Study and applications of shape memory alloys (SMA)

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***Abstract*- Shape Memory Alloys (SMAs) have been on the forefront of research for the last several decades. They have been used for a wide variety of applications in various fields. This chapter introduces the unique behavior that is observed in SMAs. Their characteristic properties and associated microstructural behavior will be discussed in detail. The different types of SMAs and some common applications will also be reviewed. Shape Memory Alloys (SMAs) refer to a group of materials which have the ability to return to a predetermined shape when heated. The shape memory effect is caused by a temperature dependent crystal structure. When an SMA is below its phase transformation temperature, it possesses a low yield strength crystallography referred to as Marten site (see Stress-Strain figure). While in this state, the material can be deformed into other shapes with relatively little force.**

The new shape is retained provided the material is kept below its transformation temperature. When heated above this temperature, the material reverts to its parent structure known as Austenite causing it to return to its original shape). This phenomenon can be harnessed to provide a unique and powerful actuator.

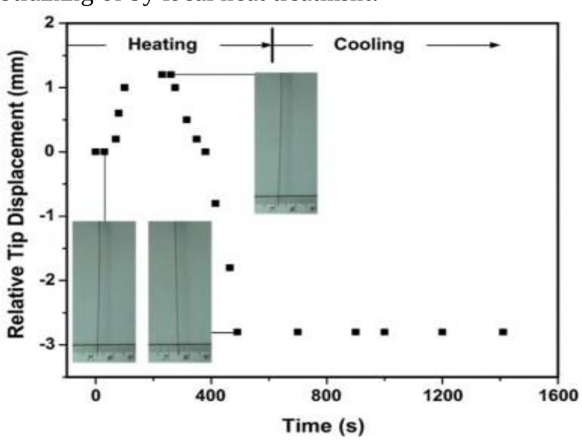
I. INTRODUCTION to SMA materials

Shape memory materials (SMMs) are featured by the ability to recover their original shape from a significant and seemingly plastic deformation when a particular stimulus is applied. This is known as the shape memory effect (SME). Superelasticity (in alloys) or visco-elasticity (in polymers) are also commonly observed under certain conditions. The SME can be utilized in many fields, from aerospace engineering (e.g., in deployable structures and morphing wings) to medical devices (e.g., in stents and filters). The most widely used shape memory material is an alloy of Nickel and Titanium called Nitinol. This particular alloy has excellent electrical and mechanical properties, long fatigue life,and high corrosion resistance. As an actuator, it is capable of up to 5% strain and 50,000 psi recovery stress, resulting in ~1 Joule/gm of work output. Nitinol is readily available in the form of wire, rod, and bar stock with transformation temperature in the range of -100º to +100º Celsius. More recently applications in Micro-Electro-Mechanical-Systems (MEMS) have led to the development of Nitinol in the form of sputter deposited thin film.

II .INTRODUCTION TO SHAPE MEMORY ALLOYS

Despite the fact that the SME had been found in an AuCd alloy as early as 1932, the attraction of this phenomenon was not so apparent until 1971, when significant recoverable strain was observed in a NiTi alloy at the Naval Ordnance Laboratories, USAToday a wide range of SMAs have been developed in solid, film and even foam shapes. Among them, only three alloy systems, namely NiTi-based, Cu-based (CuAlNi and CuZnAl) and Fe-based, are presently more of a commercial importance. A systematic comparison of NiTi, CuAlNi and CuZnAl SMAs, in terms of various performance indexes, which are of engineering application interest, has been done. NiTi should be the first choice since it has high performanceand good biocompatibility. The latter is crucial in biomedical applications, for instance stents and guide wires in minimally invasive surgery. Cu-based SMAs have the advantages of low material cost and good workability in processing, and some of them even have the rubber-like behavior after aging in a martensite state[8]. The SME in Fe-based SMAs is traditionally known to be relatively much weaker and Fe-based SMAs were most likely used only as a fastener/clamp for one-time actuation largely due to the extremely low cost. However, Tanaka *et al*. recently reported a ferrous polycrystalline SMA showing huge superelasticity (13%) and high tensile strength (over 1 GPa). All these SMAs are thermo-responsive, i.e., the stimulus required to trigger the shape recovery is heat. In recent years, good progress has been made in developing ferromagnetic SMAs, which are magneto-responsive.However, thermo-responsive SMA has matured more from the real engineering application point of view and many commercial applications have, so far, been realized.

With the current trend toward micro-electro-mechanical systems (MEMS) and even nano-electro-mechanical systems (NEMS), thin film SMAs (mainly NiTi based, produced by sputter deposition) have become a promising candidate for motion generation in these micron/submicron systemsThis is further supported by the finding that the SME even occurs in nano sized SMAs and a laser beam can be used for local annealing and/or controllable growth of SMA thin films. In addition to the SME, some of the SMAs also have the temperature memory effect (TME), so that the highest temperature(s) in the previous heating process(es) within the transition range can be recorded and precisely revealed in the next heating process. Partially different martensite after a thermal programming process is believed to be the underlying mechanism for the TME. Based on the same principle, a piece of SMA strip can be thermo-mechanically programmed to bend forward and then backward upon heating (This is a kind of phenomenon, known as the multi-SME, in which a piece of SMM recovers its original shape in a step-by-step manner through one or a few intermediate shapes. The multi-SME can be utilized to work virtually as a machine, but the fascinating point here is that the material is the machine. As there is only one intermediate shape, the behavior revealed in is the triple-SME. It should be pointed out that fundamentally this phenomenon shares no common ground as the multi-SME in a piece of SMA with a gradient transition temperature either through pre-straining or by local heat treatment.



Shape memory composites

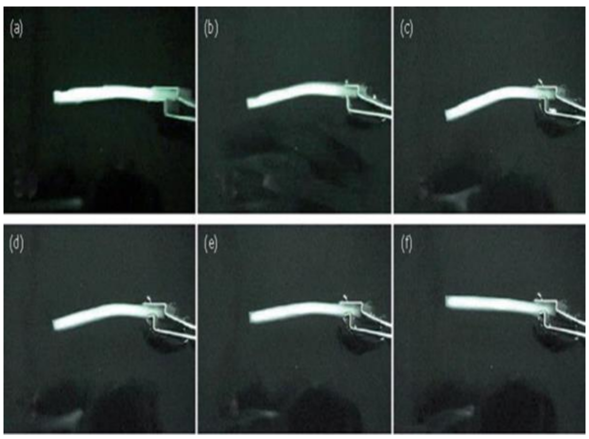
We have seen that SMPs can be synthesized/designed to have the required properties for a particular application. However, trial and error, as well as a strong background (professional knowledge and experience) is required. Shape memory composites (SMCs), which include at least one type of SMM, either SMA or SMP, as one of the components (e.g., reported by Miyazaki *et al*, Wei *et al*, and Tobushi *et al*.), can be handled comfortably by design engineers, if the properties of SMA/SMP are well known. Through careful design, together with the integration of other additional mechanism(s) (e.g., elastic buckling), more phenomena and new features can be realized in SMCs (for instance, self-healing of polymers as reported by Kirkby *et al*.).

Shape memory hybrids

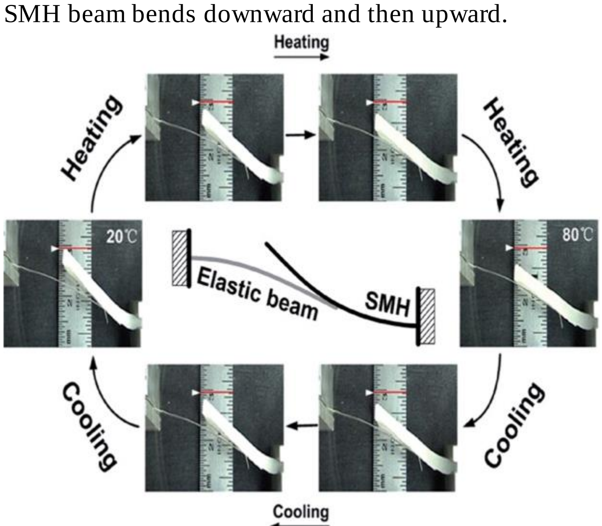
Shape memory hybrid (SMH) is a more accessible and flexible approach for ordinary people, even with only limited scientific/engineering background. SMHs are made of conventional materials (properties are well-known and/or can be easily found, but all without the SME as an individual). Hence, one can design a SMM in a do-it-yourself (DIY) manner to achieve the required function(s) in a particular application.

Similar to SMPs, SMHs are also based on the dual-domain system, in which one is always elastic (the elastic domain), while the other (the transition domain) is able to change its stiffness remarkably if a right stimulus is presented. However, the selection of the transition domains for SMHs must follow the principle that any possible chemical interaction between the elastic domain and transition domain should be minimized, if impossible to be fully avoided. This is even simpler than the hybrid organic-inorganic moiety system studied by Knight *et al*.. As such, we can precisely predict the thermo-mechanical response (or any others of our concern) of a SMH based on the material properties of these two domains. The advantages of SMHs are apparent. For instance, the elastic domain can be selected to meet the requirements on the stiffness and amount of shape recovery ratio of a SMH, while the required type of stimulus can be realized by selecting a right material for the transition domain. Furthermore, the fabrication/synthesis process is based on the well-known properties of the materials for the domains, which is straightforward. Thus, it is manageable by almost anyone even without very much experience.

For demonstration purposes, we have developed a silicone based SMH system. All features found in conventional SMAs and SMPs, namely, dual-SME, triple-SME), two-way reversible SME thermo-responsive (including by means of joule heating through passing an electrical current), thermo/moisture-responsive, etc. have been reproduced. A narrow shape recovery temperature range within 5°C has been achieved. This concept has been further extended into the design of pressure-responsive SMH, thermo (upon cooling or at extremely high temperature)-responsive SMH with some success.



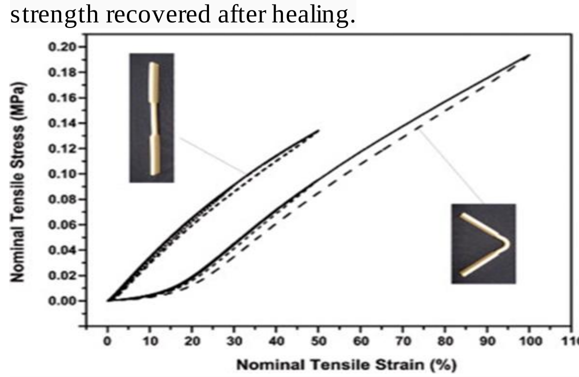
Triple-SME. Upon immersing into hot water, the SMH beam bends downward and then upward.



Two-way SME. Upon heating (top half, from left to right), the SMH beam pushes down the elastic beam (see inset for the illustration of set-up). Subsequently, upon cooling (bottom half, from right to left), the elastic beam pushes the SMH beam upward.

In addition, a rubber-like (not only in the high temperature range as superelastic SMAs, but also within the full concerned application temperature range at both below and above the transition/shape recovery temperature, and more importantly with tiny hysteresis .SMH has been demonstrated. Regardless of the rubber-like feature, after cooling, the SMH remains over 90% of the amount of the pre-strain when it is stretched to double its length at a high temperature. Subsequently, full shape recovery is instantly observed upon heating in hot water. More interestingly, this SMH has the real crack healing function upon heating, but not just for shape recovery and crack closure as reported by Files *et al*., Huang *et al*. and Xiao *et al*..

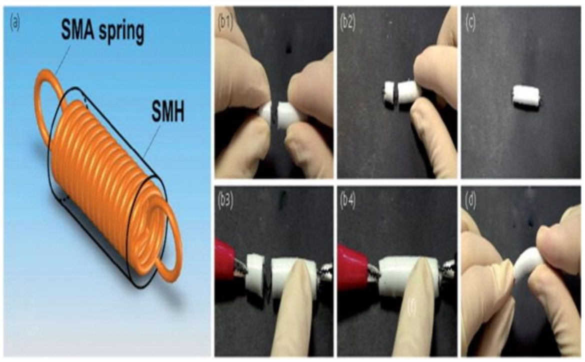
Unlike the traditional polymer self-healing, such as reported by Kirkby *et al*, which requires curing agent for polymerization and can only be used once, after more than ten cracking/healing cycles, this SMH does not show any degradation at all in terms of the strength recovered after healing.



Rubber-like SMH (in original and pre-bent shapes) under cyclic loading at room temperature (about 22°C) and at high loading speed.

For a more effective demonstration of the repeatable self-healing function, we fabricated a piece of cylindrical SMH with a piece of SMA spring embedded inside, as illustrated in temperature. Upon heating, it will return to its original shape/length. We pulled the SMH until fracture into two pieces as shown in Fig. (b1). The SMA spring was also stretched which resulted in a big gap between the two pieces of SMH even after the pulling force was fully removed (Fig. b2). Subsequently, we passed an electrical current through the SMA spring (Fig. b3). The SMA was joule heated for shape recovery so that the gap was closed (Fig. b4). In the mean time, the SMH was also heated to achieve self-healing, with assistance from the compressive force generated by the SMA spring during joule heating.

After cooling back to room temperature, the SMH became one single piece again (Fig. c). There was no apparent crack even when it was bent severely as shown in Fig. (d). This cracking-healing procedure can be repeated many times.

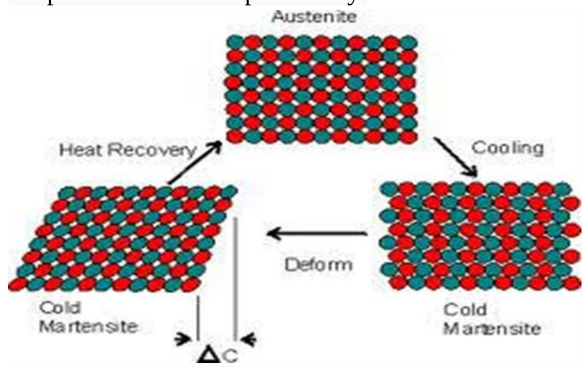


Self-healing of SMH. (a) SMH with an embedded SMA spring inside (illustration); (b1-b2) pulling SMH till fracture; (b3-b4) joule heating SMA coil for self-healing; (c) healed sample; (d) healed sample in bending.

III. WORKING OF SMA

The shape memory effect is made possible through a molecular rearrangement which is through a solid state phase change, which occurs in the shape memory alloy. Typically when one thinks of a phase change a solid to liquid or liquid to gas change is the first idea that comes to mind. A solid state phase change is similar in that a molecular rearrangement is occurring, but the molecules remain closely packed so that the substance remains a solid. a temperature change of only about 10°C is necessary to initiate this phase change in most of the shape memory alloys. The two phases, which occur in shape memory alloys, are Martensite(soft), and Austenite(hard). Martensite, is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures.

The molecular structure in this phase is twinned; the configuration is shown in the middle of Figure 2. Upon deformation this phase takes on the second form shown in Figure 2, on the right. Austenite, the stronger phase of shape memory alloys, occurs at higher temperatures. The shape of the Austenite structure is cubic, the structure shown on the left side of Figure 2. The un-deformed Martensite phase is the same size and shape as the cubic Austenite phase on a macroscopic scale, so that no change in size or shape is visible in shape memory.



Microscopic and Macroscopic Views of the Two Phases of Shape Memory Alloys:

The temperatures at which these phases begin and finish forming are represented by the following variables: Ms, Mf, As, Af. As we increase the loading placed on a piece of shape memory alloy increases the values of these four variables as shown in Figure 3. The initial values of these four variables are mainly dependent on the composition of the wire (i.e. the amount of each element present.)

Shape Memory Effect

When the temperature of a piece of shape memory alloy is cooled to below the temperature Mf the shape memory effect is observed. At this temperature the alloy is completely composed of Martensite which can easily be deformed. After distorting the Shape Memory Alloy the original shape can be recovered simply by heating the wire above the temperature Af. The heat transferred to the wire is the power driving the molecular rearrangement of the alloy, similar to heat melting ice into water, but the alloy remains solid. The deformed Martensite is now transformed to the cubic Austenite phase, which is configured in the original shape of the wire.

Shape setting in NiTi alloys

The Shape Memory Effect must be “programmed” into the SMA alloys with an appropriate thermal procedure. Basically the procedure is simple; the alloy is formed into desired austenite form and heated into a specific temperature. The temperature and the duration of the heating depend on the alloy and the required properties.

For a NiTi alloy, a temperature of 400 °C and heating duration of 1…2 minutes can be sufficient, but generally 500 °C and over 5 minutes are used. Higher heat treatment times and temperatures will increase the actuation temperature of the element and often give a sharper thermal response, but may reduce the maximum output force.

Although straightforward procedure, the parameters for the heat treatment are critical and often require experimental determination before the requirements can be met.

Two-way Shape Memory Effect

The ability of SMA to recover a specific shape upon heating and then return to an alternate shape when cooled (below the transformation temperature) is known as two-way shape memory. However, there are limitations that reduce the usability of the two-way effect, such as smaller strains (2 %), extremely low cooling transformation forces and unknown long-term fatigue and stability. Even slight overheating removes the SME in two-way devices. Setting shapes in two-way SMAs is a more complex procedure than the one used with oneway SMAs.

Superelasticity

SMA also shows a superelastic behaviour if deformed at a temperature which is slightly above their transformation temperatures. This effect is caused by the stress-induced formation of some martensite above its normal temperature. Because it has been formed**.**

Cycling effects

Cycling (repeated use) affects the properties of the SMA. This must be considered when actuators are designed for a repeated/continuous use. Cycling causes the maximum available deformation, force and hysteresis to decrease, while the transformation temperatures increase gradually.

The reduction in the maximum strain and output force must be taken into account when actuators are designed. For NiTi alloys, only 2…3 % strain and stress level of 100...150 MPa are available after 100 000 cycles.

Applications:

Titanium – nickel (Ti Ni) based shape memory alloys are used in a wide range of applications. They are especially practical as thin film actuators because large work output. Ti Ni film has been developed for use in miniature actuators for micro valves micro relays optical switches and also for building small implantable medical devices. Shape Memory metals that were developed by NASA for the space industry, and have been used for increasing applications down on earth. The following is a list of just some of the applications that shape memory alloys have been used for.

Bones: Broken bones can be mended with shape memory alloys. The alloy plate has a memory transfer temperature that is close to body temperature, and is attached to both ends of the broken bone. From body heat, the plate wants to contract and retain its original shape, therefore exerting a compression force on the broken bone at the place of fracture. After the bone has healed, the plate continues exerting the compressive force, and aids in strengthening during rehabilitation. Memory metals also apply to hip replacements, considering the high level of super-elasticity. The photo above shows a hip replacement.

Reinforcement for Arteries and Veins: For clogged blood vessels, an alloy tube is crushed and inserted into the clogged veins. The memory metal has a memory transfer temperature close to body heat, so the memory metal expands to open the clogged arteries.

Dental wires: used for braces and dental arch wires, memory alloys maintain their shape since they are at a constant temperature, and because of the super elasticity of the memory metal, the wires retain their original shape after stress has been applied and removed.

Anti-scalding protection: Temperature selection and control system for baths and showers. Memory metals can be designed to restrict water flow by reacting at different temperatures, which is important to prevent scalding. Memory metals will also let the water flow resume when it has cooled down to a certain temperature.

Fire security and Protection systems: Lines that carry highly flammable and toxic fluids and gases must have a great amount of control to prevent catastrophic events. Systems can be programmed with memory metals to immediately shut down in the presence of increased heat. This can greatly decrease devastating problems in industries that involve petrochemicals, semiconductors, pharmaceuticals, and large oil and gas boilers.

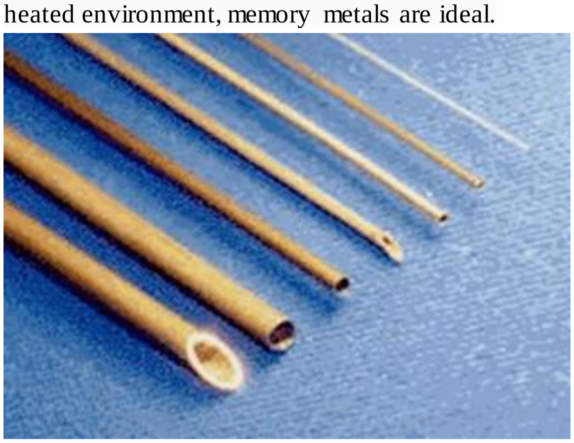
Golf Clubs: a new line of golf putters and wedges has been developed using_____. Shape memory alloys are inserted into the golf clubs. These inserts are super elastic, which keep the ball on the clubface longer. As the ball comes into contact with the clubface, the insert experiences a change in metallurgical structure. The elasticity increases the spin on the ball, and gives the ball more "bite" as it hits the green.

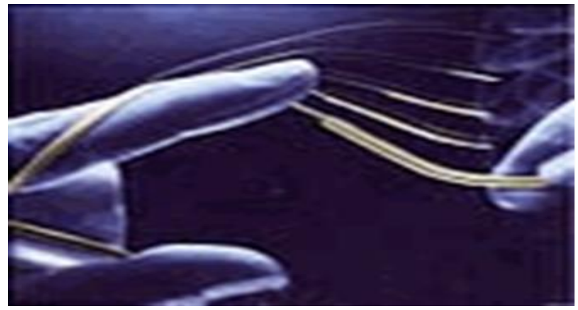
Helicopter blades: Performance for helicopter blades depend on vibrations; with memory metals in micro processing control tabs for the trailing ends of the blades, pilots can fly with increased precision.

Eyeglass Frames: In certain commercials, eyeglass companies demonstrate eyeglass frames that can be bent back and forth, and retain their shape. These frames are made from memory metals as well, and demonstrate super-elasticity.

The photo to the right demonstrates flexible eyewear.

Tubes, Wires, and Ribbons: For many applications that deal with a heated fluid flowing through tubes, or wire and ribbon applications where it is crucial for the alloys to maintain their shape in the midst of a heated environment, memory metals are ideal.





IV. ACTUATOR APPLICATIONS

Various SMA actuators such as wire, compression and tension springs and cantilever had been used in both electrical and thermal actuation systems. Utilizing direct I2R heating of electrical current, one of the earliest volume application was for the remote opening and closing of louvers on automobile fog lights which provided protection against damage from road debris. Using indirect heating, an SMA device, the Frangibolt, is used for space deployment. The bolt employs a pre-compressed cylinder which surrounds the bolt, and when heated, fractures the bolt at a machined notch. Deployment using Frangibolt avoids the use of explosive devices which are vulnerable to premature activation from electrical storms.

Thermal actuators of SMA are used as both sensors and actuators. An example now in production is a NiTiCu spring for controlling the opening of the door in a self-cleaning oven. For a period the Daimler Benz company used a similar spring to control the flow of transmission fluid in an automatic transmission during the period of initial warm up. SMA thermal actuators are also used in domestic safety devices. One of the most frequent causes of injury in the household and in hospitality buildings such as hotels is excessively hot water in the sink, tub and shower. An antiscald valve is now being produced which employs a small cantilever NiTiCu element which, when heated to 480^0 C, the temperature above which scalding will occur, closes the valve. The valve automatically reopens when the water temperature is safe [8]. A photograph of an antiscald shower valve.. An industrial safety valve actuated by a NiTiCu spring is the Firecheck. Developed originally for the semiconductor industry, the valve when heated to a predetermined temperature, vents the air valve or manifold which controls the flow of processing gases used in the manufacture of semiconductors, closing the flow of gases which are either toxic or highly flammable.

The advantage of this design is the ability to check the valve operation and then to reset it for use. In addition to the semiconductor industry, these valves are finding applications in petroleum and petrochemical plants where there is constant danger of fire. Another recent SMA safety device is a thermally activated current interrupt mechanism for protecting high energy density batteries such as lithium ion cell from uncontrollable temperature increase due to overcharge or short circuit [9]. As shown in Figure 13, a bent NiTi disc actuator is placed in-between electrical contacts, which when exposed to over-temperatures regains its flat shape and breaks the electrical pathway. Although bimetallic actuators can also be used for this application, NiTi actuators offer the advantage for size miniaturization. No discussion of SMA actuator applications would be complete without mention of micro electro mechanical devices, MEMS. These devices have grown from laboratory fabrications to large scale manufacturing, principally as a result of the introduction of semiconductor etching technique which make possible MEM units with micron size dimensions. Mini-valves, one of the more important MEM device geometry's have been developed with performance and pressure capabilities matching electrically actuated valves orders of magnitude greater in size and weight. NiTi films are sputter-deposited on silicon substrates and then etched to form the actuator element. The film is then back etched to separate it from the silicon substrate. Mini-valves are then assembled with an "O" ring and a biasing element and two etched silicon top and bottom plates to create the completed valve with typical dimensions of 15mmx9mmx7.5mm. A pneumatic mini-valve with enclosure. MEM devices are used for the control of liquid and gas flow in manufacturing processes, as pneumatic controls in instruments, and, potentially, for medical delivery systems. Other MEM devices are being developed for various optical and electro optical systems

V. CONCLUSION

SMA's have the potential to be used effectively in seismic regions.now a days there is a need of this kind of materials for many applications.by using of these shape memory alloythere is a chance to avoiding the cost of spare parts and equipments because when these materials are heated it becomes to its original shape. However, the practical applications of these alloys have just been started. The background is introduced in this section. The first objective for application was substitution for Ni-Ti alloys. The Fe-SMAs certainly have lower cost performance. But properties such as one-way operation and lower recovery strain make them unsuitable for small components in a same way as the NiTi SMAs are mainly used.