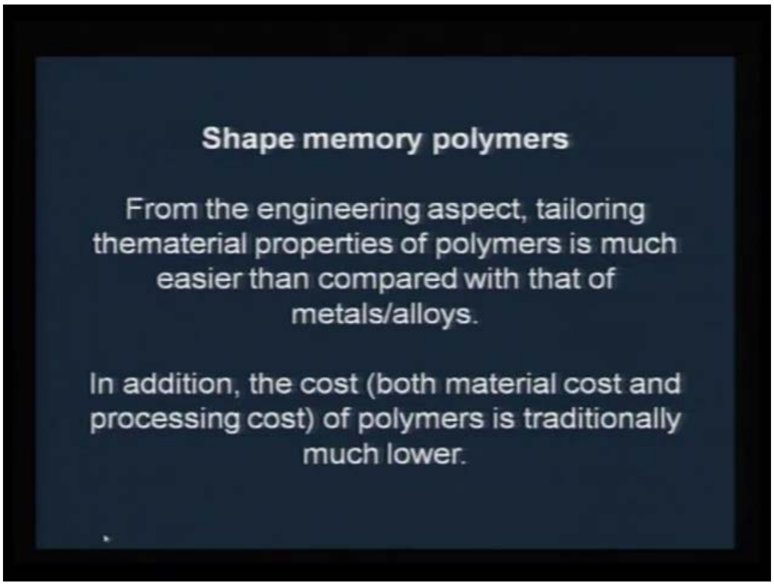

The next example that I want to touch upon is shape memory polymers, from the engineering aspect tailoring, the material properties of polymers is much more easier than alloys. Mainly because of the cost, both it is the processing cost as well as the cost of the material, polymers are much more advantageous, because you can go for wider range of application and it is traditionally much lower. Therefore, a shape memory polymers, which is also abbreviated as a SMP, Shape Memory Polymers are of equal demand.

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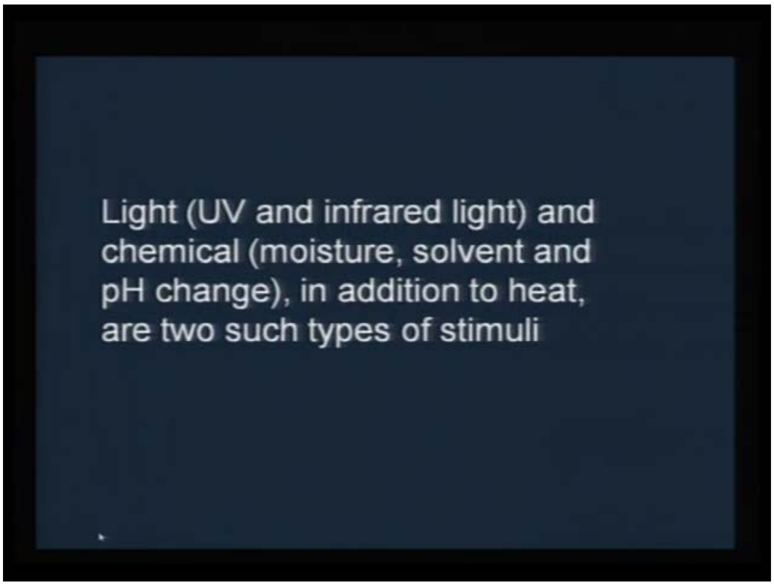

Shape memory polymer can be a restored with a external stimuli like light and either you can use UV or infrared light to reverse it back or you can use chemical effects, a solvent or PH change to revert it back or heat and these are very easy and accessible for us to bring about the shape memory.

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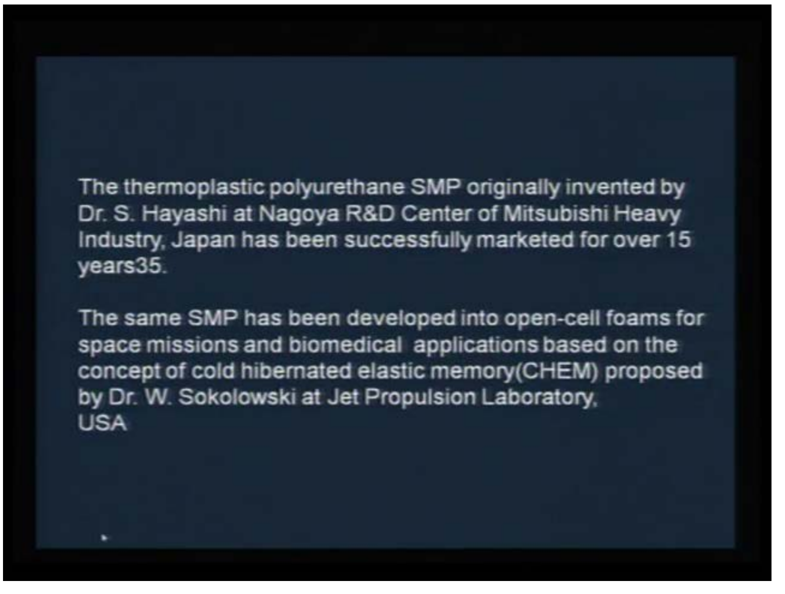

The first person who actually used a shape memory or who found this shape memory effect in polymer is a professor Hayashi and he used polyurethane, as the material to find this shape memory effect. And later jet propulsion lab in USA, they brought out many such applications using this polyurethane, specially making open cell foams and space mission foams, biomedical applications, all this they tried to evaluate using this polyurethane. So, when you think about polymers with shape memory effect, predominantly they are polyurethane based, one or two examples that I will give.

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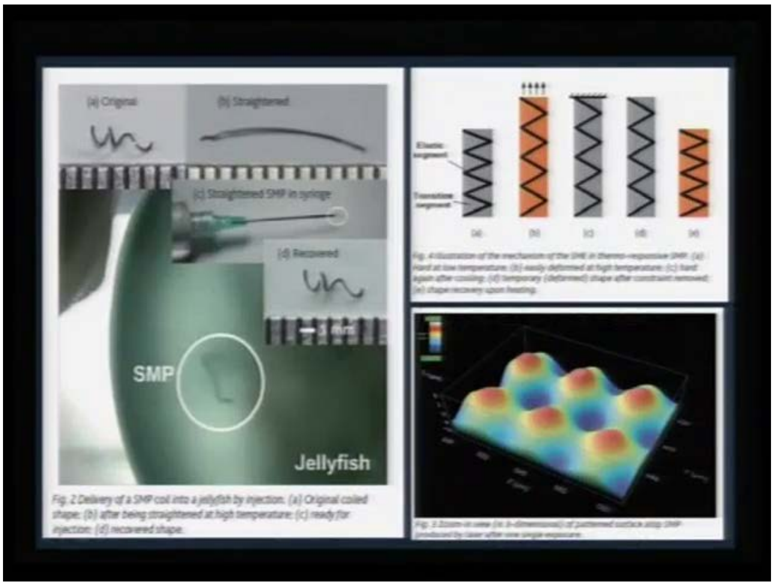

Suppose, you have a polyurethane fiber and you twist it like a spiral ring like this, now you can straighten it out. So, this is a straightened polymer, either because of application of temperature or you pulled it. Now, you can actually insert the same tube in a syringe and then you can put it inside a jelly fish and then you can actually… So, you can see the morphology of this wire, it is a straightened one, but you can actually recover it back from the jelly fish.

Once you recover it back, again goes back to it is original, why we are doing this on jelly fish, because you can try to simulate such applications when we try to deal with our cell tissues, so this polymers can become very useful in biomedical applications. And what is the mechanism, unlike the case of alloys, where in high temperature they may be hard, in low temperature it may be soft. In case of thermo responsive polymers, you have both the transition segment and elastic segment available both in the cold phase as well as in the high temperature phase.

So, this is exactly a opposite phenomena of shape memory alloys, because in autentite it may be hard, in martensite it may be softer in case of shape memory alloys. But, in this case, both the phases are present, either in the cold phase or in the hot phase. As a result, you can see, this is the morphology with which you start and then when you heat it, you can stretch this polymer along. And immediately when you cool, it can actually retain this memory and once you heat it again, it can revert back to it is original shape.

So, it has both the features in it, you can retain the memory when it is hot and you leave it there or you can heat it again and revert it back, so this is one application. Also the shape memory alloys, you can try to pattern it using laser, because in this way, when you try to pattern it, you can try to fill this shape memory alloys with anything that you want to cap it with. So, it is very useful in cell culture and in several other applications, these polymers can be easily patterned, it is not possible with shape memory alloys. So, polymers can be used for making devices.

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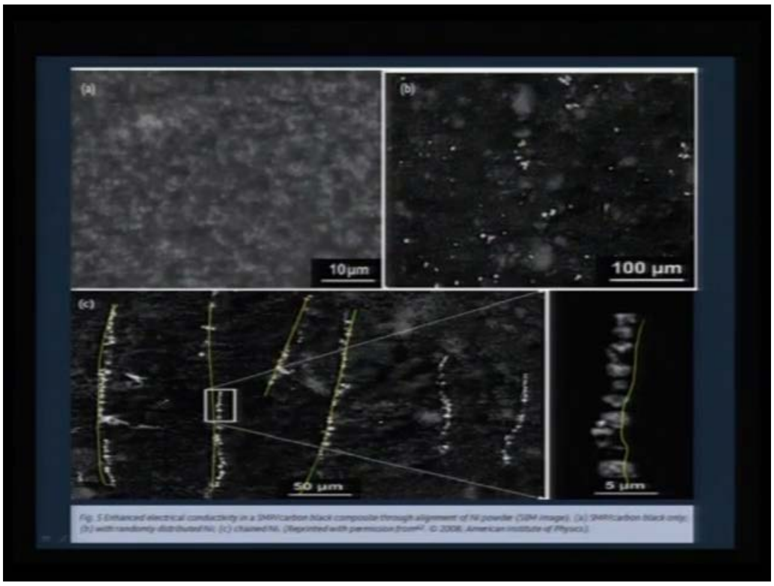

This is another application of a shape memory alloy, this is nothing but a polyurethane alloy with the black composite using a carbon black. And what we are doing now, is putting some amount of nickel here and this nickel you can actually apply parallely some magnetic field and you can alloy this nickel into straight chains like this. And a close look at it, you can see nickel actually forms a chain, why, because once it forms a chain like this then when you are heating this polymer, this can provide a electrical pathway, thereby you can heat this.

So, this whole composite becomes very, very conducting, when you try to impregnate this with the nickel and you can try to make this sort of linear chains of nickel inside the polymer. So, this shape memory, I will give a example of this in a hybrid situation, how this sort of alignment can help.

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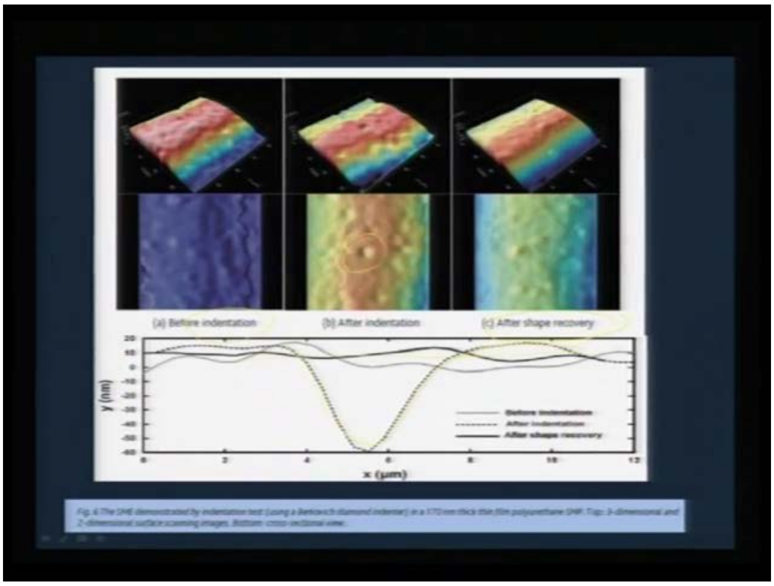

Here again, there is another example of a shape memory effect, where you actually do indentation. In other words, you try to apply very high stress and in this a region, you can see a dent is formed, this is before indentation that means, you are applying very high pressure, so it has made a mark, but once you heat it, it recovers the shape. So, this is the depth of your indentation, you can actually go minus 60 nanometer, you can just plunge it with a pressure and then once you heat it back, it again comes back to the same shape. So, the shape memory polymer incidentally can bring back the shape that you are looking for.

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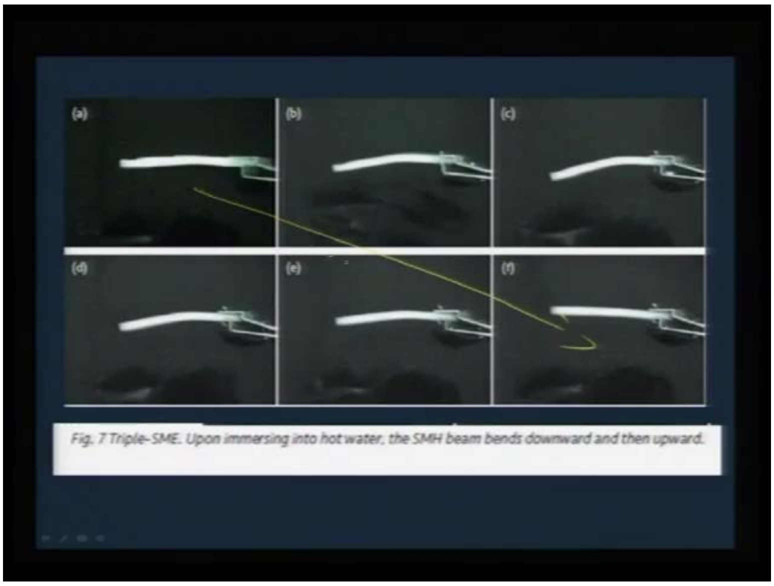

This is one other application and here, again you can see, this is a shape memory polymer, this is before you start putting it in hot water. If you immerse this in hot water you can see, slowly it changes, it bends and then once you try to take it out, it again retains back to the same shape. So, this also has a shape memory effect upon immersing in hot water.

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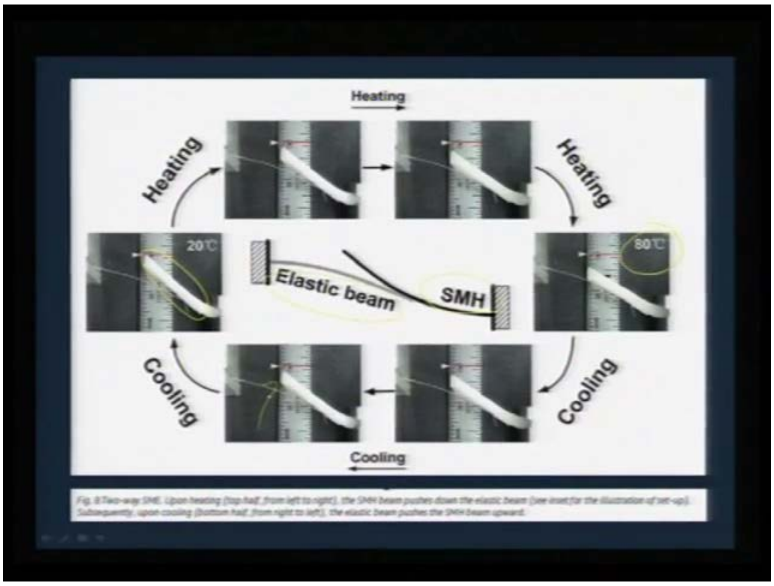

This is another a demonstration of, how a hybrid polymer can be used, this is a hybrid polymer, shape memory hybrid polymer, which is used. And now, we can start heating this a polymer and you can see here, as you heat the cycle slowly, there is bending and it is actually touching a elastic beam. This is elastic beam, this is a shape memory hybrid, now from here, it almost comes in full contact with the elastic beam, here at 80 degree C and on cooling, again you can see that, it reverts back to it is original position. So, this sort of things can be used for several applications, because you can reverse and bend the shape by changing the temperature.

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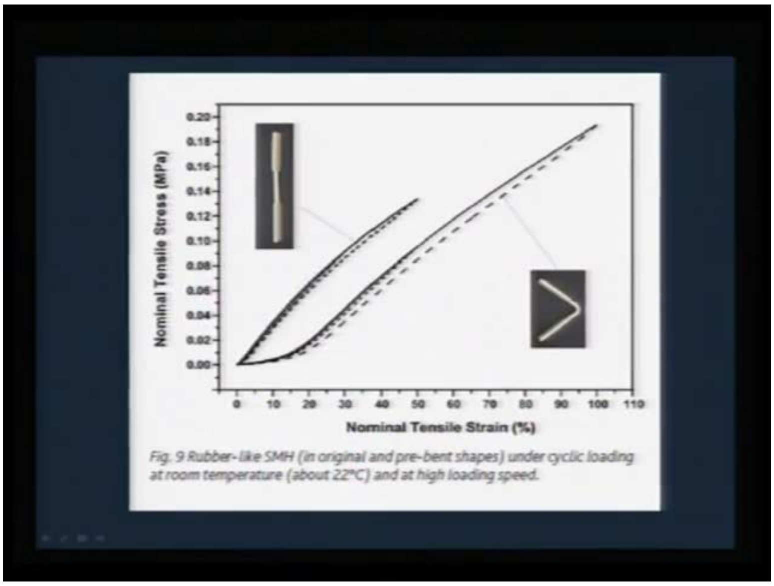

Here again you can see, the way the cyclic loading occurs when you use the shape memory hybrid, you can try to bend it any way and you can try to again retain back the same shape.

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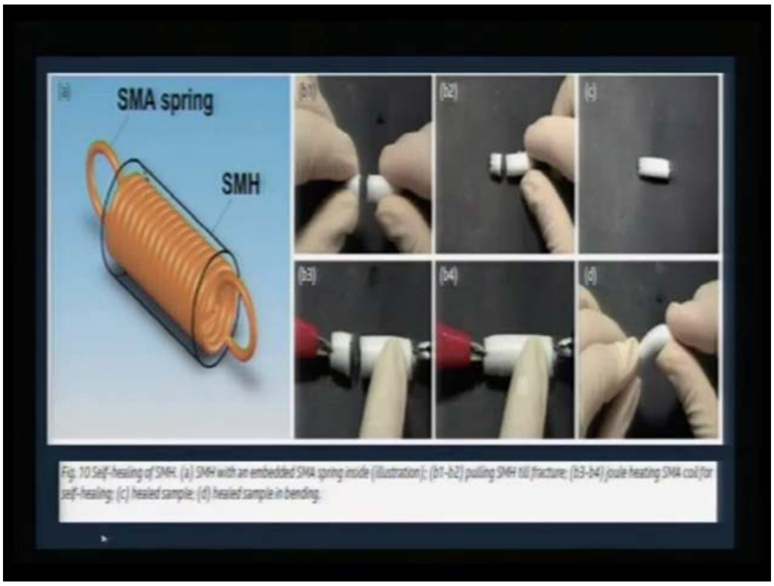

This is a rubber like stuff, this is another good example, where you are having a shape memory alloy and you have a shape memory hybrid material, which is nothing but your white stuff, which is a polymer. And inside the polymer you are actually having a shape memory alloy, now what you are doing is, just intentionally you break this hybrid material. In b 1, you are breaking it and it is now cracked here and inside is, your shape memory alloy.

So, what you start doing, you connect this to some piece and start applying some current, you can actually fuse the shape memory alloy, because that is also elongated. Now, after you heat it, you can see, it has restored back to it is original position. What has happened, the shape memory hybrid also has got fused along with the healing. A self healing has happened to the shape memory alloy, not only that, the sample is also healed, after this you can see that, you can still bend it, it has recovered back to it is shape.

So, this is a hybrid device of both shape memory alloy and a shape memory hybrid, together performing several useful applications. So, in essence, I have shown you some examples of a alloy composites or polymer composites in combination or separately, they find very useful applications. There are several applications, which I have not covered, specially in the aircraft aerospace industry. In the next few lectures, I will give you some of the bibliography, where you can actually go and do further reading to enhance or understanding on this shape memory alloys.