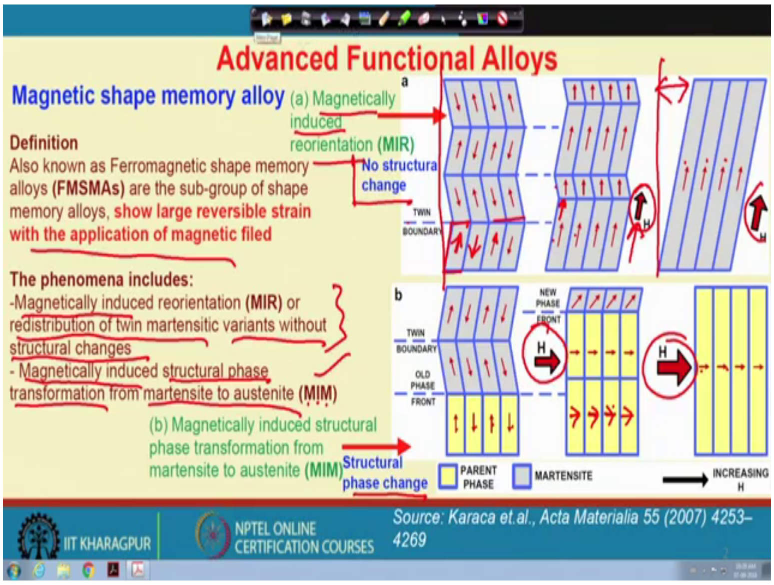
Advanced Materials and Processes
Prof. Jayanta Das
Department of Metallurgical and Materials Science Engineering
Indian Institute of Technology, Kharagpur

Lecture – 57
Advanced Functional Alloys (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. This week we are discussing about some Advanced Functional Alloys; and we have already discussed in the last class about the Heusler type of compounds or alloys for various type of functional application. Today we will continue this discussion and we will try to look at how shape memory effect can be achieved by application of a magnetic field.

(Refer Slide Time: 01:04)



Advanced Functional Alloys

Magnetic shape memory alloy

Definition

Also known as Ferromagnetic shape memory alloys (FMSMAs) are the sub-group of shape memory alloys, show large reversible strain with the application of magnetic filed

The phenomena includes:

-Magnetically induced reorientation (MIR) or redistribution of twin martensitic variants without structural changes

- Magnetically induced structural phase transformation from martensite to austenite (MIM)

(a) Magnetically induced reorientation (MIR)

No structural change

(b) Magnetically induced structural phase transformation from martensite to austenite (MIM)

Structural phase change

Source: Karaca et.al., Acta Materialia 55 (2007) 4253–4269

So, let us try to look at these magnetic shape memory alloys. This is also an advanced alloys and understanding is being developed day by day and there are many different system has been evolved with very interesting properties of shape memory effect. Now, these alloys are often called as the ferromagnetic shape memory alloys; because we also need to interact with a magnetic field. So, this should be ferromagnetic material and these are basically a subgroup of shape memory alloys. And it shows a very large reversible strain upon the application of the magnetic field.

What I want to mean in very short: there are two phenomena that are very much important to understand the phase changes or magnetic domain change by the application of a external magnetic field. So, these two effect is we can get magnetically induce reorientation and distribution of twin martensite variant. During the discussion of shape memory effect, we have learned about that shape memory effects are produced during because of the martensite, which has two different types of variants; one was called as twin 1 another one is the twin 2 ok.

So, these two variant one of them grow in expense to other due to the application of stress. But in this case here one of such a twin that grows in expense to the other one upon application of a magnetic field. So, very similar type of effect in one hand the for the conventional state memory alloy it was stress induced, in this case today what we are discussing it is actually the magnetic field induced.

Now, the redistribution of such twin martensite variant, without bringing any structural change; so this is called as MIR, this is Magnetically Induced Reorientation or redistribution of the twin variants in a martensite. Now let us have a look at these MIR effect magnetically induced reorientation effect, where there is no structural change. Here, structural change means like martensite austenite type of structural change is not present. MIR effect shows that we have twins in the martensite and this is actually one type of twin. This is one type of twin and this is the magnetic domain and we have another type twin. This is another one like that opposite in nature and these are the twin boundaries huh. So, this is the twin type 2 and this is twin type 1.

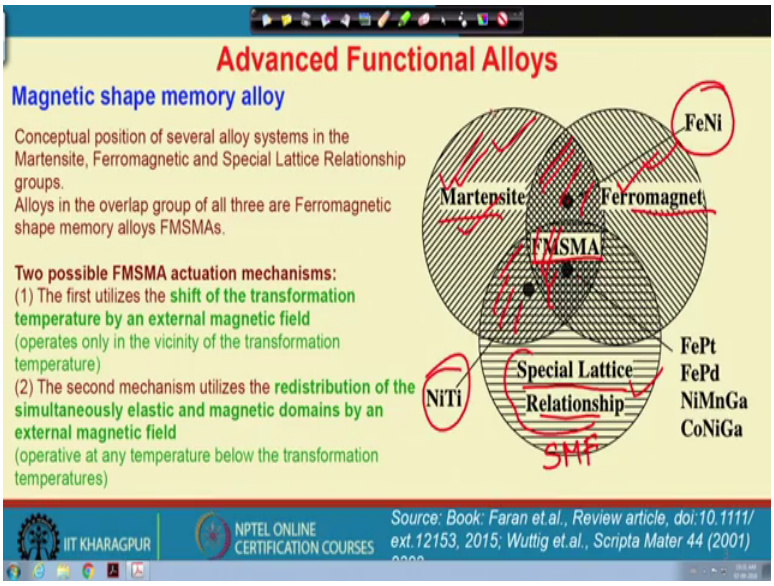
Now, we apply a magnetic field and one of the types of twin that aligned due to along the direction of the magnetic fields. So, they are all aligned now. And one type of twin is growing in expense to the other type of variant twin variant ultimately by increasing this magnetic field to a much larger value we have aligned all the twins to a particular direction or we have grown all these twin of one type. And also the magnetic domains are oriented in the same direction. So, this is a typical ferromagnetic type of behavior. However, we will get such a behavior of this large reversible strain. Means, if I withdraw these magnetic field, then again we can get back the strain that is generated. So, here this is let us say the strain axis we have generated this amount of strain right. So, this is something very interesting.

Now, the second type of second type of magnetic induced phase transition in this ferromagnetic shape memory alloy is that, we apply magnetic field. And we induce a structural transformation let us say from martensite to austenite and because of that we call these effect as MIM means Magnetically Induce Martensitic to austenitic transformation.

So, in this case since a structural phase transformation is involved, we can take very similar type of similar type of structures here. And we apply actually this is we apply actually some magnetic field. Now here we have a austenite phase where the magnetic domains are aligned anti parallel and so. And these are the old phase front and this is the twin boundary. Upon application of the magnetic field the yellow color region is the austenite and so, we produce austenite from martensite or martensite transform into austenite, at the same time we align the domain magnetic domain along the direction of the applied field.

Now, austenite phase cover the entire martensite upon application of higher magnetic field and also the domains are also aligned with increasing H. And this is typical example of MIM or magnetically induce structural phase transformation from martensite to austenite. This is also a very very interesting phenomena in case of a ferromagnetic shape memory alloys.

(Refer Slide Time: 07:49)



Advanced Functional Alloys

Magnetic shape memory alloy

Conceptual position of several alloy systems in the Martensite, Ferromagnetic and Special Lattice Relationship groups.
Alloys in the overlap group of all three are Ferromagnetic shape memory alloys FMSMAs.

Two possible FMSMA actuation mechanisms:
(1) The first utilizes the **shift of the transformation temperature by an external magnetic field**
(operates only in the vicinity of the transformation temperature)
(2) The second mechanism utilizes the **redistribution of the simultaneously elastic and magnetic domains by an external magnetic field**
(operative at any temperature below the transformation temperatures)

Source: Book: Faran et.al., Review article, doi:10.1111/ext.12153, 2015; Wuttig et.al., Scripta Mater 44 (2001)

So, we now need to recapitulate whatever we have discuss about nickel titanium you may recall. And in that case we have told that, we need a special type of lattice relationship so, that the structural transformation could be reversible ok.

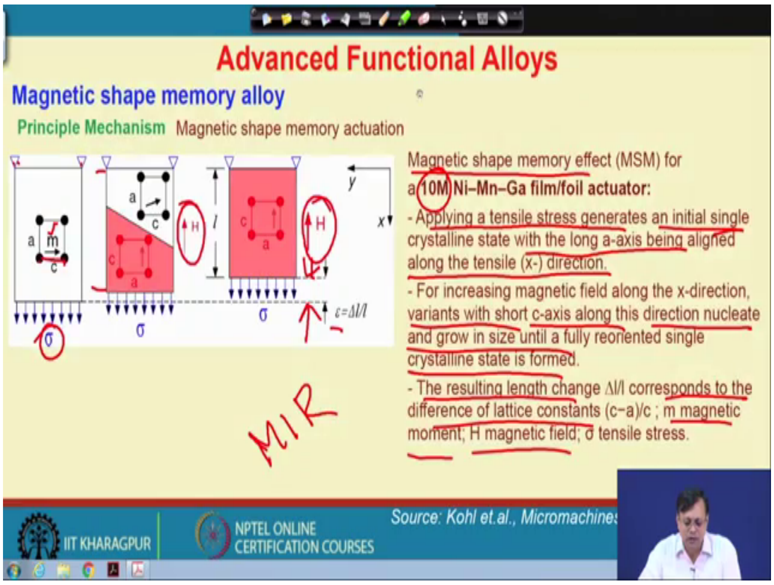
So, like a structure of b 19 dash which is a martensitic structure and let us say the b 2 structure which is the austenite structure and those structure should be reversible transform transformation should occur, definitely we also need a martensitic transformation in that case. So, let us say we have a martensitic transformation and we need some special type of relationship so, that we can get hundred percent shape recovery. So, this is let us say a typical shape memory effect or SME and so, if we combine these two different effect one is the special lattice relationship and martensitic transformation, this is a domain which should cover basically the typical shape memory alloys like nickel titanium.

Now, in other case a material which can show ferromagnetic behavior which are a ferromagnet and in case of iron nickel there is a martensitic transformation. So, the field which occupied by these two is basically like iron nickel one. Now if we combine these two these three different all three different type of behavior, then the combined region shows basically the ferromagnetic shape memory alloy. Means: these are ferromagnet there is a austenite martensite phase transition as well as they have some special relationship of the lattice so, that it exhibit a shape memory effect. And like iron platinum, iron palladium, the Haussler compound and you may recall these are the half Haussler compound that we have discussed in the last class.

So, this is just a conceptual position of different alloy system which has both martensite, ferromagnetic behavior and a special lattice relationship group so, that we achieve this shape memory effect and the overlap domain of the ferromagnetic shape memory alloy with the other ferromagnetic and shape memory alloys. Now there are two major possible actuation mechanism that are possible in this case of ferromagnetic shape memory alloy. I mean where do we use these alloys actually.

The first one is to utilize the shift of the transformation temperature by an external magnetic field of which operate only at the vicinity of the transformation temperature. Here transformation temperature means: we are talking about let us say like a martensite austenite type of transformation. And if we apply a magnetic field very close to it, then we can shift this transformation temperature we can stabilize one of the phase, whereas the second mechanism utilizes the redistribution of the simultaneously elastic and magnetic domain by an external field; which is called as MIR. Let us say the application of magnetic field reorient the martensite twin domains and so on. So, this is the second mechanism that we have discussed just a few minutes ago, and it is operative at temperature below the transformation temperature means, below the martensitic finish temperature we can get such a behavior.

(Refer Slide Time: 11:39)



Advanced Functional Alloys

Magnetic shape memory alloy

Principle Mechanism Magnetic shape memory actuation

Magnetic shape memory effect (MSM) for a 10M Ni–Mn–Ga film/foil actuator:

- Applying a tensile stress generates an initial single crystalline state with the long a-axis being aligned along the tensile (x-) direction.
- For increasing magnetic field along the x-direction, variants with short c-axis along this direction nucleate and grow in size until a fully reoriented single crystalline state is formed.
- The resulting length change Δl/l corresponds to the difference of lattice constants (c−a)/c ; m magnetic moment; H magnetic field; σ tensile stress.

Source: Kohl et.al., Micromachines

Now, we must explain those features how really the actuation can occur by the application of a magnetic field in a material or ferromagnetic shape memory alloys. So, in this case let us say we take a such a ferromagnetic material and we have a lattice, here is the direction of a axis and this is the c axis. And now we have applied a stress. So, this is already under stress. So, you can understand these are the fixed moments. So, so we have a tensile stress that is acting on the on the body.

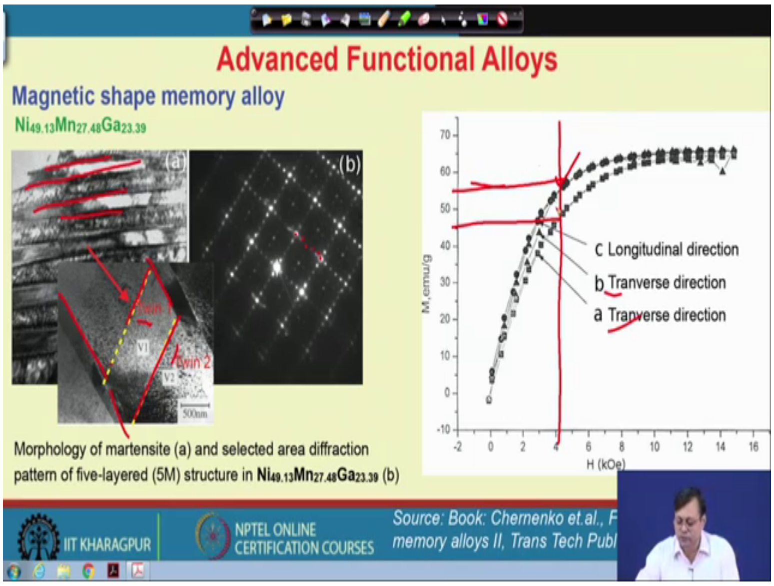
So, if now we apply a magnetic field, then due to the application of the magnetic field the martensite that basically transform into austenite ok. So, the red color here is the austenite. And due to that we also changes and align the domains and because of that, there is a there is a shortening of the length. Because you see a axis the long axis along this direction and the short axis c is in this direction. So, there will be a length change, because c axis the direction of the magnetic moment was in this way ok.

And now, if we keep on increasing the magnetic field so, we can generate this strain which is the delta l. So, the net length was total length was l, so, the strain we developed by the delta l by l along the x axis ok. So, in short let us say the magnetic shape memory effect we achieve for let us say- this was a typical 10 m martensite in a nickel manganese gallium actuator, the applying a tensile stress generate at a initial single crystalline state along the a axis that being aligned along the x direction.

So, a axis are aligned along the along the application of field and for increasing, the magnetic field along the x direction the variance with the shorter c axis these direction nucleate and grow in size the a fully reoriented single crystalline state that is formed. So, the resultant length change correspond to a difference of the lattice constant and m is the magnetic moment here, H is the magnetic field and sigma is the tensile stress.

So, this is a typical magnetic field induced orientation or a MIR type of relationship. So, magnetic induced orientation of the twin variants and so, on.

(Refer Slide Time: 14:42)



Advanced Functional Alloys

Magnetic shape memory alloy

$Ni_{49.13}Mn_{27.48}Ga_{23.39}$

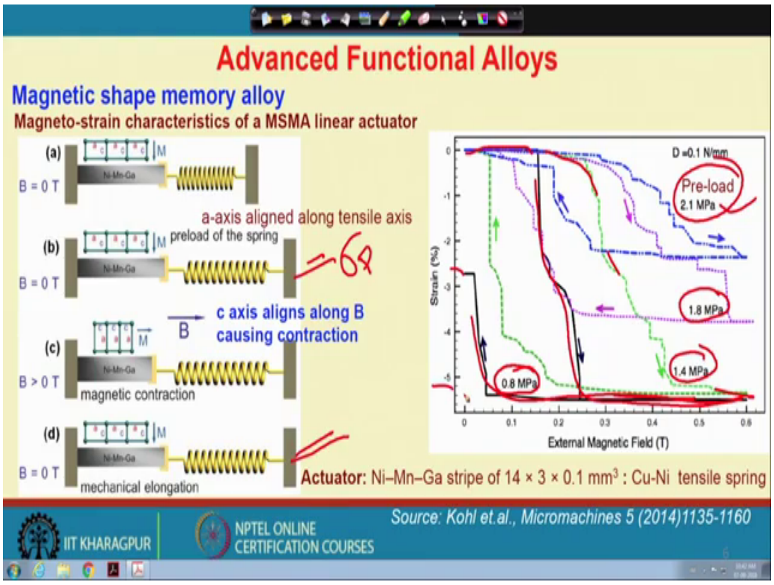
Morphology of martensite (a) and selected area diffraction pattern of five-layered (5M) structure in $Ni_{49.13}Mn_{27.48}Ga_{23.39}$ (b)

Source: Book: Chernenko et.al., F
memory alloys II, Trans Tech Publ

Now we can also get let us say morphology of such a magnetic domain and martensitic structures in a nickel manganese gallium system, one can see that these are the typical twin structures and here these are the boundary between the different twin levelly. So, inside one of these twin levelly, we may have two different type of twins. So, these are the twin boundary by application of the magnetic field, these twin 1 to twin 1 twin 2 type of growth occur and by looking at the selected a diffraction pattern from the brighter spot you can clearly see 1 2 3 4 and 5. So, this is a 5M martensite modulated martensite.

So, along let us say the c axis or let us say the transverse direction the properties are different means the magnetic moments are different, and it require the for a given application of the field. The moments that are generated along the transverse and longitudinal direction are also different. So, this is also another interesting behavior of such a magnetic shape memory alloys.

(Refer Slide Time: 16:04)



Advanced Functional Alloys

Magnetic shape memory alloy

Magneto-strain characteristics of a MSMA linear actuator

a-axis aligned along tensile axis

c axis aligns along B causing contraction

Actuator: Ni–Mn–Ga stripe of 14 × 3 × 0.1 mm^3 : Cu-Ni tensile spring

Source: Kohl et.al., Micromachines 5 (2014)1135-1160

Such a magnetic strain characteristic of a magnetic shape memory alloys linear actuator, we can also discuss this issue of how the domains are oriented with a application of a magnetic field.

So, let us say I can start with a nickel manganese gallium alloy, and this is also a at a kept at a applied field of 0. So, there is no magnetic field. Now I hold these particular stripe or nickel manganese gallium stripe, with let us say 0.1 thickness its very thin with a string that is a copper nickel tensile string, which are kept at a such a distance.

And now I put it here means I apply some stress. So, these a axis now will be aligned along the tensile axis. So, I put a tension here. So, you can see the length of the spring has increased from this position to here. So, immediately the lattice will be also reoriented along the direction to accommodate the elastic strain; however, the magnetic moments are also aligned here and so, the spring has elongated actually right.

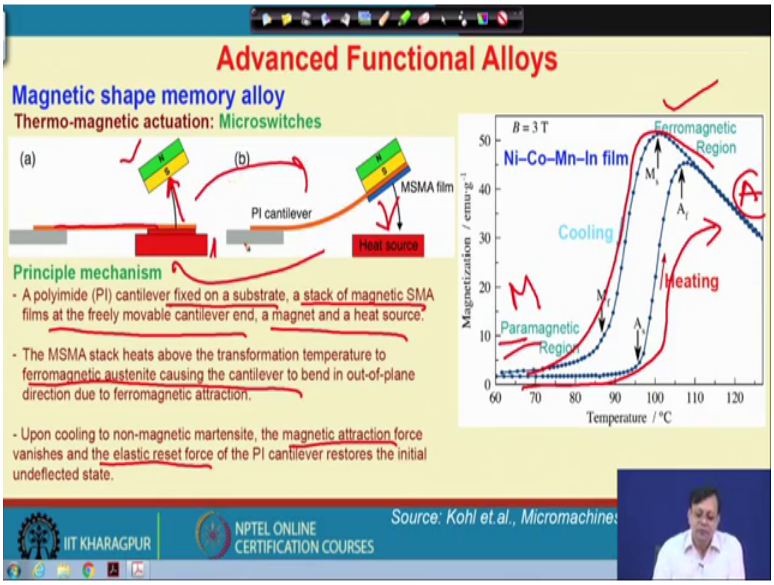
So, the spring get elongated; however, the length of the stripe remain unchanged at a zero applied field. Now what I do now the actuation really begin, now I apply a magnetic field. So, B here is the magnetic field. So, all these lattice here they now reoriented along the applied magnetic field. So, c is the axis which should be aligned with that b and. So, when the applied field is greater than 0, then there is a magnetic contraction because c axis is the smallest axis and this position this position goes back.

Now, I have much longer tensile spring. So, the load or also has increased because of the application of the magnetic fields. So, c axis aligned along B causing a contraction. Now if I withdraw the magnetic field now in that case, there is a simple mechanical elongation due to the application of this spring. So, again the magnetic domain are aligned in the opposite way and the former state again comes back. So, this is a linear actuation in case of a ferromagnetic shape memory alloys.

So, if you look at different Pre-load. So, here whatever load we have applied this is let us say a pre load. So, these is the pre load amount and let us say for 0.8, 1.4, 1.8 or 2.1. So, the net strain that one can generate could vary. So, from 0 we apply a pre load and then the strain again comes back due to the external field. So, initially the external field was 0 and then it comes back. Whereas, the green one a almost reaches to something like 5 percent strain. So, this is a very large strain that we can produced and beyond any kind of beyond the elastic limit of such a magnetically or induced strain that are recoverable strains.

So, we can easily use this material as a actuator and already being used.

(Refer Slide Time: 20:24)



Advanced Functional Alloys

Magnetic shape memory alloy

Thermo-magnetic actuation: Microswitches

Principle mechanism

- A polyimide (PI) cantilever fixed on a substrate, a stack of magnetic SMA films at the freely movable cantilever end, a magnet and a heat source.
- The MSMA stack heats above the transformation temperature to ferromagnetic austenite causing the cantilever to bend in out-of-plane direction due to ferromagnetic attraction.
- Upon cooling to non-magnetic martensite, the magnetic attraction force vanishes and the elastic reset force of the PI cantilever restores the initial undeflected state.

Source: Kohl et.al., Micromachines

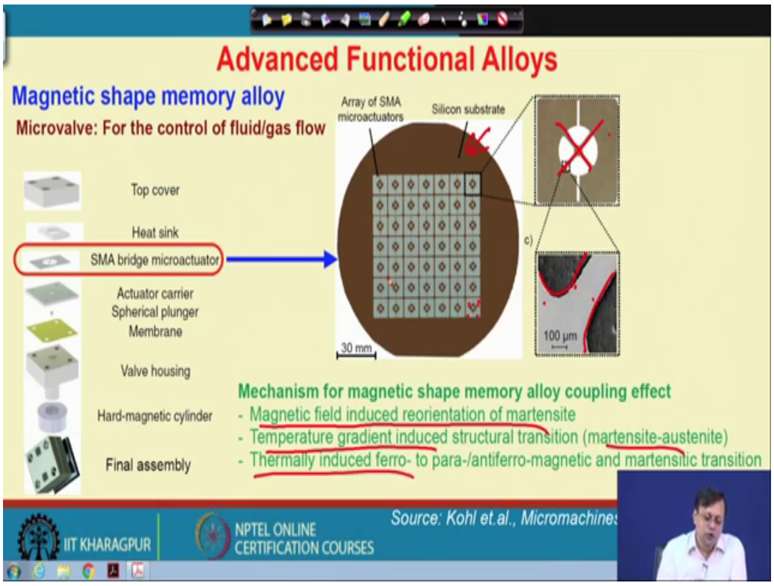
The other one here this is a heating and cooling require which is used for micro switches. And in this case what we really do, we have a cantilever and this cantilever is made of a ferromagnetic alloys and for this cantilever, we have a fixed substrate and stacked on a magnetic shape memory alloy that are freely movable cantilever at the end and a magnet and a heat source.

So, we have a magnet here and we have a heat source here ok. And these magnetic shape memory these alloys, they are stacked heat source above the transformation temperature to a ferromagnetic austenite causing the cantilever to bend out of the plane. So, here we are talking about MIM means magnetically induced martensite to austenite transformation.

So, ferromagnetic austenite that causing the cantilever to bend, because if we increase the temperature then it goes to the austenite domain and these austenite is a ferromagnetic in nature; so immediately it will be attracted to the magnet. And so, this connection will be disconnected right. And so, again when let us say the temperature will be cooled down, then it will it will come down to the martensitic phase which is a paramagnetic region. And so, again it will be connected these two points. So, during heating and cooling, we can use as a micro switch for ferromagnetic attraction as well as paramagnetic when or non magnetic during cooling non magnetic martensite paramagnetic martensite these magnetic attraction force will vanish, and due to the elastic reset force then again it will come back to here.

So,. So, this process will go on. So, we can maintain a or restore the initial undeflected state. So, so in this way we can make a micro switches, that could be that is very much usable for using this shape memory alloys by considering these magnetically induced martensite to austenitic transformation.

(Refer Slide Time: 22:59)



Advanced Functional Alloys

Magnetic shape memory alloy

Microvalve: For the control of fluid/gas flow

Mechanism for magnetic shape memory alloy coupling effect

- Magnetic field induced reorientation of martensite
- Temperature gradient induced structural transition (martensite-austenite)
- Thermally induced ferro- to para-/antiferro-magnetic and martensitic transition

Source: Kohl et.al., Micromachines

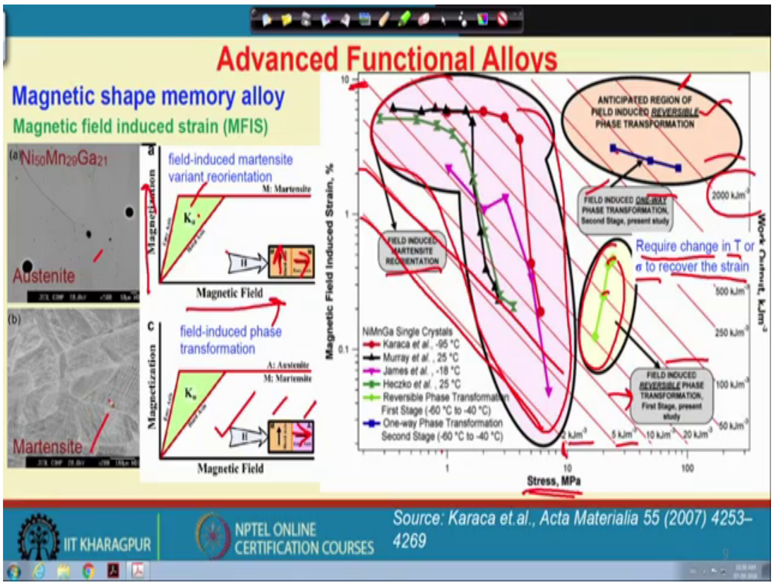
IIT KHARAGPUR | NPTEL ONLINE CERTIFICATION COURSES

We can also use this particular magnetic induced transformation for control of fluid or glass flow. One should have a look here this is a silicon substrate, where the material is grown and material means basically the alloy, that is a magnetic shape memory alloys and these particular colored region is the alloy; a higher magnified image with 100 micrometer that are shown here. So, this one is the alloy and here this is the substrate actually.

So, other version of one of such a switch is shown here. So, these are the microvalve and here these are the connecting materials of these two different parts. Now the mechanism of magnetic shape memory alloy coupling effect is due to the magnetic field induced reorientation of the martensite temperature gradient induced structural transformation from martensite to austenite and thermally induced ferro to para or antiferro or martensitic transitions.

So, means if we apply a magnetic field, then there will be a distortion in the lattice and as well as it will simply assist to close the valve or to open the valve. So, the basic structure consists of a top cover, where there is a need of a heat sink and the shape memory alloy bridge micro actuator are shown here actually, and the below that they are actuator carrier or spherical plunger and there is a membrane with a valve housing and there is a need of a hard magnet. So, finally, assembling such a such a assemble part, which we use for such a fuel flow control or gas flow control. So, also I believe that these are one of the very important aspect of ferromagnetic shape memory alloys for everyday use.

(Refer Slide Time: 25:23)



Advanced Functional Alloys

Magnetic shape memory alloy

Magnetic field induced strain (MFIS)

Require change in T or σ to recover the strain

Source: Karaca et.al., Acta Materialia 55 (2007) 4253–4269

Now, these Magnetic Field Induced Strain or MFIS are due to the variation of the martensite twin variants or a phase transition. In both way we can generate the strain and the anisotropy factor that is Ku that I have discussed earlier with you in the last class are lying here. So, this is the magnetization versus a magnetic field. So, if I apply the field the martensite which has initially a magnetic moment along this direction will be switched into the direction of the magnetic field. And with that, switching we remove one of the twin variant due to the reorientation of the martensite or otherwise we can switch from a martensite to austenite or we can change the phase from martensite to austenite by the application of the field, where we not only change the phase, but also we align the align the magnetic domain.

So, these are the two different effect one is the MIR and another is the MIM. So, field used induce martensite reorientation is occupying this region people have observed so far. However, here a minimum stress is required. So, in between let us say 1 to 10 mega Pascal stress and the strain can achieve up to up to recoverable strain can be achieve up to 10 percent right. So, this is a very high since we can already calculate the work output by considering the stress and strain. So, these are the lines that are let us say 2 kilo joule per meter cube, 5 kilo joule per meter cube. So, as we go into this right hand side direction, we can get a higher work output of this right.

And on the other hand let us say the field induced reversible phase transformation that are present which are occupying this particular region, but the best idea will be to go to this side actually right. But so far there is magnetic field induced one way phase transformation has been observed, which require the why this is one way because it required change of temperature or the stress in order to recover the strain. So, if we rather our magnetic field then it does not recover the strain actually this is a one way phase transition ok.

So, but the target is to get a reversible phase transformation in this domain so that we can get the maximum work output of 2000 kilo joule per meter cube ok. But if people are developing these alloys day by day and so many interesting alloys or material could be develop using these kind of half or full Haussler type of compound, and switching between austenite to martensite and to develop these ferromagnetic shape memory alloying.

With this I stop today’s discussion. And we will continue with the discussion of some of the other functional behavior of these advance functional alloys in the next class.

Thank you very much.