Advanced Materials and Processes

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Lecture - 25
Shape Memory Alloys: Case Studies and Applications (Contd.)

Welcome to NPTEL, myself Dr. Jayanta Das from department of Metallurgical and Materials engineering IIT, Kharagpur. I will be teaching you Advanced Materials and Processes. Last couple of classes, we were discussing about shape memory effect and pseudo- elasticity. Along this direction, we have discussed, how the origin of the shape memory effect or how it really originates due to microstructural change and how pseudo-elasticity is linked with the shape memory effect.

Now, one thing is very much important that to achieve a shape memory effect, the alloy need a particular way of preparation; we have discussed this as an elaboration technique. In that technique, we have seen that different non-ferrous alloys required different processing technique. It depends on the phase diagram and the phase evolution also which include shaping. Let us say I can develop a shape memory alloy and the phase itself is very much brittle like in case of copper-zinc where β phase is a ordered phase and very brittle.

Now, to prepare those phases or to shape that particular product, we need assistance of some two phase region, means the phase diagram has to be closely looped, and particular heat treatment which help on evolution of α - FCC phase and then we can deform it. Again we need to reheat to β phase and arrest that β phase, so that it transform into a martensite 100 % which covered the micro structure to get the best shape memory effect.

So, you can see there are many different metallurgical or engineering tricks involve on the development of this alloys. And there are many different considerations. And now today, we will be focusing mostly on the application side of these shape memory effect and pseudo-elasticity. Like in a shape memory effect, we plastically deformed those martensite, which appears to be like an elastic because the strain again recovered, so we can use that strain for particular actuation purpose. On the other hand, in a pseudo-elasticity, when we deform austenite above austenite finish temperature due to the application of stress, the M_s temperature raises and due to that austenite transform into martensite. Once we unload it, then again the martensite transform into austenite.

So, in this way, we can use the stress-strain curve; and below the stress-strain curve there is a large area where energy can be stored. So, this is something like an energy density. So, if you think about a particular weight of a specimen, then this energy density will change right or per unit kg we can calculate this energy density, and we can store this energy density. So, you can see starting from an actuation or a sensor, we can apply this material to an energy storage, which is the wide range of application or engineering application. And let us start today’s discussion along this direction.

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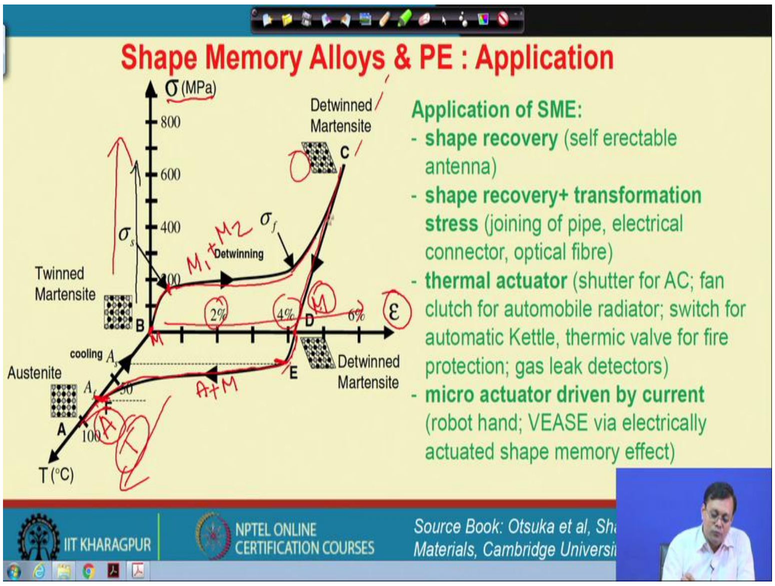

Once again if we need to recapitulate, so here this axis represents the stress which is given in Mega Pascal. And in this direction, it is the strain. Now, if you closely look, we can take or start with a martensite; this is the martensite. Now once we start deforming martensite, from here the type-I twin basically, this is the yield point of the martensite, type-I type twin which basically transform into other type two twin or vice versa. In that case, you can think about that it is some people call, it is like a detwinning process, but it is basically the growth of one type of twin in expense to other type of twins. Now, here it almost completed.

And now if you keep on deforming more and more, then basically you will introduce dislocation and that will not help at all in the shape memory effect. Now, if you unload it, then it will come back here. So, here this 2 %, 3 %, 4 %, these are in terms of total elongation means I have a sample length *l*. And I can introduce 4 % deformation; out of the total length *l*, 0.04**l* can be deformed with the use of the twinning process.

And now, now we have these let say detwinned martensite, and then we simply raise the temperature. So, here this is the austenite start temperature, this is a temperature axis actually this is the temperature axis along this way. So, now I am moving in this way, and then it come back to austenite phase field. And austenite finish temperature means, all the martensite, here is also I have martensite. So, this martensite transform into austenite, and here I have 100 % austenite; in this region, it has austenite + martensite. And in this region, I let say for at this moment $M_1 + M_2$ means martensite of different twin variants that is all.

So, you can see that starting from this point with a stress axis, we return back this position. And now if we try to understand the effect of pseudo-elasticity in this same diagram, yes, it will be little difficult to understand because we start here, and let us draw an imaginary plane here.

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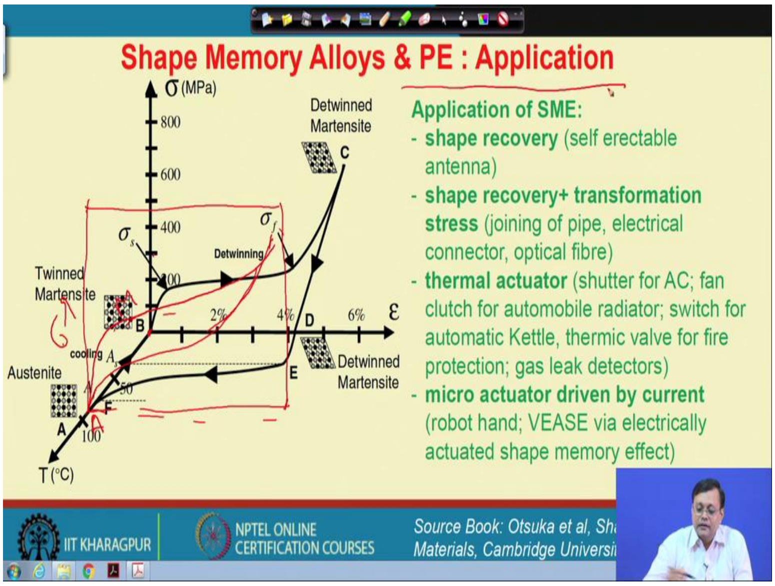

And here I have austenite; if we deform, then this austenite will transform into martensite, means this martensite temperature it comes here, so the axis follow here; because this is a stress axis, and it goes and here is the strain axis. So, martensite goes here. Again if we unload the sample, then it comes back. So, this is a very interesting phenomena, so pseudo-elasticity occurred in the austenite phase field. And so we can use both these phenomena.

So, let us have a look at different application side of these two different effects. The first point is the shape recovery, because we can recover these amount of strain to 0, and this can be exploited as a self-erectable antenna. What does it mean that under extreme environment condition, when temperature changes, then the antenna open up, because of sunlight appear and environment get cleaner, and then antenna again become close under some bad condition. So, that kind of phenomena we can incorporate by using this kind of phase transition process using a shape recovery.

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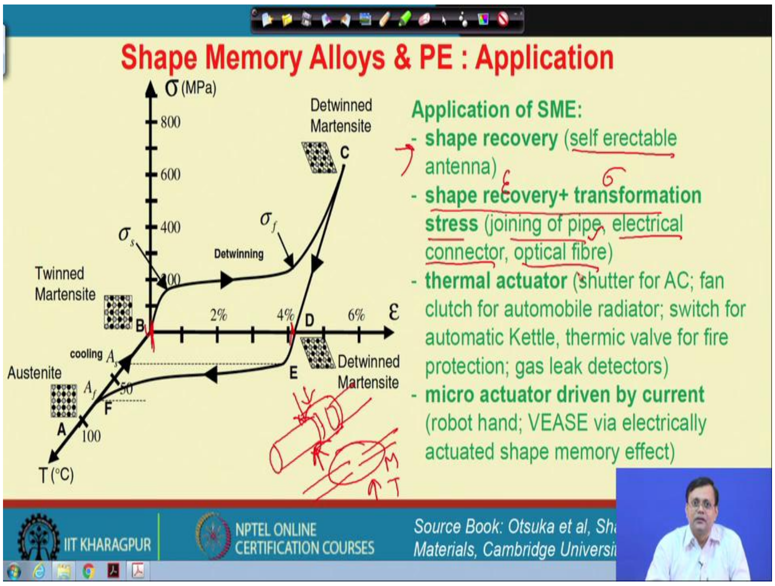

However, here this is a simple antenna which open up and close. Here there is no stress, the stress part of this particular application is not involved. And now since here both stress and shape recovery means strain and stress both are involved then this is the strain and this is the stress part. We can use this as joining of a pipe. How? Let say I have two pipe; this is one pipe, and this is another pipe. I want to join together. And then I can simply take a very close size of this outer diameter of another shape memory alloy. And in the martensite state, I expand it, so it will be something like this a little bit bigger size in martensite state.

And then I have a chance to put this two pipe inside, and then I simply warm it up, so that it goes to the original shape of that austenite phase, then it will give some stress. So, this is something like a joining of optical fiber or let say electrical cable. So, this particular phenomena we can use as a joining of the pipe, or electrical connecter, or let say some sort of optical fiber joining. It is very same actually; we use a same thing by heating up, it simply strains and then it gives the stress, so that it hold together for infinite time. And this is also another very nice example of using shape memory alloy.

Now, let us come to a very different aspect of the application side which is the thermal actuation system. Let say I have a room, where there is AC, and the AC should be switched off upon reaching to a particular temperature. Or maybe the shutter of the AC should be open and close for a given temperature range. Here also I can use as an actuation system the shape memory alloy.

So, or may be in an automobile radiator, there is a cooling process, where a fan rotate to cool the water or a coolant. In that case, when coolant reach to a particular temperature, then the fan should automatically switched on. And after cooling, when it has reach to a certain temperature which is well below, then the desired then automatically the fan will be switched off. This is the actuation system you need. And here we can use a shape memory alloy very well, and that works very fine.

Now, we often use every day in home the electric kettle you can remember, when electric kettle actually reaches to a temperature or the water is warm up for use, then automatically the power switched off, so that we can save some electricity. In that case also, we can use this thermal actuation system for an electric kettle.

And there is also some other kind of application like, in most of the security and fire protection system, where if there is any fire involved in a room, which is very much important in terms of the temperature, very slight temperature changes due to the fire a simply need a actuation system where automatic water spray or some other inert gas spray will be done in order to avoid any kind of firing event in a big building.

So, in that case also we can use as a thermic valve for a protection, or let say simple a gas detection or gas leak event. So, there also we need those kind of sensors or thermal actuators, where a simply we can use the shape memory effect for maintaining and protecting several issues. Now, so far we have discussed mostly on a stress driven phase transformation or temperature driven phase transformation.

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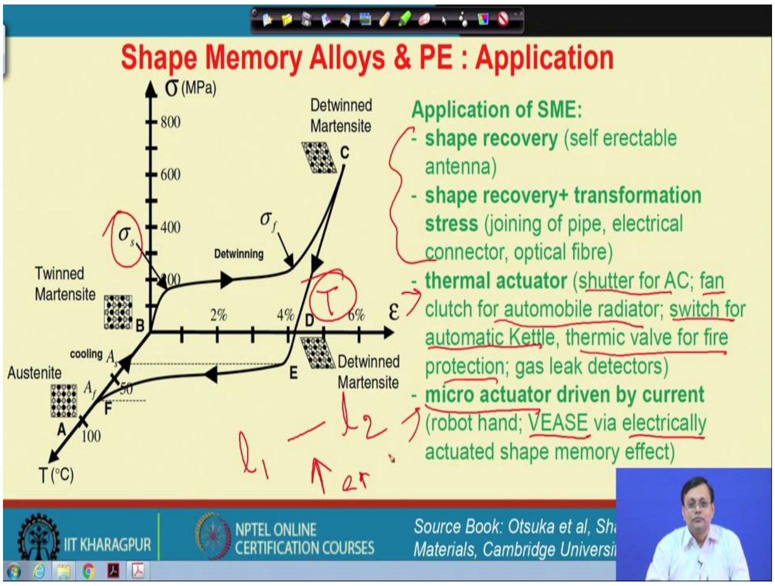

However, there is one thing that is important in a shape memory alloy that is we can use electrical pulse for the phase transition to occur in a shape memory alloy. And this is a phenomena we call it as VEASE - V E A S E. It basically said via electrically actuated shape memory effect. This is very interesting it means that if we give an electric pulse, phase transition will occur, and then we can get back or we can switch between different length, let say l_1 and l_2. It only need an electrical pulse. So, this is called as a micro actuator.

Let us assume that we want to design an artificial hand for a robot, which will hold a soft material softly and hard material hardly. In that particular case, we simply give some electrical pulse, and then there will be some degrees of freedom between the fingers and the hand, so that this robot has a hand which will operate automatically. Or may be different kind of biomedical purposes, we can develop some micro pump for kidney transfer, there also we need pumping, so for the body fluid pumping and all these. So, there is a large application of these shape memory alloys.

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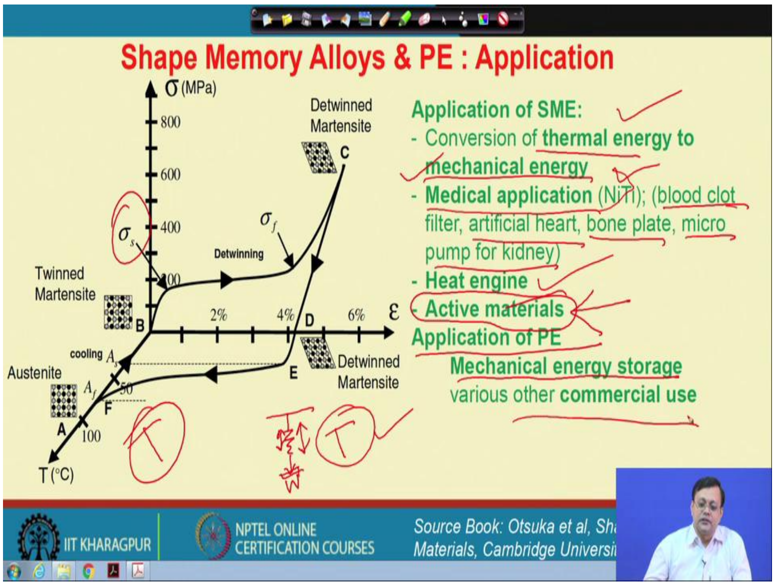

Let us continue this. Since, there is again a interplay between a stress and a temperature actually so we can use this phenomena as a thermal energy to mechanical energy conversion system means, I have a shape memory spring which has a weight, I put a weight there. And this weight actually assist in terms of elongation of the wire. And now I provide some heat or temperature and again it basically reduces. So, this is a continuous process where we can use thermal energy to a mechanical energy.

Now, there are other medical application where nickel titanium dominates than the copper based alloys, because copper based alloys are not good for biocompatibility. But nickel titanium is very useful where the blood clot filter or let say artificial heart, or some sort of bone plate or micro pump for kidney can be used.

And now, switching between temperature and stress, we can use as a heat engine which is very common for any kind of Carnot cycle we can use actually. And that is very important part, we since these a material a shape memory alloy can be integrated with electrical circuit temperature and shape, we can use it as an active materials means whenever it is necessary an electrical pulse will go, or whenever it is necessary a temperature will be given with the shape change, or vice versa means there is a shape change, I get electrical pulse and then I use it for further modification.

So, it become an active material which I will discuss later on today. Now, for pseudo-elasticity as I discuss that we can simply use the mechanical energy storage for various commercial use. So, let us move along this direction and discuss a little bit into detail like with the pseudo-elasticity we will start with the pseudo-elasticity first.

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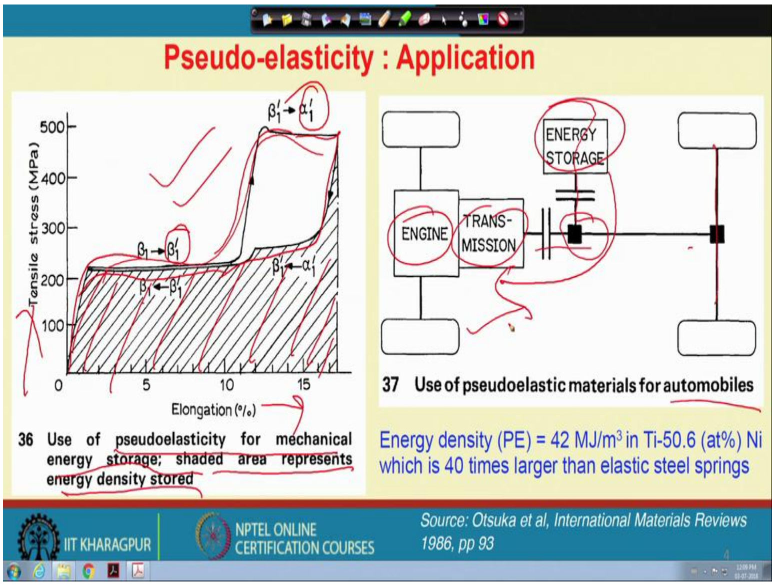

So, let say, I have austenite, the austenite phase a simply transform due to the stress to intermediate phase and then finally it goes to another martensitic phase. And then I once unload it, it against come back. So, under this stress-strain curve, I have a large area which is the energy storage. And this is a pseudo-elasticity for let say mechanical energy storage, where the shaded area represent the energy density that has been stored. Here this is a tension stress, and this is the elongation.

Now, I can exploit this particular property for any let say curve. So, in an automobile sector, let say this is the engine, and here is a transmission, it rotates the wheel. And now during this particular process, I have an energy storage where this particular effect can be given, an engine can be stopped for some time, and we can use this energy for further.

So, this is like many different car manufacturer they are trying for this kind of hybrid technology. We call it as hybrid means I have an energy storage system where we really do not use the fuel, fuel means I am talking about the gas for moving a car, but we use the storage energy for moving the car, so that energy can be used. So, we can use many of these hybrid kind of cars these days.

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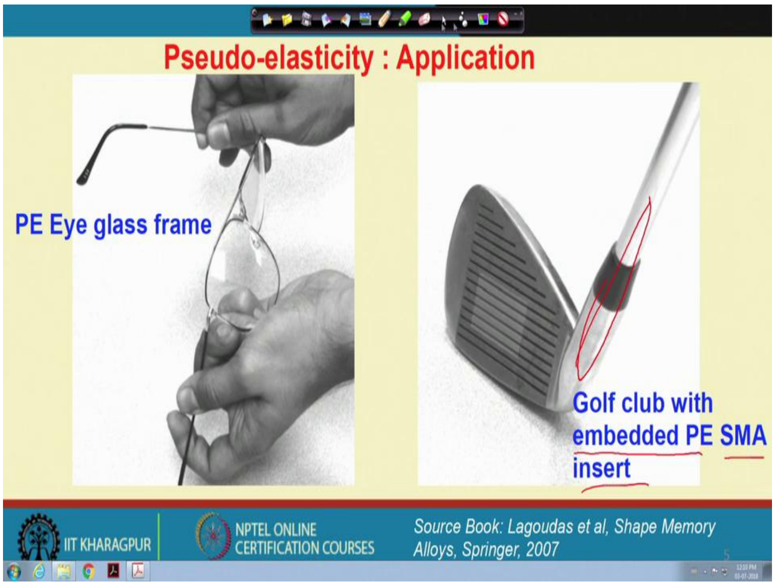

Now, the same pseudo-elasticity effect can be used for let say a spectacle frame, where the spectacle frame here, we have intentionally bended to show. And during this particular application of the stress, it bended; and once it is unloaded means you simply leave the hand, then automatically the frame comes back to the original shape. Or maybe in a golf club, there are some part where we use some pseudo-elastic material. Shape memory alloy inserted into it which store the energy, and gives us a larger resilience and knock the ball to a very long distance. So, this is also another very important application areas of pseudo-elastic effect.

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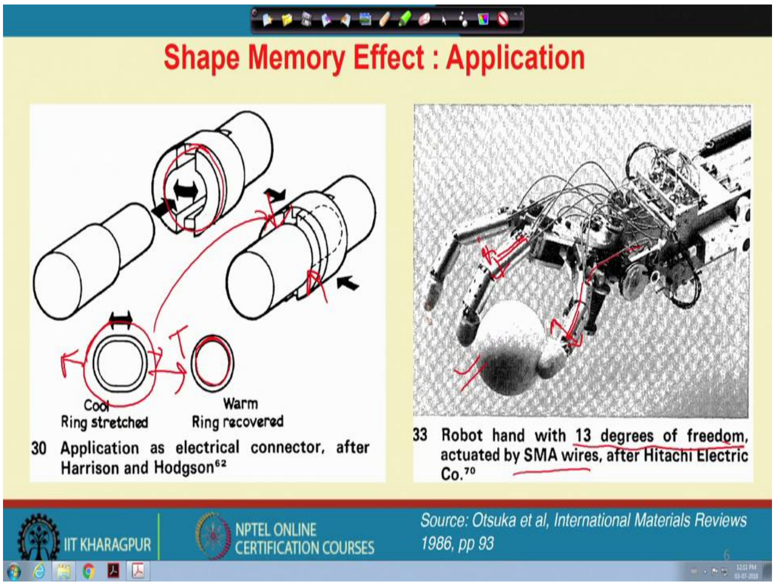

Now, let us try with the electrical connector or pipe joining, how using the shape memory effect can be exploited where stress and temperature both are actually used. In that case, we see that we see here this is the martensite the joining part which is in a cold state, and the ring is stretched intentionally means martensite is deformed. And we put this martensite plate here, and then during warm up if we apply temperature, then it get shortened, so dimension become shortened. So, it gives stress to this pipe to assist in the join.

Now, this is a robot hand where we have some degrees of freedom. And this is the VEASE effect that I said that by providing some electrical pulse, we have the shape memory plate which basically moves in and out, due to the phase transition and it helps to hold the object.

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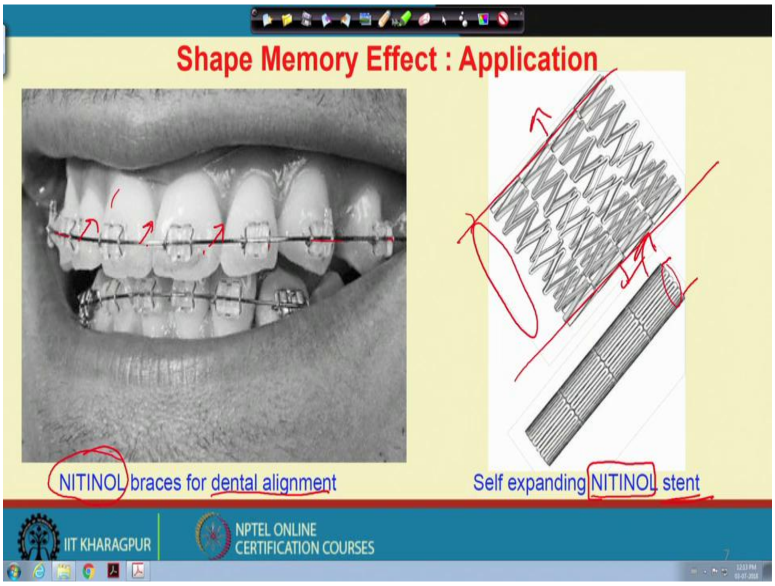

Now, another very interesting phenomena that often we use that for shaping our tooth, so use for dental alignment. So, this these particular teeth which are not allying properly, we take a shape memory wire and deform it and then put it in a in a cold state, we put it in the mouth then it comes to the temperature of our inner mouth which basically provide some stress, so that with slight stress these teeth can be shaped properly. So, this is a very common example, almost we use by many people use where this NITINOL is nickel-titanium alloy is very much famous for using that.

So, similarly in case of heart operation, where we need the application of a stent; the stent which is inserted into the vein, which has a thinner diameter, when it comes in contact with the blood then automatically it expand, and it provides a larger channel in a region where the veins are chocked. So, this is also another application areas, where we can apply shape memory effect for real life application.

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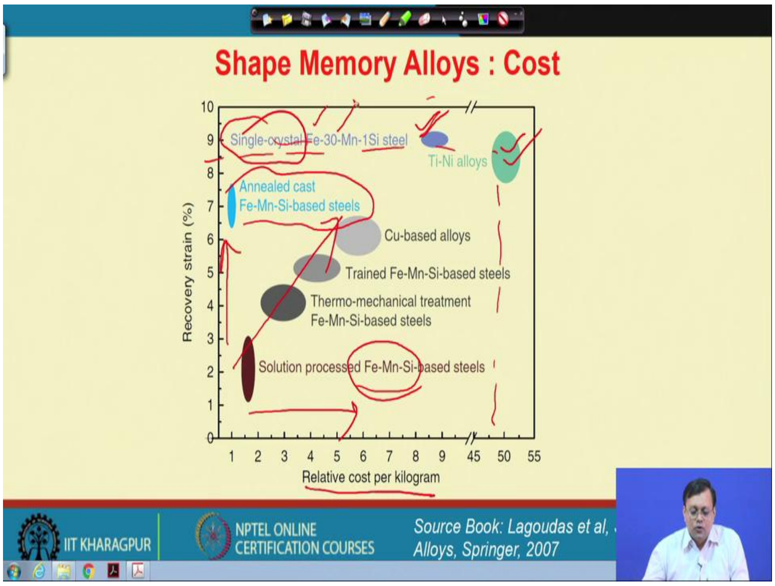

Now, another important part of this discussion is, how much is the cost of the material, because we are talking about application, and if I just compare with a relative cost. So, a definitely the iron-manganese-silicon alloys are relatively lower cost compared to other alloys. Where if you go for a larger recovery strain, then it require more and more training, means basically thermo-mechanical treatment or a particular type of thermo-mechanical treatment, where the recovery strain increases, the cost is also increases, so in both way it goes in that way.

However, it has been observed that annealed cast material is relatively lower cost, where titanium-nickel or nickel-titanium alloys used for biomedical application, is the most expensive material and gives the maximum recovery strain. On the other hand, we can get higher shape memory effect when we apply some single crystals. So, let us this is Fe-30Mn-1Si steel, single crystal growth is a very expensive process.

So, in that case these expense goes higher, even the expense is much higher than this copper zinc or copper high temperature copper, aluminum nickel or beryllium alloys. So, in that case we see that probably the cost is little bit higher in case of nickel-titanium alloys.

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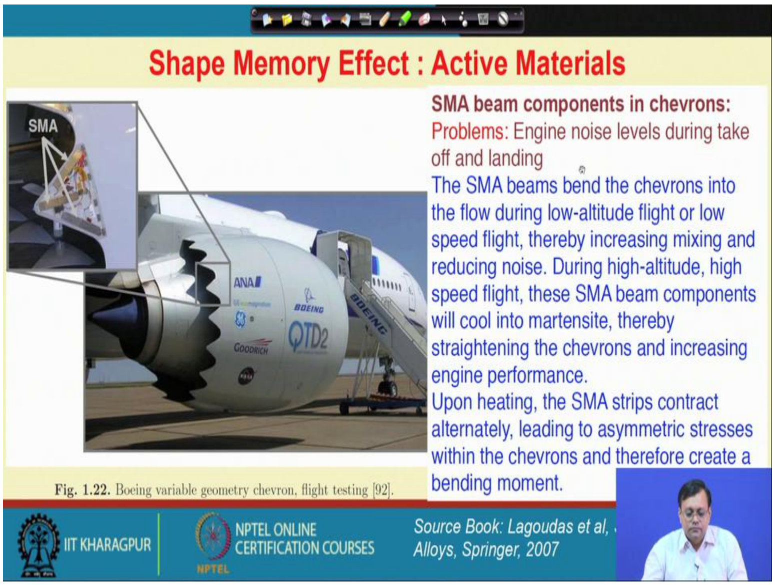

Now, the second part of this discussion is the active materials. So, let us assume that a flight become very much unstable, during a landing and during takeoff. This is the most important point, where the engine require maximum power. So, most of the failure in aircraft occur either during landing or during takeoff; but during flight itself the engine does not need very high energy actually.

So, because during takeoff, it has to go against the gravitation force and so on. And also because of that the engine noise level goes very high or let us say there is a turbulence. Turbulence means there are some air pocket in the in the higher altitude or there are some strong the flight goes up and down, and creates very disturbance where we need the material that changes the shape of the geometry automatically under certain programming conditions.

In that case, shape memory alloy has the best which is used in this chevron, where this shape memory alloy beam that has been incorporated in those components of chevrons. So, these are the chevrons where this is the magnified view of this part actually where this shape memory alloy plates are incorporated. You can have a look, this is the shape memory plate, this is also another one, this is also another one, and it is sticking here actually.

So, what it really does, the shape memory beam that bend the chevron into the flow, during lower altitude fight or low speed flight, thereby by increasing the mixing and reducing the noise. During higher altitude or higher speed flight, these shape memory beam component will cool into martensite, and thereby it basically get straightened the chevrons and increase the engine performance.

So, upon heating this shape memory strips contract alternatively, and leading to asymmetric stresses within these kind of chevron and therefore, create a bending moment. So, where there will be a turbulence, then the air flow between in this through that air basically flows that is controlled by this chevrons. And this is something very interesting feature where shape memory effect can be exploited and this material with along with let us say the temperature and stress and the shape can be used as an active material.

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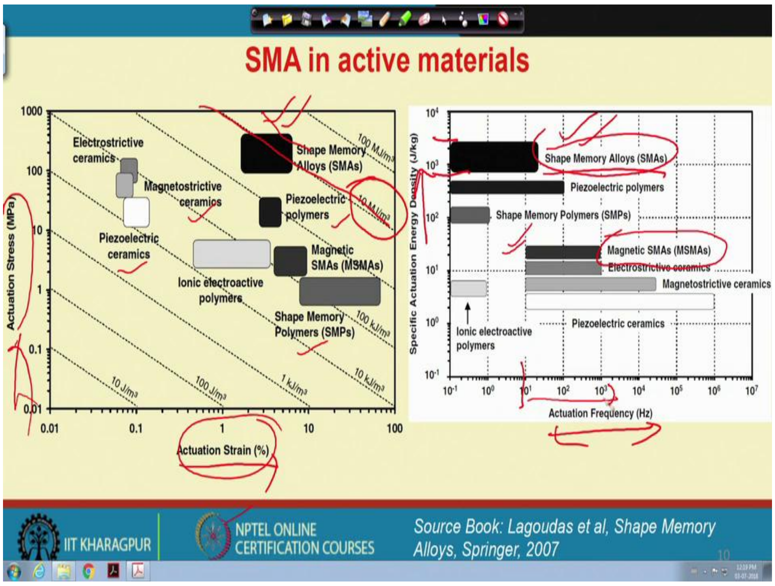

So, this is one of the very interesting part, and we must look into this particular issue in terms of a diagram which will help us to assist in terms of a actuation strain and actuation stress, there are many other competitive material that gives a strain and stress a there is a link.

So, like piezoelectric ceramic, or let say shape memory polymers, or let say magnetostrictive ceramic or piezoelectric polymers and so on. So, there are many materials that has are capable of storing some energy in terms of strain and stress, but shape memory effect or these material dominate higher because it has the highest energy density. You can see it is almost like 10 mJ/m^3 or even in higher side something like 40 or so, which is almost 10 to 15 times or higher than any steel springs, so that is a very high value actually.

And the actuation frequency you can see that we have a large energy density that is involved in these shape memory alloy and in a lower actuation frequency.

So, this is a very important aspect of shape memory alloy. And this same shape memory effect can be obtained in Heusler type of alloy; these are called as magnetic shape memory alloy means the phase transition occur due to the application of a magnetic field. So, here is also the actuation frequency is little bit higher where they are also in competition with other ceramic material or let us say some of the polymers. And you can see that definitely the polymer has a lower actuation energy density than the shape memory alloy.

So, with this we try to understand that the shape memory alloy has a very high engineering application not only in case of structural, but also starting from a structure to a biomedical to an actuation to a thermal actuator to a micro pump for kidney. So, there is a wide range of application. And we have almost covered up all the different aspects of shape memory effect in metals and alloys and pseudo-elasticity effect very thoroughly. So, with this we should complete this week discussion on shape memory alloys. And next week, we will start with a different topic.

Thank you.