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"MONOLITHIC SHAPE MEMORY ALLOY ACTUATORS": A NEW CONCEPT FOR DEVELOPING SMART MICRO-DEVICES

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ABSTRACT

In micro-robotics and for micro-systems, one cannot simply scale down conventional actuators. Specific difficulties like friction forces between parts and the assembly have to be considered carefully and need a special design strategy adapted to this "micro-world". Shape Memory Alloys (SMA) have strong potential in micro actuators. So far, most of SMA devices used the SMA material as a part of a mechanical system, which raised several problems when scaling down. In this paper, a concept of monolithic SMA micro-devices, which consists in considering the SMA as a mechanical system by itself, is presented. Several applications are shown to illustrate this concept.

INTRODUCTION

SMA are one of most interesting materials for micro engineering: SMA actuators are "smart" (i.e. they can react to their environment), solid-state, easy to actuate and have the highest force/weight ratio among all known actuators. Several SMA micro-applications have been developed. Among them, K. Ikuta [1] uses an antagonistic design where an SMA flat spring deforms its counter part to actuate a micro-gripper; M. Kohl et al. [2] have developed micro-valves with stress-optimized SMA actuators cut out from a cold-rolled sheet and S. Aramaki et al. [3] have designed a tube-like micromanipulator actuated with SMA plates.

Unfortunately, the shape memory effect is not intrinsically reversible. If no special treatment on the material has been carried out, an external force must be applied to deform the material after the shape recovery. Therefore, a pullback spring is often used to deliver this external force. Moreover, to initiate the shape change, a mechanical pre-straining is also required.

In micro-robotics, adhesion forces like electrostatic forces, which can be neglected for larger systems, become more important. Therefore, the assembly of small components becomes a tough and expensive job. Therefore, the smaller the device, the harder it is to introduce a simple pullback spring or to pre-strain the structure. Moreover, additional effects like friction must be considered carefully.

To address the challenge of miniaturization, we have developed a new concept for SMA micro-devices [4]. This concept consists in considering the SMA not only as a part of a mechanism but rather as a complete mechanical system. Therefore, the device will only consist of one single piece of material, which we call "monolithic SMA micro-device".

To obtain a reverse motion without external bias force, several solutions have been proposed [5] such as the use of the Two-Way Shape Memory Effect (TWSME), a "push-pull" design or the local heating and local annealing. All these designing methods are part of the *concept of monolithic SMA devices* and will be presented in this paper and illustrated by some examples of applications.

THE CONCEPT OF MONOLITHIC MICRO-DEVICES

Basic idea

In general, active mechanical systems consist of a force generator, a coupling device, a transmission system, a guiding system and an output element. A “smart SMA mechanism” should have the same elements and functionalities. A monolithic design tries to integrate all these functions within the same piece of material.

As mentioned before, without special treatment, the shape memory effect is not intrinsically reversible. The martensite must be deformed preliminarily to produce a shape change while heating up to the parent phase (austenite). The easiest way is to use a pullback spring, which deforms the SMA material. In a monolithic design, one region of the material itself has to produce this biasing force. Several solutions have been proposed to do so [5] and are summarized below.

The Two-Way Shape Memory Effect (TWSME) applied on small devices

Thanks to a thermo-mechanical treatment of the material, one can introduce internal stress, which will generate preferentially oriented martensite variants on cooling. In a certain way, a second shape is “memorized” within the material. A micro-gripper for micro-endoscopes assembly has been developed using this principle [6] (fig.1). The training process used was a constrained thermal cycling of deformed martensite.

The micro-gripper is laser cut using a Nd-Yag slab laser in fundamental mode. The basic material is a sheet of NiTiCu with a thickness of 0.15 mm. The material is annealed at 515°C during 15 min. During the training process, a shaft is used to deform the gripper up to 4 to 5 %. The maximum motion range is reached after 50 cycles. A residual plastic deformation is observed and has to be considered while designing the gripper. For a hinge thickness of 70 µm, a range of motion of 150 µm is obtained (figure 2) and a grasping force of 16 mN is measured. The force in the opposite direction is approximately 4mN. Fatigue experiments consisting in grasping and releasing cycles have shown that the motion loss saturates after 100’000 cycles. After 200’000 cycles, the motion loss are 10 % and the loss after 1’000’000 cycles are estimated to be the same. TWSME is well adapted to micro-grippers because it has not to deliver any force during opening.

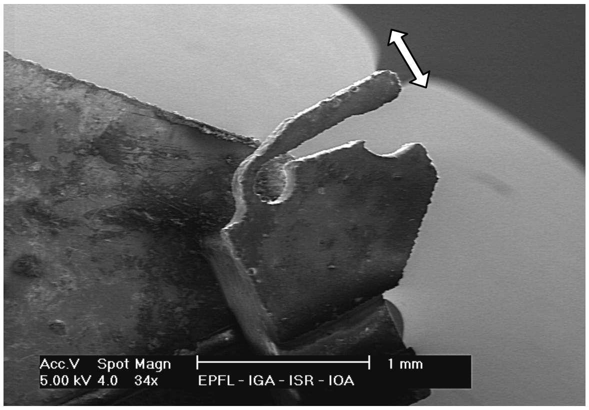

Fig.1 – The TWSME micro-gripper for lens assembly

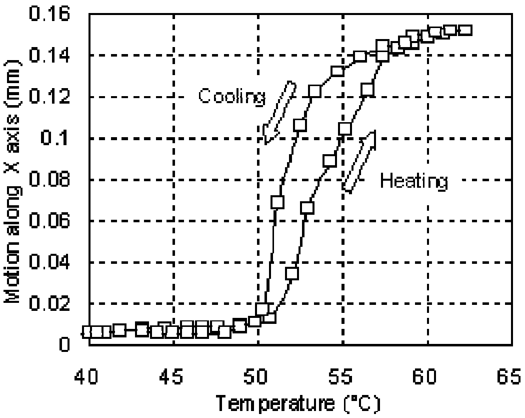

Fig. 2 – Range of motion versus temperature

Local heating of the material

One part of the material is in the martensitic state while the other is in the austenitic state. The martensitic part can be used as a bias spring. This method requires a careful definition of the electrical path and of the heat transfer within the structure. A realization is shown on figure 3.

This device is an optical micro-switch. The motion can be compared to a semaphore. After cutting the bridges (dash lines) used for manipulation, the structure is pre-strained (#3). When a current is passing through the structure, the active part (#1) is heated up to the transformation temperature and then pulls down the shutter (#4). On cooling down, the bias spring (#2) pulls back the structure causing the reverse motion.

The range of motion of the shutter is about 190 μm. The switching time in one direction is less than 50 ms for a power consumption of 5 mW.

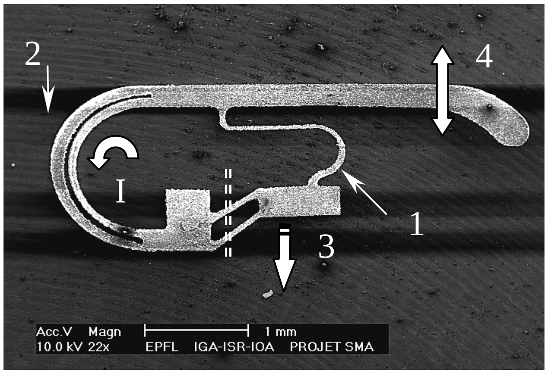

Fig. 3 – A micro-switch: the reversible motion is obtained by a locally heated actuating part.

The fabrication process is quite similar to the one used for the micro-gripper presented above. In that case, a 20-μm thick sheet of NiTiCu is used with the same annealing conditions as described before.

Antagonistic or "push-pull" design

The principle is to heat up only one part of the material at a time. Depending on which part is heated, the device will move in one direction or the opposite. Each actuating part is working against another actuating part.

A one axis monolithic linear stage has been realized using a push-pull design (fig. 4). This structure has been laser cut with a Nd-Yag Slab laser from a 0.2 mm sheet of NiTiCu fully annealed at 515°C for 15 min.

Each leaf spring (#3 and #3*) is pre-strained by the movement of (#1, #1*) in order to obtain a reorientation of the martensite. When passing a current through one spring (#3 or #3*) and the fixed part of the structure (#2), the spring pulls the mobile part (#5) in its direction. As the springs are mounted opposite to each other, a two-way motion can be obtained. To prevent an unwanted motion due to machining imperfections and non-uniform heating, a guiding system (#4) has been added. This guiding system consists of two serial-mounted four-links parallel linear stages.

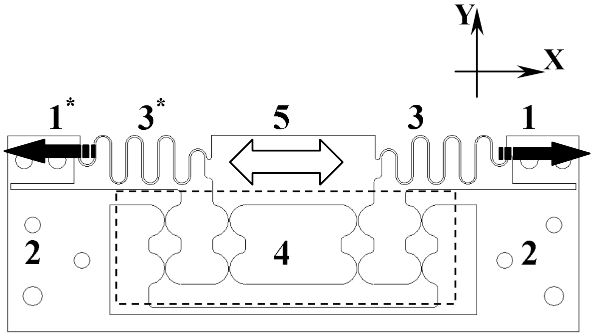

Fig. 4 – One-axis translation stage with integrated guiding system
(dimensions are 36 x 12.4 mm, the thickness of the sheet is 0.2 mm)

The stiffness in the motion direction (X) is about 500N/m when only one spring is powered. The range of motion varies depending on the pre-strain level between 0.2 mm to 0.5 mm. The maximum recovery force is about 0.2 N. Typical performances are shown in figure 5 and figure 6.

Fig. 5 – Motion range versus current passing through the springs.

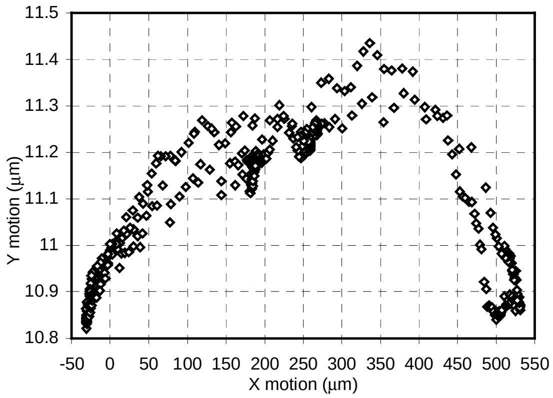

Fig. 6 – Movement of the output part (#5, on fig 4) in the plane. X is the direction of movement of the linear stage.

Local annealing of SMA (LASMA)

The key idea is to select and anneal the place where a shape memory or superelasticity is desired and to let the remaining parts non-annealed. With this method, different mechanical states as well as active and passive parts can be introduced within a single piece of material [6].

This method can be applied on SMA thin film, on cold-rolled sheets, on cold-drawn wires or others materials which have been work-hardened. In the case of sputter deposited thin films, the as-deposited material is amorphous and an annealing process is required to crystallize the material. In the case of the cold-rolled sheets, the annealing process reduces the amount of internal stress. The mechanical behavior of cold-rolled sheet before and after annealing in a furnace is shown in figure 7.

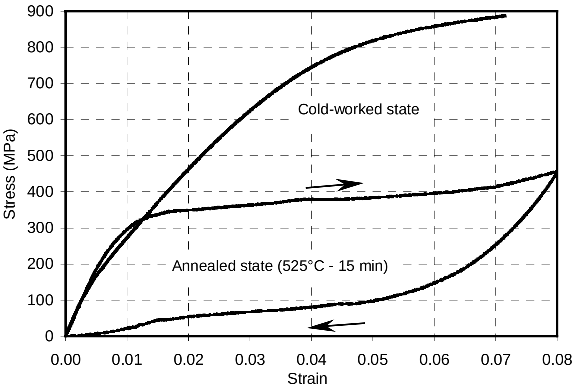

Fig. 7 – Stress-strain behavior of a cold-rolled sheet before and after annealing in a furnace.

The local annealing can be performed using an electrical current or a laser [6]. Nevertheless, the annealing by laser is the most versatile and flexible method, which can be applied to nearly any kind of shape. For an on-line control of the annealing process, several methods have been tested. Among them, the resistance measurement during annealing seems to be the most efficient, although this method requires an electrical connection, which does not exist in all cases. An alternative way, but much more expensive and complex, is to use an infrared camera to control directly the temperature distribution in the element.

Figure 8 shows the resistance behavior of a thin film micro-device during the laser annealing process. The micro-device is made out of a 10 µm sputter-deposited thin film. This thin film is amorphous after deposition. A laser pulse of 0.5 s is applied. Three different domains can be seen on the resistance curve. The first one is assumed to be the consequence of the temperature raises (region A). Then, the resistance decreases (region B). According to us, the crystallization process occurs during this period. The last part (region C) seems to be the heat dissipation.

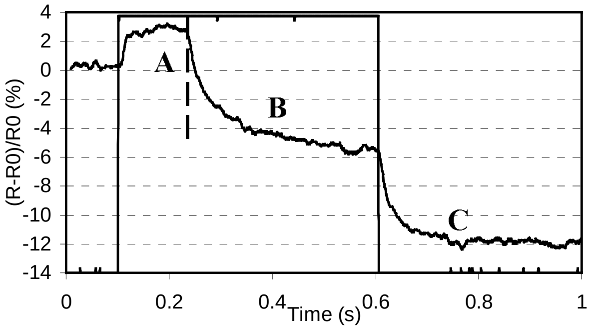

Fig. 8 – Resistance change vs time during the annealing process. A power step is applied.

Moreover, in the case of laser annealing thin films, we have noticed that the annealing induced a shape change of heat-affected zone: the material is expanded. A close examination has demonstrated that the material has not been locally melted. That means that the LASMA process can be used to introduce at the same time, a pre-strain within the material.

Figure 9 presents a Differential Scanning Calorimetric (DSC) measurement performed on two samples cut out from the same piece of material.

The first one has been laser-annealed (inner curves) while the second one has been annealed under vacuum in a furnace at 800°C during 30 min. Some differences resulting from the annealing method can be pointed out. Peaks on the LASMA sample are wider than for the furnace-annealed one. This might be due to the local non-homogeneity of the temperature distribution around the laser impact. The hysteresis on the LASMA sample is shorter than on the furnace annealed-one (about 5°C less). The different cooling condition might explain this phenomenon (the furnace-annealed sample has not been quenched).

This new technology has been applied for the development of a micro-switch. This micro-switch is shown in figure 10. The device was cut out a 4-microns thick sputter deposited thin film of binary Ni-Ti. After being removed, from the substrate, the thin film has a reproducible curvature. This curvature is used to create a motion out of the plane. The local annealing is performed on the middle bar, which expands and bends the structure out of the plane. The biasing stiffness is given by the non-annealed part of the structure (outside bar). Therefore, the LASMA process itself gives the mechanical pre-strain. The range motion is in the order of 50 µm. The bandwidth defined at –3dB varies between 5 and 10 Hz

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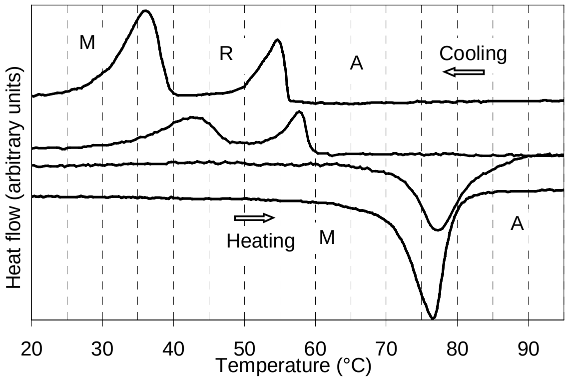

Fig. 9 – DSC curves of a thin film annealed by laser

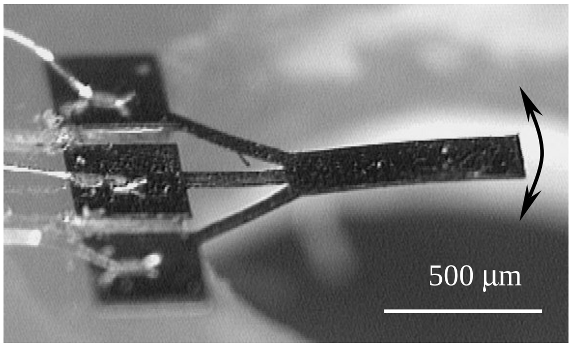

Fig. 10 – Micro-switching device: the middle bar has been locally annealed

This annealing process has also been used for developing new kinds of micro-grippers machined on cold-rolled sheet [6].

DESIGNING METHODS OVERVIEW

Several methods for producing a reversible motion within a monolithic SMA device have been presented. The best method to apply will depend on the applications specifications. The table below summarizes some known advantages and limitations of the different methods.

Special treatments (ex. ion implantation) or fabrication methods (ex. melt spinning) create an internal “two-way shape memory effect”. These special treatments have not been mentioned below because they produce a global effect in one direction like bimetal actuators and therefore, can only be used for a limited range of applications like micro-valves for example.

Designing methods	*Material state*	*Pre-Strain*	*Advantages*	*Limitations*
TWSME	Annealed	No	Actuation methods Low volume required	Low force in one direction Training process
Local heating	Annealed	Yes	No local treatment	Low stiffness of martensite Special heating path
“Push-Pull”	Annealed	Yes	High range motion	Volume required
Local hardening*	Annealed	No	Stamping process, well known in watch industry	Miniaturization
LASMA	Amorph. Work-Hardened	No Yes	High integrated design Different annealing condition	Managing the annealing process

* The local hardening is the exact reverse effect of the LASMA applied on cold-rolled sheet.

CONCLUSION

Designing micro-devices requires suitable methods, which take into account the small size of components and the specific problems related to the “micro-world”. The concept of monolithic SMA micro-devices helps to design small-devices and is a step forward miniaturization and higher integration. Nevertheless, it requires new solutions to create reversible motion effect and therefore make the monolithic SMA an actuator. Among all the proposed methods, the laser annealing of SMA is the most promising.

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