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Shape memory alloys for microsystems: A review from a material research perspective

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Abstract

One important challenge of microsystems design is the implementation of miniaturized actuation principles efficient at the micro-scale. Shape memory alloys (SMAs) have early on been considered as a potential solution to this problem as these materials offer attractive properties like a high-power to weight ratio, large deformation and the capability to be processed at the micro-scale. This paper reviews various attempts made to introduce SMAs in microsystems as well as design principles for SMA microactuators. It presents the status of current research and potential developments from a material research perspective.

Keywords: Shape memory alloy; Thin films; Microactuators; Review; Ni–Ti; Nitinol; MEMS; Microsystems

1. Introduction

Micro-electromechanical systems (MEMS, see for instance [1]) (also referred to as microsystems) have flourished during the last decades to rapidly penetrate a broad range of applications like automotive parts, consumer products or biomedical devices.

Microsystems perform sophisticated tasks in a miniaturized volume. Shaping or analyzing light signals, mixing, processing or analyzing ultra-small volumes of chemicals, sensing mechanical signals, probing gas, sequencing biomolecules are common operations realized by these tiny machines.

Rationales for the use of microsystems are numerous. The reduction of consumables (e.g., less chemicals in Lab-on-a-Chip), a faster response time (e.g., airbag sensors), enhanced portability (e.g., RF-MEMS), higher resolution (e.g., Inkjet printer head), higher efficiency (e.g., micro-chemical reactor), less-volume, etc. are typical benefits sought.

Conventional actuating principles used at the micro-scale do not scale down favorably from a manufacturing as well as from an efficiency point of view. Therefore, there is a need for actuating principles that can be easily integrated and miniaturized and that can generate enough power output. In that context, shape memory alloys (SMAs) have early on been considered as an actuating material of choice: Over the last decade, micro-grippers [2–5], micro-valves and micro-pumps [6–9], spacers [6], actuated micro-endoscope [10], nerves clamp [12], tactile displays [11] are a few examples which have been reported.

Despite these numerous developments, the impact of SMAs on MEMS technologies remains limited to a handful of applications. The lack of comprehensive design rules, unresolved materials issues and technological barriers or simply the existence of competitive but yet simpler technologies have limited their broad acceptance in microsystems. The high output force is almost systematically cited to support the use of SMAs in microsystems. While it is an important argument, it has to be balanced with known limitations of SMA actuators: a poor bandwidth (<100 Hz) and the lack of intrinsic reversibility. While the limited bandwidth is a direct consequence of the fact that SMA actuators are driven by heat transfer, the lack of intrinsic reversibility can be addressed through design as it will be shown later on.

This paper provides a critical overview on the use of SMA materials for microsystems. As this review is intended for a broad audience, a brief introduction on SMAs is first proposed. It is followed by a review of SMA microsystems design principles. The emphasis is put on material issues as seen from an actuator design perspective. Finally, the paper concludes with future prospects. Specific issues related to material processing

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and in particular thin-film processing are not addressed. Details on these particular aspects can be found for instance in [3,13–15].

2. Shape memory alloys: definition and design objectives

Shape memory alloys (SMAs) are materials that have two (or sometimes several) crystallographic phases for which reversible transformations from one to the other occur through diffusion-less transformations (the so-called "reversible martensitic transformations" [16]). Two remarkable effects are related with the phase change: the shape memory effect and the superelasticity. As these effects have been extensively documented elsewhere (see for instance [16–18]), we just briefly summarize their main features from a microsystems design point of view.

The superelasticity occurs when the martensitic phase transformation is stress-induced at a constant temperature. The transformation is characterized by a plateau and a hysteresis upon unloading. The magnitude of reversible 'pseudo-elastic strain' can be as high as 8% or even more for single crystals.

The shape memory effect (SME) refers to the ability of the material, initially deformed in its low-temperature phase (called "martensite"), to recover its original shape upon heating to its high temperature phase (called austenite or "parent phase"). The SME is a macroscopic effect of thermally induced crystallographic phase changes. An important aspect is that it is a one-way occurrence. This phenomenon is illustrated in Fig. 1.

Let us consider a SMA material initially in its parent phase (β) (step 1 in Fig. 1). On cooling, the material transforms to the martensitic phase (step 2). This phase is characterized by a lower symmetry than the parent phase and has different possible crystallographic orientations (called variants). Multiple martensitic variants with different crystallographic orientations (for instance A, B, C and D in Fig. 1) nucleate so that the deformation strain energy is minimized (step 1 to step 2). These particular variants are called "self-accommodating". From a macroscopic point of view, there is no change of shape as the volume globally remains the same. If a stress is applied on the material (step 3 in Fig. 1), variants that have a favorable orientation "grow" at the expense of less favorably oriented ones. This effect is called "de-twinning" as self-accommodating variants disappear. Once the stress is released (step 4), as the newly formed martensite variants are stable, the material retains the applied deformation (ε_0 in Fig. 1). Upon heating above the phase transformation, the parent phase – that has a higher symmetry – nucleates and progressively replaces the martensite causing the disappearance of the apparent deformation (ε_0). The ability to recover its original shape (i.e. the shape corresponding to the parent phase) is the shape memory effect. Cooling again with no applied stress, self-accommodating variants will form (step 2) and no macroscopic change of volume will be observed.

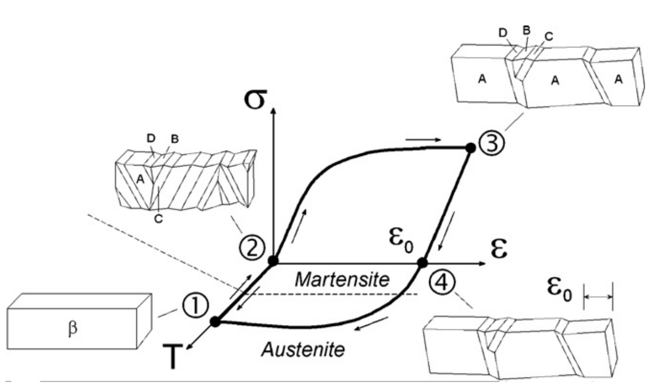

Fig. 1. Illustration of the shape memory effect ("one-way").

From a macroscopic shape change point of view, the SME is therefore not intrinsically reversible: a change of shape is only observed if non-self-accommodating variants have nucleated. The design objective of an SMA actuator is therefore to achieve a reversible macroscopic shape change, i.e. to have the capacity to switch between two shapes. From a microstructure point of view, it is equivalent to have non-self-accommodating martensitic variants nucleating upon cooling.

To provide the necessary reversible shape memory effect, two approaches have been explored which we classify respectively as intrinsic and extrinsic methods.

Intrinsic methods consist of modifying the material microstructure so that certain martensitic variants orientations will preferably nucleate upon cooling. Extrinsic methods refer to the addition of an "external" element coupled to the SMA material that provides the required stress to induce stress-oriented variants. A third method is based on monolithic design that is a kind of combination of intrinsic and extrinsic methods.

3. Intrinsic methods: tailoring the microstructure

The martensitic variants nucleation is influenced by oriented precipitates and oriented defects. Oriented defects lead to the two-way shape memory effect (TWSME). Different thermo-mechanical processes that result in a TWSME have been identified [19–21] like severe deformation of the martensitic phase, thermo-mechanical cycling under constraints and isothermal mechanical cycling in the austenite phase. These thermo-mechanical processes that lead to the TWSME are also called "training processes" as the material "memorizes" progressively a new shape.

A micro-gripper that uses the TWSME [5,22] is shown in Fig. 2. The millimeter-size device consists of a single piece of metal laser-cut from a 180 μm-thick Ni–Ti–Cu cold-rolled sheet. It is used by a micro-endoscope manufacturer to assemble sub-millimeter lenses.

The principle is shown in Fig. 2 ('operating mode'): upon cooling the gripper jaw opens and closes up on heating. The heat is provided by a simple resistive layer onto which the gripper is glued to. To achieve the reversible finger motion, the gripper is deformed and constrained so that it cannot recover its original shape (step 2 in Fig. 2). About hundred thermal cycles are applied between the austenite and martensite phases. During cycling, stress builds up in the finger hinge introducing permanent oriented defects. The micro-gripper shows excellent fatigue properties (>200,000 cycles) [22] and stability regarding mechanical perturbations [23].

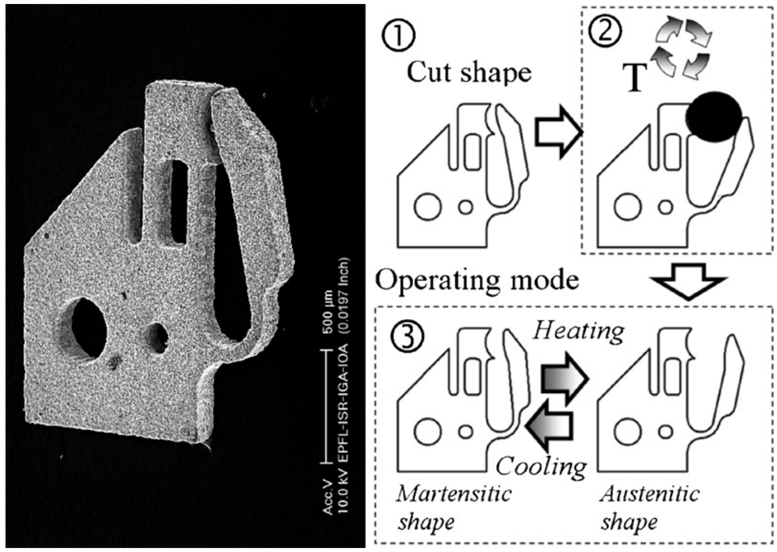

Fig. 2. (Left) Scanning electron micrograph of the TWSME micro-gripper for sub-millimeter lens handling [22]. (Right) The desired shape is laser cut (1) and thermo-mechanically cycled under constraint (training process) (2). The working principle is also shown (3) (scale bar is 500 μm).

Remarkable effects are associated with the stability of the TWSME [23,24] and are briefly described: after the training process, on cooling, non-accommodating variants nucleate and lead to a macroscopic shape change ("the second memorized shape"). Yet, the material can still be deformed isothermally in martensite so that another metastable configuration of variants is introduced. This martensite microstructure does not appear spontaneously upon cooling but by mechanically deforming the material from its martensitic shape. It is therefore a prepared state, "artificially" introduced and the material is somewhat put in a sort of "out-of-equilibrium" state, i.e. outside the sequence of spontaneous shape changes introduced by the TWSME and in a state that cannot be spontaneously reached by the system and that disappears upon heating.

The material response to this out-of-equilibrium configuration is quite spectacular and is shown for two cantilever beams in Figs. 3 and 4. The two cantilever beams are identical but made of different material (Ni–Ti (50.21 at.% Ni, Ti bal.) and Ni–Ti–Cu (44.71 at.% Ni, 5 at.% Cu, Ti bal.)—annealed at 515 °C for 30 min) [24]. The specimens are trained in bending according the procedure known as "thermal training under constrain". Both figures show the relative displacement of the cantilever. Step 1, the cantilever is deformed in martensite ("prepared state"). Upon heating, the deformation slowly disappears until the phase transformation temperatures are reached. (We call this first sequence "approach-to-equilibrium".) At this point, the cantilever follows the motion path introduced by the TWSME (sequence 2–3–4–5). The prepared state is not stable as it disappears after one complete heating–cooling cycle. A proposed interpretation [23,24] of this phenomenon is a two-step mechanism: first, upon heating, variants introduced by the perturbation are unstable and are reoriented within the stress field introduced by the training process. Second, when the martensite to austenite transformation temperature is reached, some variants start to transform into austenite.

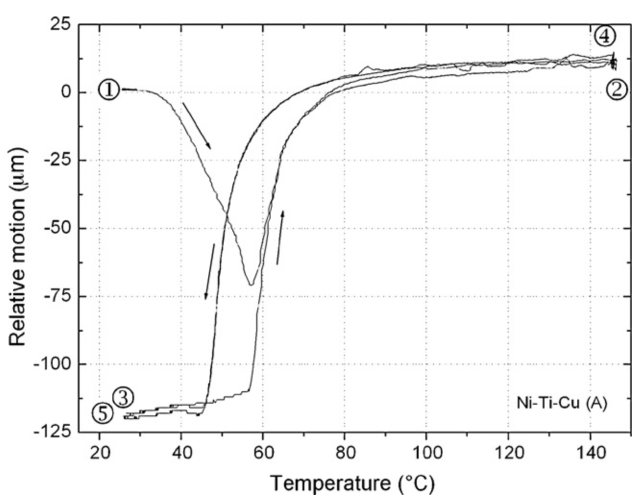

Fig. 3. Out-of-equilibrium behavior of a Ni–Ti–Cu alloy.

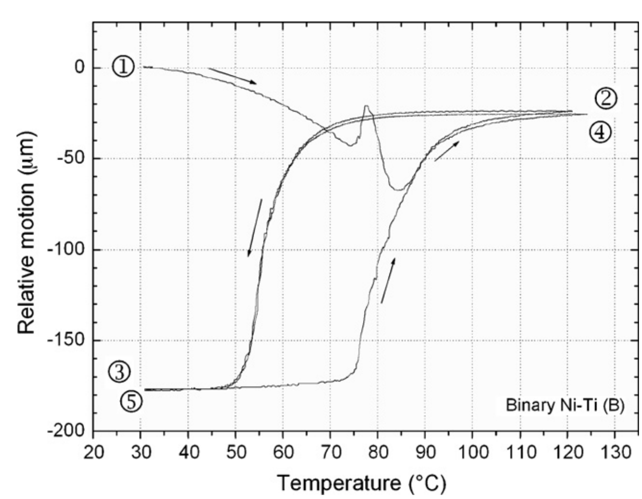

Fig. 4. Out-of-equilibrium behavior for a binary Ni–Ti alloy.

Both specimens – although with different chemical composition – show an overall consistent behavior. However, for the binary Ni–Ti alloy a "bump" on the curve corresponding to the approach-to-equilibrium is observed. This particular feature could be related to the R-phase (an intermediate crystallographic phase between martensite and austenite present in some binary Ni–Ti alloys) as such behavior is not observed in Ni-rich specimen annealed at 700 °C [24].

Although, much remains to be done to further understand the mechanism related to this effect, it shows that the TWSME is a robust effect. From an application stand point, in the case of the micro-gripper shown in Fig. 2, it demonstrates that the actuator can recover from unwanted deformation introduced in martensite.

The use of the TWSME in thin films has been recently reported for temperature controlled surface protrusions [25]. The TWSME is induced by severe plastic deformation: spherical indents are made on the surface of a Ni–Ti alloy in its martensite phase followed by a planarization step to restore a flat surface. Protrusions appear upon heating and disappear upon cooling.

Oriented precipitates were reported to induce a reversible shape change [26,27]. The principle is explained in Fig. 5. Precipitates (Ti_3N_4) with ellipsoid shape form during constrained-aging of Ni-rich Ti–Ni alloys. In compression, these precipitates are roughly oriented perpendicular to the direction of applied stress while in tension, they are oriented parallel. For a beam loaded in bending, about half of it is in tensile stress while the rest experiences a compressive stress. For an initially flat material initially aged under constraint so that it remains bent during the heat treatment, precipitates form with two opposing directions across the material thickness. During the phase transformation, the material shape changes spontaneously: from curved to flat and then, to curved again but in the opposite direction (as illustrated in Fig. 5).

Numerous studies have been conducted to analyze the effects of coherent Ti_3Ni_4 precipitates on the phase transformation. Multiple-step transformations were reported and analyzed in Ni-rich Ni–Ti [28,29]. It was observed [28] that these precipitates produce an internal stress field [28,30] which modifies locally the thermodynamic equilibrium. The R-phase and martensite morphologies are both affected by the stress field which induces the growth of specific variants [28]. Furthermore, rather low stresses [31] in the order of a few MPa are reported to modify the precipitates distributions.

Kuribayashi reported the use of this process for a SMA active joint for miniature SCARA robot [32,33]: a 5 μm-thick sputtered thin film is deposited on Na-Cl substrate. The film is removed from the substrate and annealed at 1073 K between two crystal plates for 10 min. Finally, the film is aged in a quartz tube of 3.5 mm in diameter at 673 K for 6 h. A drawback of the precipitation process is that it results in an increase of Ni (due to the precipitation process during aging) which results in a decrease of reverse transformation temperatures [17].

4. Extrinsic methods

These methods consist of using an additional mechanical element to provide the necessary force to promote the nucleation of stress-induced variants. This mechanical element can be either a bias spring, another SMA ("antagonistic design"), a dead-weight, etc. The most used element is the bias-spring as it is rather easy to implement.

A typical mechanical construction is sketched in Fig. 6. A SMA coupled to a bias spring is preloaded so that the system is under stress: martensite variants are then reoriented to minimize the strain energy ("de-twinned', see stage 3 in Fig. 1) inducing a net macroscopic deformation. Upon heating, the material transforms back to the parent phase and pushes the spring as it tries to recover its original shape. The output of the mechanism is taken between the SMA and the bias spring.

A variety of small devices utilize this principle (for instance micro-valves [6–8], gripper [2,4], endoscope [10] or tactile displays [11]). As an illustration, a micro-valve is shown in Fig. 7 [6]. It consists of an actuator die with a poppet controlled by a micro-patterned Ni–Ti layer. At low temperature, the bias spring (a Cu–Be micro-fabricated layer) pushes the poppet toward the orifice and deforms the Ni–Ti ribbon (de-twinning process). Resistive heating causes the ribbon to transform back to austenite (the parent phase) and to lift the bias spring-up thus opening the valve.

Another example of construction is shown in Fig. 8. This micro-device is a millimeter-size micro-endoscope with five degrees-of-freedom actuated by shape memory elements that are locally heated on certain portions. Sensors based on strain gauges are also incorporated in the structure. In another version, tactile sensors have been added that give reflex functions to the catheter so that when the tube touches something, it automatically bends in the opposite direction.

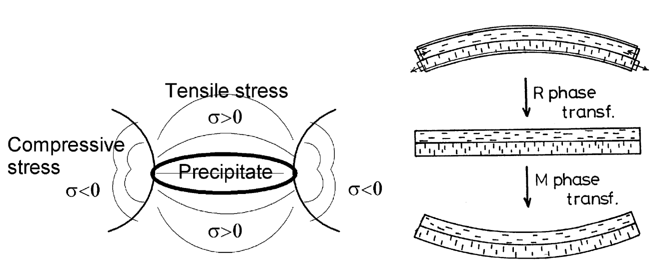

Fig. 5. (Right) Schematic of the "all-around" effect (figure adapted from [27]). The specimen is aged under constraint in a curved shape. (Left) The stress distribution around precipitates.

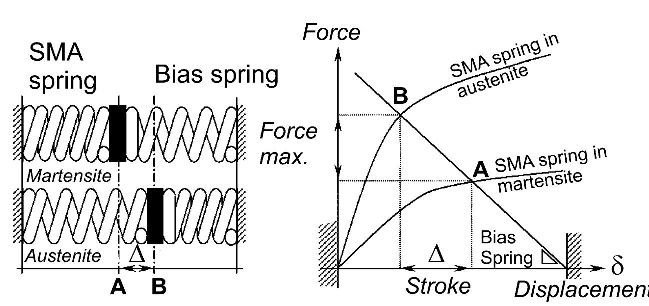

Fig. 6. General principle of a spring-based design.

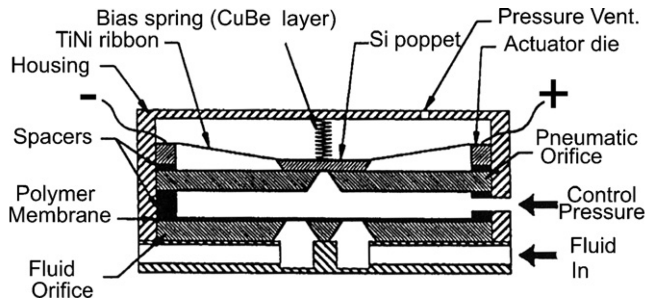

Fig. 7. Micro-valve with SMA actuator (Ti–Ni ribbon) (adapted from [6]). The valve is shown in its closed configuration. Dimensions of the assembly are 5 mm × 8 mm for a thickness of 2 mm. The film thickness is a few micrometers.

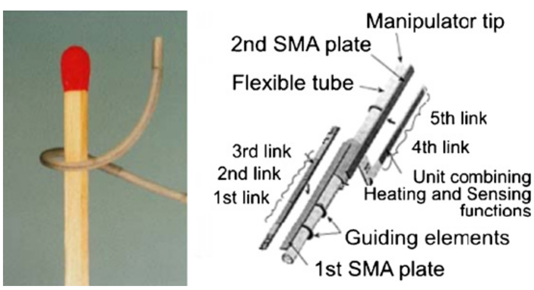

Fig. 8. The Olympus Co. micro-endoscope [10,9]—(left) the endoscope winding around a match; (right) exploded view of the inside structure.

While possible for miniature devices, the preload step required for bias spring-based design, becomes extremely difficult for sub-millimeter mechanism as it requires micro-manipulation and/or hybrid process integration at smaller scale.

For thin films based devices, an elegant method to solve this issue is to take advantage of the stress introduced during thin film deposition and annealing, for instance, on silicon substrate. The stress build-up mechanism during processing is illustrated in Fig. 9: a Ni–Ti film is deposited on a Si substrate. At the deposition temperature considered (T_d), the film is amorphous. To be functional, an annealing step is required. This is achieved by heating the film to typically 700–900 K.

Upon heating, due to the difference between the coefficient of thermal expansion between film and substrate, a compressive stress builds up. Upon crystallization at a temperature T_a, the stress is relaxed and the film is under tensile stress on cooling. In

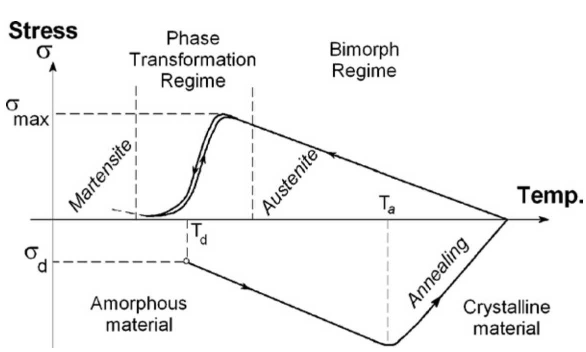

Fig. 9. Mechanism of stress-generation for Ni–Ti deposited on Si substrate. σ_d represents the stress in the film at the deposition temperature (T_d).

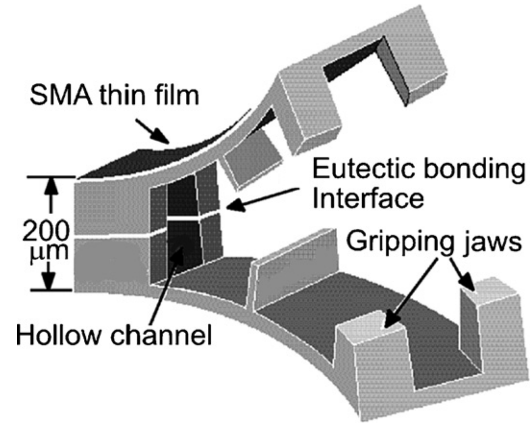

Fig. 10. SMA/Si bimorph micro-gripper (adapted from [3]).

the device operating mode, this biasing stress can be efficiently used to deflect a Si-cantilever beam or a membrane.

This effect has been demonstrated for a micro-gripper [3]. This device is shown in Fig. 10. A 5 μm-$Ni_{42}Ti_{50}Cu_8$ thin film is deposited on a silicon substrate. The jaws are fabricated by precision sawing and bulk-micromachining of silicon.

The bimorph-like effect obtained by controlling the stress during deposition and annealing, is used to obtain and close the gripper jaws.

Polyimide thin film has also been proposed as a biasing mechanism to create bimorph-like device construction [34]. Similarly, SMA composites consisting of Ti(Ni,Cu)/Mo have recently been reported [15]. It was noted that the work output is about 10 times larger than the work output of the corresponding bimetallic effect [15,28].

5. Monolithic design: laser annealing of SMA (LASMA)

At the micro-scale, the use of an additional element to provide the biasing force is difficult to implement and do not scale in a favorable manner. On the other hand, the use of bimorph structure limits the designing option to out-of-plane bending actuator.

To bypass the need for a bias spring and to enlarge the design space, monolithic integration has been suggested [35,22]. The key idea is to tailor spatially the SMA microstructures across the device. Fig. 11 illustrates this principle: let us consider a micro-actuator consisting of two springs opposing each other. The actuator is monolithic and symmetrical but yet has different mechanical characteristics. This can be achieved for instance by local annealing [36] instead of annealing the complete material.

For thin-films, when the material is deposited, it is amorphous unless the substrate is heated sufficiently. Similarly, for cold-rolled sheets, a final annealing step is necessary to restore the crystallographic structure severely deformed during the cold-rolling process.

Fig. 12 shows for instance a tensile test experiment performed on a binary Ni–Ti test specimen before and after annealing. Before annealing, the transformation is suppressed and no superelasticity is observed due to the large amount of defects that

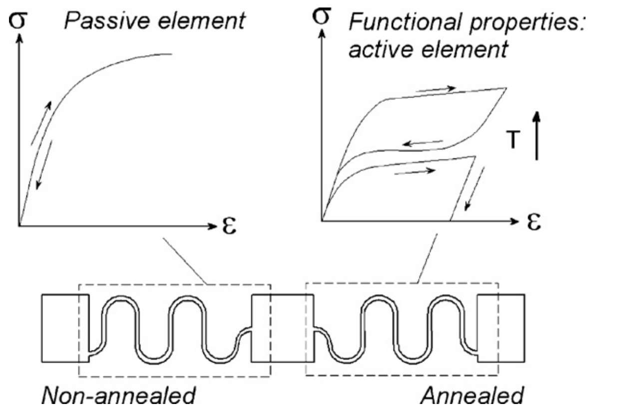

Fig. 11. Schematic of monolithic integration. By locally annealing the material, mechanical properties are distributed across the material.

has been introduced during the forming process. After annealing, the material re-crystallizes and its functional properties are restored.

Local annealing can be performed by direct joule heating [35,36]: electrical current flows between two contact points and dissipates heat. This method assumes that the electrical path matches the desired mechanical element that needs to be annealed.

Another approach is to use laser annealing [36]. For annealing application, near-infrared lasers (in the 600–1000 nm) are appropriate: in that wavelength range, essentially heat is transferred to the material. In that wavelength range the Ni–Ti absorbs about 30–35% of the incident radiation (for a thin film, with near normal incidence). Typical irradiances to anneal SMA micro-devices are a few W/mm^2. Irradiance levels depend on the material thickness, geometry and substrate. Process feedback can be achieved using infrared sensors or by monitoring the change of electrical resistivity during annealing. The latter has been demonstrated on thin-film based laser-annealed micro-switch [39]. In the annealing temperature ranges, Ni–Ti oxidizes rapidly in the presence of oxygen: a protective atmosphere may be required for certain application. However, due to the short high-temperature exposure time, these effects remain negligible for most cases. On thin-films, the oxide thickness of laser-annealed specimens in normal air was measured for various laser irradiances and scanning speed [37]. It was found that the oxide thickness does not exceed 250 nm for the laser irradiances of interest.

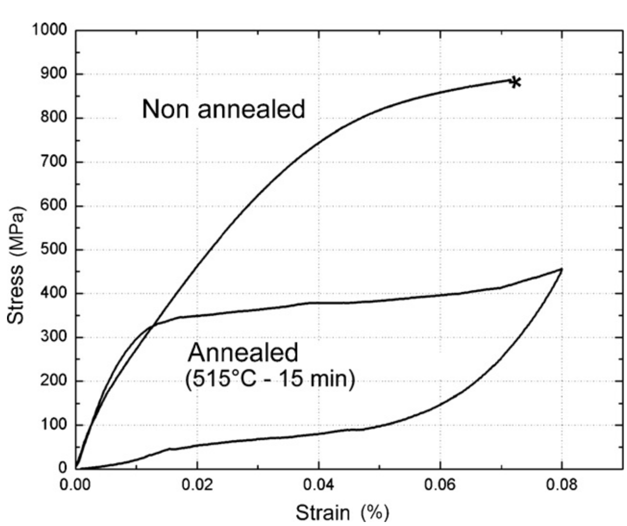

Fig. 12. Tensile characteristics of annealed and non-annealed binary Ni–Ti.

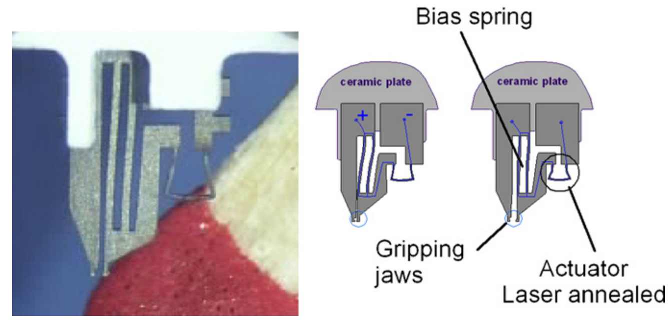

Fig. 13. Laser-annealed monolithic micro-gripper [40]. This example illustrates the integration of multiple functionalities in a same substrate.

Wang et al. [38] have performed a systematic analysis of the microstructure found for various scanning parameter and laser power. It was found that the microstructure is homogeneous in the laser spot region.

In the previous paragraph, it was shown that for film deposited on a Si substrate, stress generated during deposition and annealing can be used to achieve a reversible motion. Similarly, in the case of laser annealing of free-standing micro-device, stress induced during annealing and thermal expansion can also be used to introduce a two-way effect without the need to introduce a pre-strain: during local laser exposure, the device can locally be put under compressive stress due to asymmetric thermal expansion; this stress is relaxed during annealing and turns into a tensile stress on cooling [39].

A laser-annealed micro-gripper is shown in Fig. 13 [40]. This device was designed for the manipulation of scaffold parts used in bone reconstruction therapy. The raw material is a cold-rolled Ni–Ti–Cu (5 at.% Cu) sheet. The device is laser-cut using a Nd-YAG slab laser. The raw material, as received, does not exhibit a phase transformation. This can be seen on the differential scanning calorimetry presented in Fig. 14 (raw material).

The laser-cut itself induced a partial annealing effect localized in the laser-affected zone. This annealing effect is limited to the so-called heat-affected-zone (typically 8–10 μm). Note that this annealing process resulting from the machining process is not desirable: it can be significantly reduced by choosing a less heat producing micro-manufacturing method (like femtosecond lasers or combined laser-machining with water-jet).

The effect of laser annealing on the DSC signal is clearly visible. A sharp, well-defined, transformation peak is observed. (Smaller secondary peaks are related to the DSC specimen preparation itself that required additional laser cutting.)

From a design point of view, this device is similar to the bias-spring/actuator configuration. As the raw material is a cold-rolled sheet, the pre-strain is achieved by introducing an offset between the contact pads during assembly. As mentioned earlier, this pre-strain can be bypassed for laser-annealed thin film-based micro-devices.

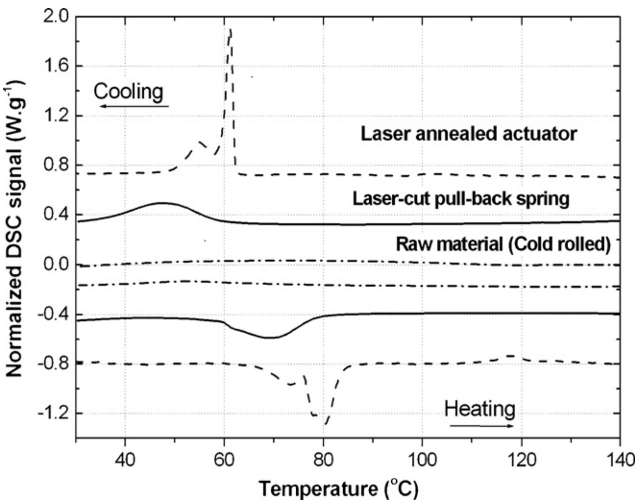

Fig. 14. Differential scanning calorimetry (DSC) of the micro-gripper main parts, namely, the pull-back spring and the actuator element (laser annealed). The signal for the raw material – as received – is shown for comparison. For each of the three DSC the mass specimen are similar.

6. Summary of design principles to achieve a reversible effect

As stated before, the main design objective in SMA micro-actuators is to achieve a macroscopic reversible shape change in which the actuator switches back and forth between two shapes with a work output.

Fig. 15 summarizes the various principles available to induce a reversible macroscopic shape change. The most commonly found techniques were briefly outlined in the previous paragraphs. In addition to these techniques, one should add ion bombardment as a means to produce localized amorphization or inhomogeneities which combined with unaffected zones tend to induce an intrinsic two-way effect [41]. Special fabrication processes can also lead to intrinsic two-way effects: this is the case for melt-spinning (where molten metal is rapidly solidified on a high speed spinning wheel) and thin-film fabricated by stacking sequence of thin layers of Ni and Ti [42]. These two-way effects essentially result from the particular microstructures found across the material thickness that induce an out-of-plane bending effect. As for the bimorph-like construction, it offers limited design options.

Local annealing technique offers a way to bypass process compatibilities issues resulting from the need for high-temperature processing as well as a convenient method for in-plane micro-actuators design.

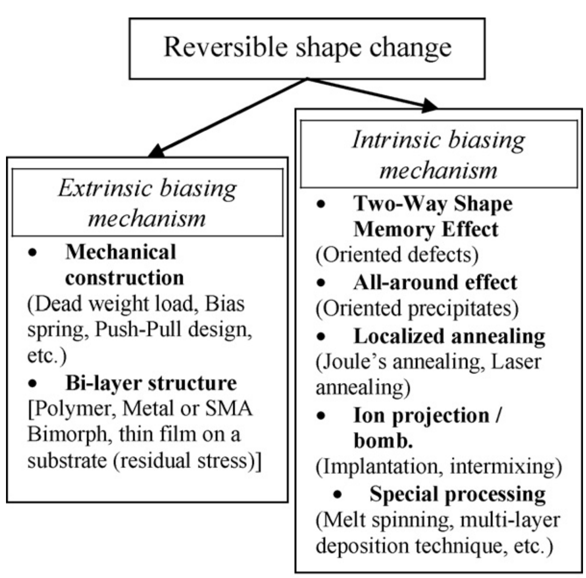

Fig. 15. Overview of methods that induce reversible shape change in SMA.

7. Future directions

Electronics on flexible substrate are developing at a fast pace. So-called polymer electronics or "plastic" MEMS are rapidly emerging as powerful platform for multifunctional integration in a variety of packages and substrates. This is particularly attractive for biomedical applications where fluidic, optics and electronics can be merged on a single, flexible substrate (smart bandage for instance). Ni–Ti alloys being bio-compatible materials are quite attractive in that context. Although early demonstrations of Ni–Ti/polyimide actuator [34] were made, more work is needed to expand the process capabilities.

Observing SME effect at the nanoscale has been of great interest recently both from an application and theoretical point-of-view. Nano-indentations experiments [43,44] have demonstrated nano-scale shape memory effect. Waitz et al. [45] have also shown that the type of microstructure found in nanograins is size dependant and has a unique crystallographic structure [46].

These works may trigger new developments toward nano-SMA actuators.

In conclusion, carefully designed, SMA micro-actuators offer a very attractive solution for low-bandwidth microsystems in general and in particular for applications where force, compactness as well as smooth and continuous actuation is needed.

References

[1] N. Maluf, An Introduction to Micro Electro Mechanical Systems Engineering, 1st ed., Artech House Publishers, 1999, ISBN 0-89006-581-0.
[2] K. Ikuta, Proc. IEEE Int. Conf. Robotics Autom., Cincinatti, 1990, pp. 215–216.
[3] P. Krulevitch, A.P. Lee, P.B. Ramsey, J.C. Trevino, J. Hamilton, M.A. Northup, J. MEMS 5 (1996) 270–282.
[4] J. Hesselbach, R. Pittschellis, E. Hornbogen, M. Mertmann, Proc. Shape Memory and Superelastic Technol., Pacific Grove, CA, 1997, pp. 251–256.
[5] Y. Bellouard, R. Clavel, J.-E. Bidaux, R. Gotthardt, T. Sidler, Proc. Shape Memory Superelastic Technol., Pacific Grove, CA, 1997, pp. 245–250.
[6] A.D. Johnson, V.V. Martynov, Proc. 2nd Int. Conf. Shape Memory Superelastic Technol., Pacific Grove, CA, 1997, pp. 149–154.
[7] J.D. Busch, A.D. Johnson, Shape-Memory Alloys Micro-Actuator, US Patent 5,061,914, June 27 (1989).
[8] M. Kohl, D. Dittmann, E. Quandt, B. Winzek, S. Miyazaki, D.M. Allen, Mater. Sci. Eng. A 273–275 (1999) 784–788.
[9] W.L. Benard, H. Kahn, A.H. Heuer, M.A. Huff, J. MEMS 7 (1998) 245–251.

[10] S. Kaneko, S. Aramaki, K. Arai, Y. Takahashi, H. Adachi, K. Yanagisawa, J. Intell. Mater. Syst. Struct. 7 (1996) 331–335.
[11] H. Fischer, R. Trapp, L. Schüle, B. Hoffmann, J. Phys. IV France 7 (1997), C5-609-614.
[12] S. Takeuchi, I. Shimoyama, J. MEMS 19 (2000) 24–31.
[13] S. Miyazaki, A. Ishida, Mater. Sci. Eng. A 273–275 (1999) 106–133.
[14] Y. Fu, H. Du, W. Huang, S. Zhang, M. Hu, Sens. Actuators A 112 (2004) 395–408.
[15] B. Winzek, S. Schmitz, H. Rumpf, T. Serzl, R. Hassdorf, S. Tienhaus, J. Feydt, M. Moske, E. Quandt, Mater. Sci. Eng. A 378 (2004) 40–46.
[16] L. Delaey, in: R.W. Cahn, P. Haasen, E.J. Kramer (Eds.), Material Science and Technology, vol. 5, “Phase transformations in Materials”, VCH, Weinheim, 1991.
[17] K. Otsuka, X. Ren, Prog. Mater. Sci. 50 (2005) 511–678.
[18] K. Otsuka, C.M. Wayman (Eds.), Shape Memory Materials, Cambridge University Press, Cambridge, UK, 1998.
[19] J. Perkins, D. Hogson, in: T.W. Duerig, K.N. Melton, D. Stöckel, C.M. Wayman (Eds.), Engineering Aspects of Shape Memory Alloys, Butterworth-Heinemann Ltd., 1990, ISBN 0-750-61009-3.
[20] H. Scherngell, A.C. Kneissl, Acta Mater. 50 (2002) 327–341.
[21] H. Scherngell, A.C. Kneissl, Scripta Mater. 39 (1998) 205–212.
[22] Y. Bellouard, PhD Dissertation, no. 2308, Lausanne, 2000.
[23] Y. Bellouard, R. Clavel, R. Gotthardt, J. Phys. IV 11 (2001) Pr8583–Pr8588.
[24] Y. Bellouard, R. Clavel, R. Gotthardt, J. van Humbeeck, J. Phys. IV (112) (2003) 765–768.
[25] Y. Zhang, Y.-T. Cheng, D.S. Grummon, Appl. Phys. Lett. 89 (2006), 041912.
[26] M. Nishida, T. Honma, Scripta Metall. 18 (1984) 1293–1298.
[27] R. Kainuma, M. Matsumoto, T. Honma, Proc. Int. Conf. Martensitic Transform, The Japan Institute of Metals, Nara, Japan, 1986, pp. 717–722.
[28] L. Bataillard, J.-E. Bidaux, R. Gotthardt, Phil. Magn. A 78 (1998) 327–344.
[29] J. Khalil-Allafi, A. Dlouhy, G. Eggeler, Acta Mater. 50 (2002) 4255–4274.
[30] W. Tirry, D. Schryvers, Acta Mater. 53 (2005) 1041–1049.
[31] J. Michutta, Ch. Somsen, A. Yawny, A. Dlouhy, G. Eggeler, Acta Mater. 54 (2006) 3525–3542.
[32] K. Kuribayashi, Proc. of MEMS, IEEE, 1990, pp. 217–221, doi:10.1109/MEMSYS.1990.110279.
[33] K. Kuribayashi, S. Shimizu, T. Nishinohara, T. Taniguchi, M. Yoshitake, S. Ogawa, Proc. of IROS, 1993, pp. 1697–1702, doi:10.1109/IROS.1993.583865.
[34] K. Kuribayashi, T. Fujii, Proc. of Int. Symp. on Micromechatronics and Human Science (MHS) (1988) 165–170.
[35] Y. Bellouard, R. Clavel, R. Gotthardt, J.-E. Bidaux, T. Sidler, H. Borgmann, Actuators, Int. Conf. on New Actuators, Bremen, Germany, June 17–19, 1998, pp. 502–505.
[36] Y. Bellouard, T. Lehnert, J.-E. Bidaux, T. Sidler, R. Clavel, R. Gotthardt, Mater. Sci. Eng. A 273–275 (1999) 733–737.
[37] F. Khelfaoui, Y. Bellouard, T. Gessmann, X. Wang, J. Vlassak, M. Hafez, Proceedings of the International Conference on Shape Memory and Superelastic Technology (SMST-2004), Germany, ASM International, 2004.
[38] X. Wang, Y. Bellouard, J.J. Vlassak, Acta Mater. 53 (2005) 4955–4961.
[39] Y. Bellouard, T. Lehnert, R. Clavel, R. Gotthardt, J. Phys. IV 11 (2001) Pr8571–Pr8576.
[40] H. Zhang, Y. Bellouard, E. Burdet, R. Clavel, A.-N. Poo, D.W. Hutmacher, Robotics and Automation, 2004. Proceedings of the ICRA ’04. 2004 IEEE International Conference on Robotics and Automation, vol. 5, April 26–May 1, 2004, pp. 4918–4924. doi:10.1109/ROBOT.2004.1302497.
[41] D.S. Grummon, R. Gotthardt, Acta Mater. 48 (2000) 635–646.
[42] T. Lehnert, S. Tixier, P. Böni, R. Gotthardt, Mater. Sci. Eng. A 273–275 (1999) 713–716.
[43] G.A. Shaw, D.S. Stone, A.D. Johnson, A.B. Ellis, W.C. Crone, Appl. Phys. Lett. 83 (2003) 257.
[44] X.-G. Ma, K. Komvopoulos, Appl. Phys. Lett. 83 (2003) 3773.
[45] T. Waitz, V. Kazykhanov, H.P. Karnthaler, Acta Mater. 52 (2004) 137–147.
[46] T. Waitz, Acta Mater. 53 (2005) 2273–2283.