Shape Memory Alloys

A Great Boon for the Industrial Application

Subrat Kumar Barik
Assistant Professor,
Mechanical Engineering Sri Sivani College of Engineering,
Chilakapalem, Srikakulam, Andhra Pradesh, India

Dr. P. Srinivasa Rao
Dean, R&D
Centurion University of Technology and Management,
Paralakhemundi, Odisha, India

***Abstract*—Based upon the problems developed by the metals and non-metals a new composition came into existence as alloys. Alloys processed almost all the solutions to the existing problems. With the advent of time alloys also posed certain problems to the society hence a new source named shape memory alloy was sorted to be the latest solution. Shape memory alloys are metallic systems that remember and regain their original shapes. These alloys undergo martensitic phase transformations because of applied thermo- mechanical loads and are capable of recovering permanent strains when heated above a certain temperature. This paper focuses on shape memory alloy and its substantial help to the society by their applications in industry, medical science and engineering fields. The two major properties such as super elasticity and shape memory effect and its applications will be discussed broadly in this paper.**

Keywords—Shape memory alloy, super elasticity, back memory effect.

I. INTRODUCTION

With the need for human wants growing day by day research on finding suitable materials took gear. This research bought opportunities for various new techniques and technology. In the last decade a tremendous change in the way of life style of humans is seen. These changes are basically due to the invention of new materials. These materials act and change and respond as per the human need with just wink of eye or with snap of fingers. Development of these materials started with research on certain changes of materials when heat, electric current, magnetic field are applied on these materials. Explaining them further we can demonstrate the thermo- response materials and magneto response materials. Those materials which change to heat which provided are known as thermo-response materials and those which change according to the magnetic field supplied is known as magneto responsive material. Briefly these materials are described as shape memory alloys. A broader study on these alloys states us that they show two unique qualities as shape memory effect and super elasticity. [4]

The shape memory effect deals with the shape recovery of the alloys. It states that the material can be recovered to its original geometry after being deformed by the heat provided. The martensitic transformation provided up to the critical temperature helps in causing this shape memory effect. Of course, the temperature and the material properties affect this effect to a great extent. The super elasticity property makes the material to endure large cyclic deformation without residual strains gaining a hysteretic loop which makes the material to remove energy to the surrounding. Studies on these two properties provides us with many extraordinary properties which when applied makes the shape memory alloys a great possibility in the way we see the world.

II. SHAPE MEMORY ALLOY

The transformation from alloy to shape memory alloy follows a cyclic path. Every material has a tendency that if we will provide particular temperature in perfect environment then the alloy transforms its phase. Here we discuss the important components of transformation from alloy to shape memory alloy.

A. Martensitic transformation

In near equal atomic number alloys martensite forms on cooling from the body centered cubic high temperature phase, known as austenite, by a shear type of process. This martensitic phase is heavily twinned. The transformation which yields super elasticity and the shape-memory effect is diffusion less phase transformation in solids, called martensitic transformation. During this transformation, the atoms are cooperatively rearranged into a different crystalline structure with identical chemical composition, through a displace distortion process. [14]

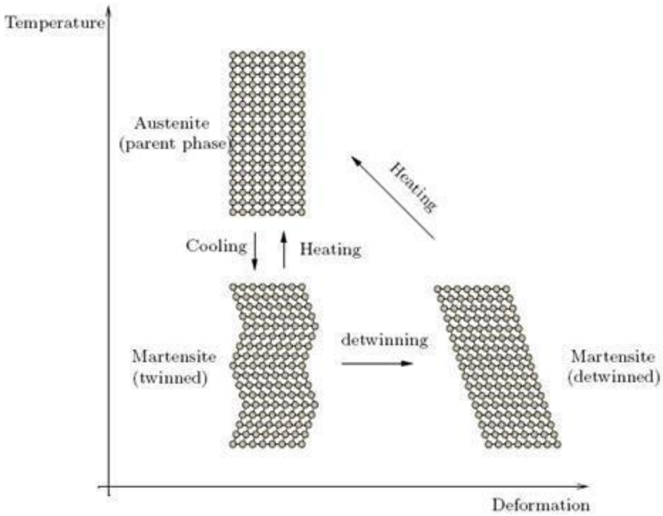


Fig. 1. Austenite to martensite phase transformation

In SMAs, the martensitic transformation changes the material from the parent phase, a high-temperature (high-energy) phase called austenite, to a low-temperature phase (low-energy) called martensite shows in Fig.1. During the transformation from the high-temperature phase to the low temperature phase, these martensitic variants are formed in a twinned pattern, in which the atoms achieve displacements with mirror symmetry. This occurs since the crystal lattice strives to achieve minimal potential energy states for a given temperature. If a deformed martensite is now heated, it reverts to austenite. The crystallographic restrictions are such that it transforms back to the initial orientation, thereby restoring the original shape. The transformation from austenite to martensite and the reverse transformation from martensite to austenite do not take place at the same temperature. A plot of the volume fraction of martensite as a function of temperatures shown in Fig. 2 The complete transformation cycle is characterized by the following temperatures: austenite start temperature (As), austenite finish temperature (Af), martensite start temperature (Ms) and martensite finish temperature (Mf). [14]

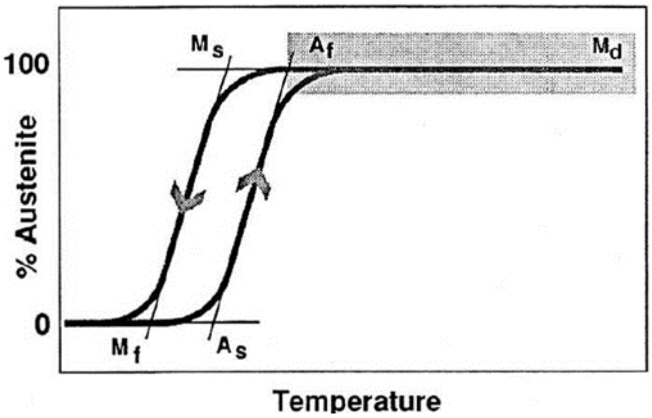


Fig. 2. Temperature vs. volume fraction of austenite plot

B. Shape memory effect

The other manifestation of the thermoelastic martensitic transformation in SMAs is so called shape memory effect. Whereas stressed induced martensite consists of a single preferential variant according to the applied stress, martensite produced by cooling consists of a random mixture of several variants (including twins). Twin boundaries can be relatively easily moved by the application of stress. When the twin boundaries of the crystal are moved due to application of the stress it will results in the change of the lattice orientation this phenomenon is known as de-twin. During the de-twinning process of the martensitic crystal structure, when facing a unidirectional loading, the stress remains almost constant until the martensite is completely de-twinned. Crystals favourably aligned to the load direction deform first, at a lower stress level, (o-a-b) in Fig..3 Less favourably aligned crystals deform later, at higher stresses (b-c). Further straining causes the elastic loading of the detwinned martensite (c-d). Unloading from any point in (o-d) initially results in elastic unloading of the de-twinned material. The deformation recovered is much smaller than the one supplied by de- twinning, giving the apparent impression of permanent deformation. This deformation can be recovered by raising the temperature above Af, transforming the de-twinned martensite back to austenite; see Fig..3. This shape is maintained during cooling below Mf, when the material re-transforms to twinned martensite. Straining further than point (d) will first cause the slipping of the martensite lattices and eventually lead the specimen to failure, corresponding to point (e). The force exerted by a specimen when it transforms from martensite to austenite is associated with a first-order phase transition, involving enthalpy of transformation. During this transition, the system absorbs an amount of energy, through heating. This force may be much higher than the force needed to deform the martensite specimen, causing it to de-twin.[5]

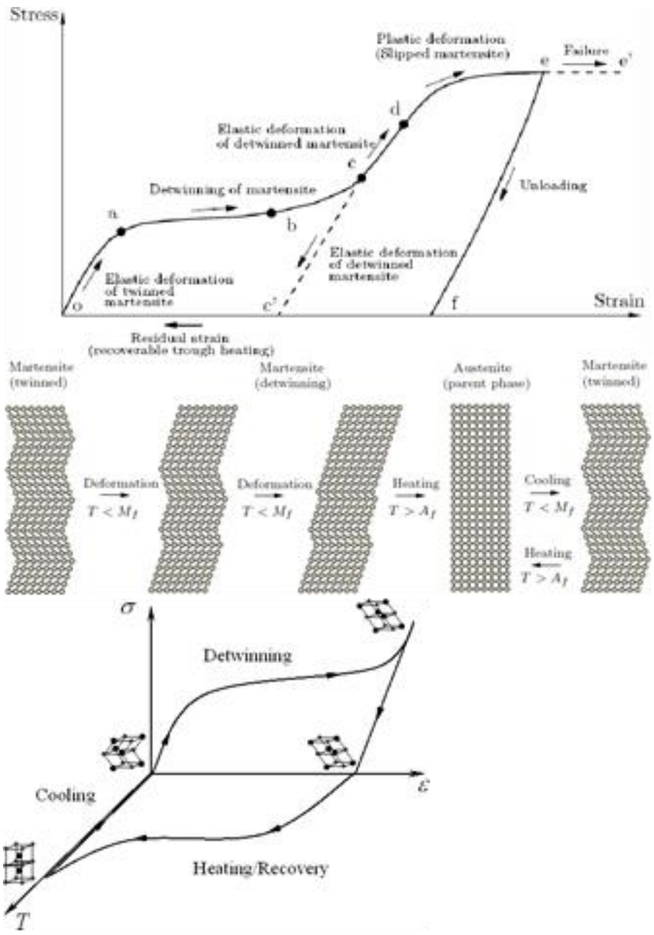


Fig. 3. De-twinned martensite to austenite transformation plot

There are two categories of shape memory effect namely one way shape memory effect and two way shape memory effect. In one way memory effect material remembers its shape only in cold state where as in two way shape memory effect it will remembers their original shape in both cold and heat condition.

C. One way shape memory effect

When a shape-memory alloy is in its cold state, the metal can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again it will remain in the hot shape, until deformed again.

With the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low-temperature shape. On heating, transformation starts at As and is completed at Af (typically 2 to 20 °C or hotter, depending on the alloy or the loading conditions). As is determined by the alloy type and composition and can vary between −150 °C and 200 °C.

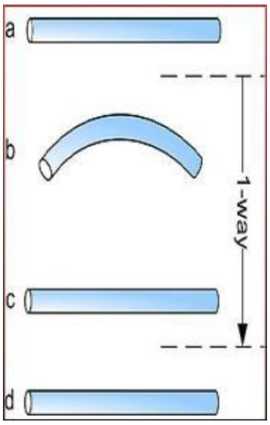


Fig. 4. One way shape memory effect

D. Two way shape memory effect

The two-way shape-memory effect is the effect that the material remembers two different shapes: one at low temperatures, and one at the high-temperature shape. A material that shows a shape-memory effect during both heating and cooling is said to have two-way shape memory. This can also be obtained without the application of an external force (intrinsic two-way effect). The reason the material behaves so differently in these situations lies in training. Training implies that a shape memory can "learn" to behave in a certain way. Under normal circumstances, a shape-memory alloy "remembers" its low-temperature shape, but upon heating to recover the high-temperature shape, immediately "forgets" the low-temperature shape. However, it can be "trained" to "remember" to leave some reminders of the deformed low-temperature condition in the high-temperature phases. There are several ways of doing this. A shaped, trained object heated beyond a certain point will lose the two-way memory effect.[5]

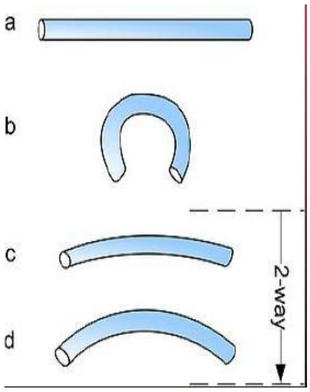


Fig. 5. Two way shape memory effect

E. Super elasticity

When a unidirectional stress is applied to an austenitic specimen, within a temperature range between Af and Md (Md > Af), an elastic distortion of the austenitic lattice starts to occur (o-a). There is a critical value (a) whereupon austenite becomes unstable and a transformation from austenite to stress-induced martensite (SIM) takes place; see Fig. 6 in which stress strain curve shows as the deformation proceeds the stress remains almost constant until the material is fully transformed (a-b). During this part of the response the two phases coexist. Upon stress removal, the elastic unloading of the detwinned martensite (b-c) takes place. Since martensite becomes unstable below a critical stress (c) a reverse transformation occurs as the unloading process continues. De- twinned martensite reverts back to austenite, at a lower stress plateau than during loading (c-d).

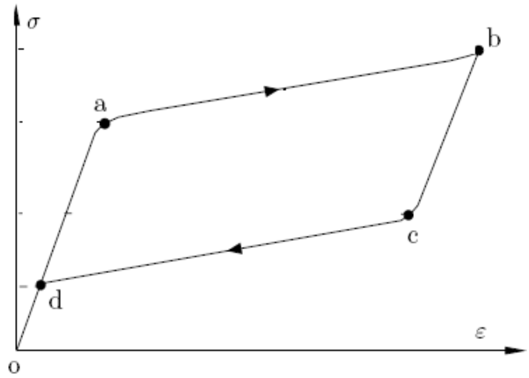


Fig. 6. Stress strain diagram of transformed material

When the material is fully transformed to the parent phase (d) further unloading will follow the initial loading path, with full recovery of the deformation shows in Fig. 7. A hysteretic effect is hence produced. If the temperature is greater than Af, the strain attained during loading is completely recovered at the end of the unloading. This process is translated by an energy-absorption capacity with zero residual strain, called super elasticity.

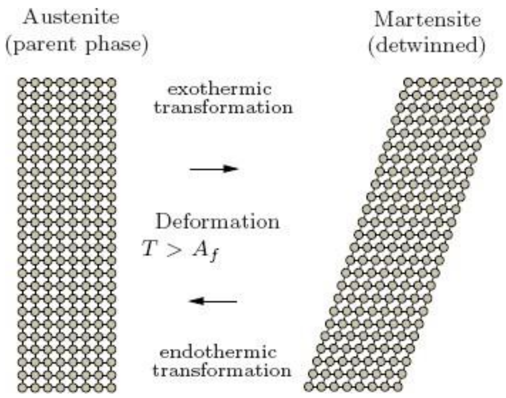


Fig. 7. Full recovery of deformation

III. TYPES OF SMA

A. High temperature shape memory alloys

Extensive research for HTSMAs with other ternary additions to the NiTi SMA (e.g. Au, Hf, Pd, Pt and Zr) has been undertaken, due to the increasing demands for high-temperature applications. Practically, HTSMAs are defined as SMAs that are operating at temperatures above 100 _C, and can be categorized into three groups based on their martensitic transformation ranges.

B. Magnetic shape memory alloys

Magnetic shape memory alloys (MSMAs), which are also known as ferromagnetic shape memory alloys (FSMAs) can actuate at higher frequencies (up to 1 kHz) because the actuation energy is transmitted via magnetic fields and is not hindered by the relatively slow heat transfer mechanism.

FSMA strain rate is quite comparable to magneto strictive and piezoelectric active elements, but at strains as large as SMAs. FSMA can also provide the same specific power as SMAs, but deliver it at higher frequencies.

C. Shape memory material thin films

SMM thin films evolved from the advancement of fabrication technology, where SMMs are deposited directly onto micro machined materials or as stand-alone thin films to become micro- actuators. Moreover, in the rapidly growing field of micro-electro-mechanical systems (MEMSs), NiTi thin films have become the actuator of choice at the micro-scale level, due to the attributes as described earlier (i.e. higher actuation force and displacement), but at relatively low frequency (up to 100 Hz) and efficiency as well as the non-linear behaviour The versatility of NiTi thin film with multiple degrees of freedom and compact structure, expand the potential of NiTi in biomedical, aerospace, automotive, and consumer products applications.

D. Shape memory polymers

Shape memory polymers (SMPs) are relatively easy to manufacture and fast to train (or program) as well being able to be tailored for a variety of applications. SMPs are claimed to be a superior alternative to SMAs for their lower cost (at least 10% cheaper than SMAs), better efficiency, biodegradable and probably by far surpass SMAs in their mechanical properties. In addition, SMPs can sustain two or more shape changes when triggered by thermal (heating or cooling) electricity, magnetic field, light or solutions (e.g. chemical or water). Generally, there are three categories of SMPs, and most of them are naturally either thermo- or chemo-responsive. When one considers the vast commercial application of polymer products, it is apparent that SMPs have significant commercial application, such as smart fabrics, self- repairing (or seal-healing) plastic components, spacecraft sails, biomedical devices and intelligent structures.

There are three basic working mechanisms for the SME in polymeric materials: Dual-state mechanism, dual-component mechanism (DCM) and partial-transition mechanism (PTM). The recovery precision of more than 99% makes SMPs suitable for highly demanding applications. Similar to SMAs, the SME of SMPs varies depending on the composition of the material used, i.e. weight fraction of the switching segments and the molecular weight of the polymer-chain employed. The biodegradable nature of certain SMPs provide advantages over metal implants, where the removal of the implant after regeneration can be avoided, thus gentler, more effective and more economical treatments can be offered. However, despite the advantages described above, SMAs are still preferred for applications that require higher actuation forces and faster response.

IV. RECENT APPLICATION

In the 1990‘s, the term shape memory technology (SMT) was introduced into the SMM community. SMA application design has changed in many ways since then and has found commercial application in a broad range of industries including automotive, aerospace, robotics and biomedical. Currently, SMA actuators have been successfully applied in low frequency vibration and actuation applications. Therefore, much systematic and intensive research work is still needed to enhance the performance of SMAs, especially to increase their bandwidth, fatigue life and stability.

Recently, many researchers have taken an experimental approach to enhance the attributes of SMAs, by improving the material compositions (quantifying the SMA phase transition temperature) to achieve a wider operating temperature range, and better material stability, as well as to improve the material response and stroke with better mechanical design (or approach), controller systems and fabrication processes. Research into alternative SMMs, forms or shapes, such as MSMA, HTSMA, SMP, shape memory ceramic, SMM thin film or a combination of them (i.e. hybrid or composite SMMs), are also intensively being conducted, and the number of commercial applications is growing each year More details of recent applications and development of SMA are described in the subsequent sections.

A literature analysis has been carried out using the Scopus and USPTO search engines with search keywords of ‘shape memory alloy’ or ‘nitinol’ for related areas are presented in. BCC research reported that the global market for smart materials was about USD19.6 billion in 2010, estimated to approach USD22 billion in 2011 and forecasted to reach over USD40 billion by 2016 with a compound annual growth rate (CAGR) of 12.8% between 2011 and 2016. The largest application segment of the market is actuators and motors, with sales of nearly USD10.8 billion (55% of the total market) in 2010 and forecasted to reach USD25.4 billion (approximately 64% of the market) by 2016 with CAGR of 15.4% between 2011 and 2016.

Some of the important applications are listed below.

A. Aerospace application

Plane wings with SMA wires can change shape by inducing voltages in them. This can replace hydraulic and electromechanical actuators.

Boeing, General Electric Aircraft Engines, Goodrich Corporation, NASA, and All Nippon Airways developed the Variable Geometry Chevron using shape memory alloy that reduces aircraft's engine noise.

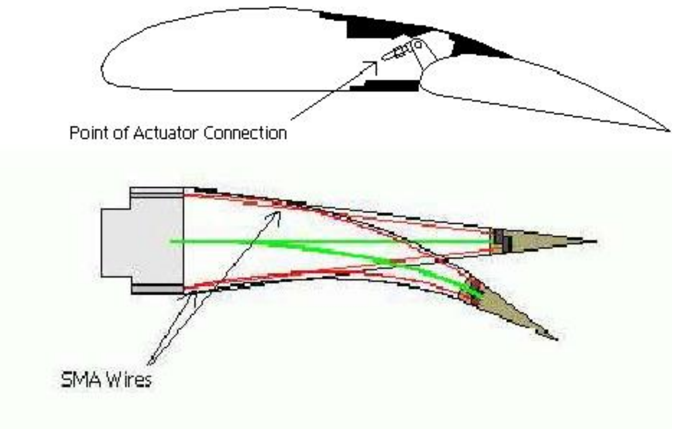
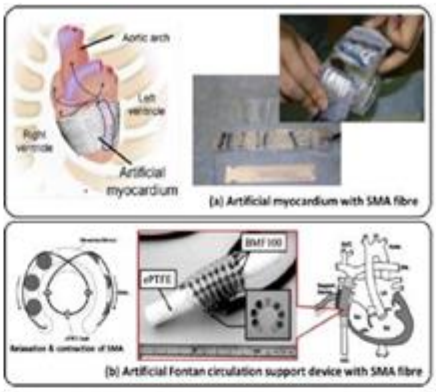


Fig. 8. SMA wire used in aerospace applications

B. Biomedical

Shape memory alloys are applied in medicine, for example, as fixation devices for osteotomies in orthopaedic surgery, in dental braces to exert constant tooth-moving forces on the teeth and in stent grafts where it gives the ability to adapt to the shape of certain blood vessels when exposed to body temperature.



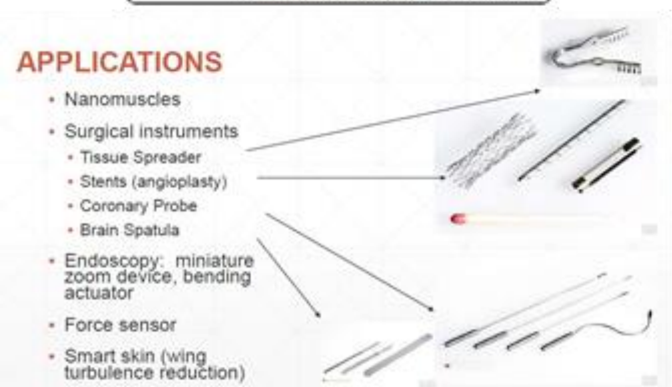


Fig. 9. Applications of SMAs in aerospace industry

C. Robotics

There have also been limited studies on using these materials in robotics (such as Roboter frau Lara), as they make it possible to create very light robots. Weak points of the technology are energy inefficiency, slow response times, and large hysteresis.

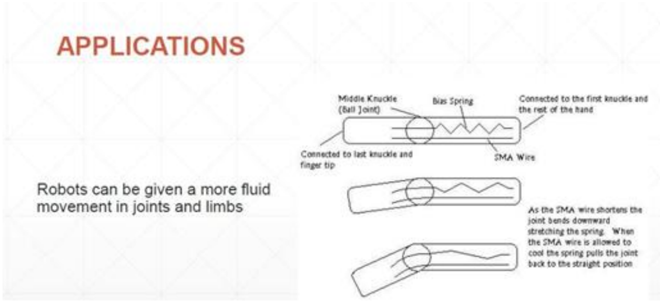


Fig. 10. Applications of SMAs in robotics

D. Manufacturing

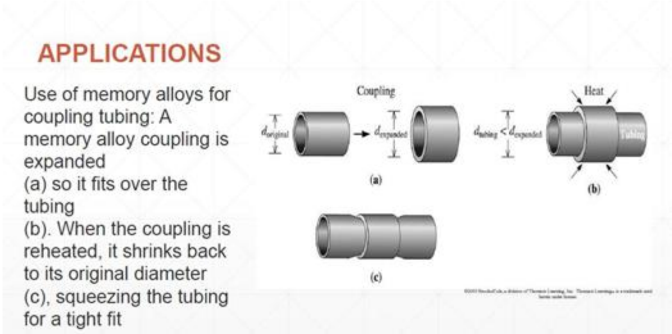


Fig. 11. Applications of SMAs in manufacturing industries

V. FUTURE APPLICATION

Some future applications are listed as follows:

- Eliminate vibrations of read/write heads in hard disk drives
- Micro stents
- Promote flow in tubular passages
- Reinforce weak blood vessels
- Microsurgery
- Cardio vascular applications
- Orthopaedic applications

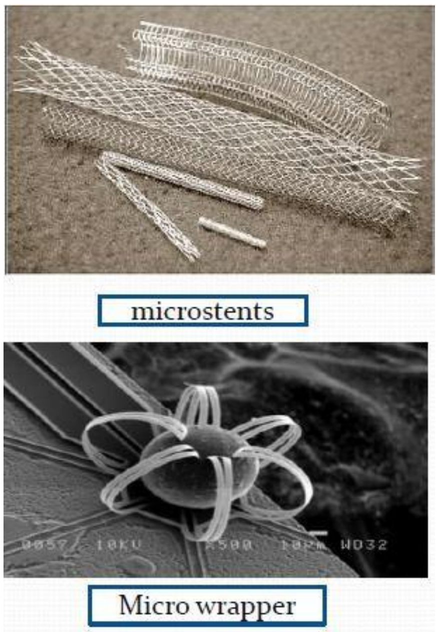


Fig. 12. SMAs in microstents and micro wrapper applications

VI. MATERIALS

Alloys of metals having the memory effect at different temperatures and at different percentages of its solid solution contents:

Ag-Cd 44/49 at.% Cd

Au-Cd 46.5/50 at.% Cd

Cu-Al-Ni 14/14.5 wt.% Al and 3/4.5 wt.% Ni

Cu-Sn approx. 15 at.% Sn

Cu-Zn 38.5/41.5 wt.% Zn

Cu-Zn-X (X = Si, Al, Sn)

Fe-Pt approx. 25 at.% Pt

Mn-Cu 5/35 at.% Cu

VII. ADVANTAGE

The advantages of shape memory alloys include:

- High strength
- Good elasticity
- Fatigue Resistance
- Wear resistance
- Easy fabrication
- Easy to sterilize
- High Power/weight ratio
- Light weight
- Shape memory
- Grab tiny foreign objects for removal from the body
- Facilitates access to intricate regions of the body
- Micro assembly for MEMS devices
- Intravascular Therapy

VIII. DISADVANTAGE

The disadvantages of shape memory alloys include:

- Cost Effective
- Sensitivity of material properties in fabrication.
- Residual Stresses developed in thin films.
- Nonlinearity of actuation force.
- Lower maximum frequency compared to other micro actuator devices.
- Inferior fatigue Property.

IX. CONCLUSION

To summarize in this paper, we have got into the shoes of a novice and briefly tried to explain the two basic properties for the existence of shape memory alloys (shape memory effect and super elasticity).

With the focus on these two properties we described the martensitic structural changes and austenitic twinned transformation. Further in the paper describes the types of SMA as high temperature shape memory alloys, magnetic shape memory alloys, shape memory material thin films and shape memory polymers.

The important part of any invention lies in the application part so we enumerated certain brief applications used in day to day life by the layman also so that the crucial development of SMA comes into a serious note based on these applications.

Its extensive description of the properties has made its applications to reach a far range. Some of them which were described are in the field of automotive aerospace robotics and biomedical. The day is not far when the applications of SMA will revolutionize the way we see the world where worried patient of cardio problems will be traded by micro stents and will get greatly relieved. Or the blood vessels will be replaced and made fit for utilization without any much stress. Storage in the hard disk will be unfolded to a great extent with the use of SMA application.

These are just a few glimpses of how the world will look once the application come into real world with in-increase in scope for its application day by day.

Shape memory alloy have the potential to be used effectively in seismic regions. Their capability to allow the development with smart structures with active control of strength, stiffness and ability of self-healing and self-repairing opens the door for exciting opportunities making them a largely usable material in future.

Hence, we would like to conclude that a small step towards large revolution has just started which would take miles of steps with the wonder elements of shape memory alloy, “THE FUTURE OF TOMORROW’S ENGINEERING APPLICATION”.

REFERENCES

[1] O.BenMekki and F.Auricchio,”Performance evaluation of shape-memory-alloy super elastic behaviour to control a stay cable in cable-stayed bridges,” Elsevier International Journal of Non-Linear Mechanics, 2011, Vol. 46, No 2, PP 470–477.
[2] Kin-tak Lau, “Vibration characteristics of SMA composite beams with different boundary conditions,” Materials and Design, 2002, Vol.23, PP 741–749.
[3] Reza Mirzaeifar, Reginald DesRochesand Arash Yavari, “A combined analytical, numerical, and experimental study of shape-memory-alloy helical springs,” International Journal of Solids and Structures, 2011, Vol. 48, PP 611–624.
[4] G. Songa, N. Maa and H.-N. Lib, “Applications of shape memory alloys in civil structures,” Elsevier Engineering Structures, 2006, Vol. 28, PP 1266–1274.
[5] Lexcellent, S. Leclercq, B. Gabry and Bourbon, “The two way shape memory effect of shape memory alloys: an experimental study and a phenomenological model,” International Journal of Plasticity, 2000, Vol. 16, PP 1155- 1168.
[6] Farzad Ebrahimi and Hussein Sepiani, “Mesh free modelling of shape memory alloy wires thermomechanical behavior,” International Journal of the Physical Sciences, 2011, Vol. 6, No.20, PP 4739-4748.
[7] U. Icardi, L. Ferrero, “Preliminary study of an adaptive wing with shape memory alloy torsion actuators‖,” Materials and Design, 2009, Vol. 30 PP 4200–4210.
[8] Alaa M. Sharabash, Bassem O. Andrawes, “Application of shape memory alloy dampers in the seismic control of cablestayed bridges‖, Engineering Structures, 2009, Vol.31, PP 607-616.
[9] Ottavia Corbi, ―Shape memory alloys and their application in structural oscillations attenuation‖, Simulation Modeling Practice and Theory, 2003, Vol. 11, PP 387–402.
[10] Victor Birman, “Shape memory elastic foundation and supports for passive vibration control of composite plates,” International Journal of Solids and Structures, 2008, Vol. 45, PP 320–335.
[11] Yutaka Toi, Jong-Bin Lee, Minoru Taya, “Finite element analysis of superelastic, large deformation behavior of shape

memory alloy helical springs," Computers and Structures , 2004,Vol.82,PP 1685–1693.

[12] D.S. Burton, X. Gao, L.C. Brinson, "Finite element simulation of a self-healing shape memory alloy composite," Mechanics of Materials, 2006.,Vol. 38 ,PP 525–537.

[13] S.M.T. Hashemia, S.E. Khademb, "Modeling and analysis of the vibration behavior of a shape memory alloy beam," International Journal of Mechanical Sciences,Vol. 48, PP 44–52.

[14] J.M. McNaney , V. Imbeni , Y. Jung , Panayiotis Papadopoulos , R.O. Ritchie , "An experimental study of the superelastic effect in a shape-memory Nitinol alloy under biaxial loading," Mechanics of Materials, 2006., Vol. 35, PP 969–986,2003.

[15] Mauro Dolce, Donatello Cardone, Roberto Marnetto, "Implementation and testing of passive control devices based on shape memory alloys," Earthquake Engineering and Structural Dynamics, 2000, Vol.29, PP 945-968.

[16] Yu-Lin Han, Q. S. Li, Ai-Qun Li, A. Y. T. Leung, Ping- Hua Lin, "Structural vibration control by shape memory alloy damper," Earthquake Engineering and Structural Dynamics,2003, Vol.32, PP 483-494.

[17] J. Raghavan, Trevor Bartkiewicz, Shawna Boyko, Mike Kupriyanov, N. Rajapakse, Ben Yu, "Damping, tensile, and impact properties of superelastic shape memory alloy (SMA) fiber-reinforced polymer composites," Composites: Part B , 2010 ,Vol.41 PP 214–222.