Residual stress-loaded titanium–nickel shape-memory alloy thin-film micro-actuators

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Abstract

Residual stress in titanium–nickel thin films has been exploited as a force load for thin-film shape-memory alloy micro-actuators, thus eliminating the need for providing 'external' force load for device training and operation. Thermal cycling during device operation is accomplished using electrical current-induced Joule's heating for temperature ramp-up and thermal conduction/convection-induced cooling for temperature ramp-down. In response to thermal cycling, hysteresis loops in both the displacement and electrical resistance of the micro-actuator have been observed—thus demonstrating the existence of shape-memory effect in the micro-actuators. Elimination of manual training of individual devices makes it possible to operate large arrays of shape-memory alloy micro-actuators realizable using micro-fabrication techniques.

1. Introduction

Because of the unique advantages [1] offered by shape-memory effect (SME) induced actuation, much effort has been devoted to developing titanium–nickel (TiNi) thin-film shape-memory alloy (SMA) [2, 3] micro-actuators [4–7]. Despite the apparent advantages, the realization of TiNi thin-film micro-actuators has been hindered by various challenges including the deposition [8] and heat treatment [9] of stress- and compositionally sensitive films, integration with other micro-fabrication materials and processes, as well as the difficulty in proper device design due to the complex thermo-mechanical behavior of SMA thin films.

Although some micro-actuators [5, 10–12] based on sputtered and freed TiNi thin films have been fabricated, they need to be individually and manually trained to exhibit the requisite two-way SME [3] before they can be operated without external force load. One of the most powerful advantages of micro-fabrication is the ease of realizing large arrays of micro-devices. Obviously, individual training of a large number of devices is rather impractical. Therefore, alternative methods of providing force load for training or operation are desired.

In this work, the design, implementation, and characterization of thin-film TiNi SMA micro-actuators requiring no manual training are reported. The central idea is the utilization of the naturally occurring residual stress, thermally induced or otherwise, in the thin films as the force load.

2. Micro-actuator design

A photograph of a prototype micro-actuator, in the form of a pair of micro-tweezers, is shown in figure 1(a). The actuator consists of two rotating gripping jaws (J_L and J_R) and three actuator beams B_L , B_C and B_R . One end of each B_L and B_R is anchored on a bond pad for electrical connection and heat sinking. When an external bias is applied between the bond pads P_L and P_R , an electric current flowing through the actuator beams is induced. The beams are heated and deformed due to thermal expansion, perhaps superimposed on a phase transformation if the local temperature somewhere along the heated beams reaches above a critical SMA phase transformation temperature. Expansion of the actuator beams leads to mirror-symmetrical rotation of the jaws J_L and J_R . The two jaws close upon each other, decreasing their separation

Figure 1. Photographs of a released micro-actuator. (a) The complete device. A representative set of device dimensions is included. (b) A magnified view of the jaw separation after power is applied. (c) A magnified view of the initial jaw separation before the application of power.

from L_0 to $L_0 - \delta L$ (figure 1(b)). When the current is switched off, the actuator beams cool down. Thermal contraction occurs, perhaps accompanied by a reverse phase transformation when the corresponding local temperature of the beams drops below a different but lower critical value. The jaws open up, returning to the original separation L_0 (figure 1(c)).

Perkins and Hodgson [13] showed that two-way SME could be achieved in a slightly Ni-rich TiNi alloy if it is mechanically constrained during a high-temperature aging treatment. Subsequent to the constrained-aging treatment, the device can be changed between the high- and low-temperature shapes simply by cycling the temperature. Based on this idea, SMA micro-tweezers requiring no manual training have been realized. The residual stress of the TiNi thin film during the aging treatment is responsible for the force load on the thin-film SMA devices. The design and fabrication of such micro-tweezers presented a number of challenges. The geometry and structures of the actuation units needed to be carefully designed not only to obtain a suitable stress profile and adequate deformation, but also to avoid beam fracture or structure de-lamination.

For an actuation unit (figure 1) consisting of a homogeneous phase and uniform Young's modulus (E), the remaining residual stress (σ) and the residual stress-induced rotation angle (α) are constrained according to the following equations [12]:

$$\sigma = \frac{E\alpha W_n^2}{6d \left[L_n + \left(\frac{W_n}{W_f} \right)^3 (L_f - L_n) \right]}, \quad (1)$$

Figure 2. Schematic summary of the fabrication process of the micro-actuator. (a) SiO_2 growth. Deposition and patterning of the poly-Si and Cr sacrificial layers. (b) Deposition and patterning of the TiNi structural layer and (c) etching of the sacrificial layers to release the mobile structure.

$$(1 - \nu)\sigma_{\text{res}} = \frac{E\alpha}{L_f} \left[\frac{d}{2} + \left(\frac{W_n^2}{6d} \right) \frac{L_n + \frac{W_n}{W_f}(L_f - L_n)}{L_n + \left(\frac{W_n}{W_f} \right)^3 (L_f - L_n)} \right], \quad (2)$$

where ν and σ_{res} are, respectively, Poisson's ratio and the initial residual stress of a given thin film. The geometric parameters L_f , W_f , L_n , W_n and d are, respectively, the length of beam B_L , the width of beam B_L , the length of the 'neck' connecting a beam to a jaw, the corresponding width of the neck and the offset between beams B_L and B_C . It can be seen that α , the jaw rotation angle, depends not only on σ_{res} , but also on the geometry of the actuation units.

3. Device fabrication

Device fabrication started with the growth at 1000 °C of an insulating layer of 600 nm thick thermal silicon dioxide (SiO_2) on a Si substrate. This was followed by a low-pressure chemical vapor deposition (LPCVD) at 620 °C of a 450 nm thick polycrystalline silicon (poly-Si) layer in a conventional horizontal hot-wall furnace. Subsequently, a 150 nm chromium (Cr) layer was deposited at a rate of 9.1 nm min⁻¹ in an ARC radio-frequency (rf) sputtering system. The power and the argon pressure were set at 120 W and 6 mTorr, respectively. Patterned as sacrificial layers (figure 2(a)), the Cr and the poly-Si were etched, respectively, in CEP-200 Micro-Chrome and Freckle etch solutions at room temperature. Reference markers were also patterned on these layers as rulers for measuring device displacements. The etch rates of Cr and poly-Si were 240 nm min⁻¹ and 10 nm min⁻¹, respectively.

A Ni-rich $\text{Ti}_{0.47}\text{Ni}_{0.53}$ film, about 6 μm thick, was next sputtered at a controlled substrate temperature of 300 °C using

Figure 3. Differential scanning calorimetric curves of TiNi thin films freed after crystallization and aging.

rf magnetron sputtering in a Denton sputtering system, Model SJ/24LL. The composition of the 5 cm diameter target was $\text{Ti}_{0.48}\text{Ni}_{0.52}$. The target-to-substrate distance was about 7 cm. The base pressure in the sputtering chamber was 1 μTorr . The rf power and the argon pressure were set at 300 W and 3 mTorr. A deposition rate of 45 nm min^{-1} was obtained. After the deposition, the TiNi structural layer was patterned (figure 2(b)) at an etch rate of $\sim 500 \text{ nm min}^{-1}$ in a room-temperature mixture of $\text{HF}:\text{HNO}_3:\text{H}_2\text{O} = 1:1:20$. Finally, the Cr and poly-Si sacrificial layers were removed and the actuation structures released (figure 2(c)). Subsequently, the devices were crystallized at 750 $^{\circ}\text{C}$ for 30 min and aged [2, 3, 9, 14] at 500 $^{\circ}\text{C}$ for 100 h in a 0.44 μTorr vacuum.

The displacement of the micro-tweezers was measured using an optical microscope at a magnification of 1000 $\times$. The phase transformation temperatures of freed TiNi thin films, prepared using conditions identical to those used for the construction of the devices, were determined using differential scanning calorimetry (DSC).

4. Results and discussion

The DSC measurement results are summarized in figure 3. It is apparent that there are two peaks (exothermic reactions) upon cooling and two valleys (endothermic reactions) upon heating, thus implying a two-stage [15] phase transformation process. During heating, the TiNi sample transforms from the *M*-phase to the *A*-phase through the *R*-phase. The reverse transformations occur during cooling. The *M*- and *R*-phase start temperatures, M_s and R_s , were determined from the DSC cooling curve to be about 6 $^{\circ}\text{C}$ and 43 $^{\circ}\text{C}$, respectively. The *M*- to *R*-phase and the *R*- to *A*-phase reverse transformations overlap appreciably during the heating process.

The high-temperature shape of the micro-tweezers is determined by the residual stress at 500 $^{\circ}\text{C}$ during the extended aging step [13, 14]. Upon cooling to room temperature after aging, the jaws rotate due to changed thermal and residual stresses, finally settling in the low-temperature state. The devices were characterized by measuring the dependence of the electrical resistance and the mechanical deformation on

Figure 4. Typical dependence of the electrical resistance (Z) and the displacement (δL) on applied power for the devices realized on amorphous and aged TiNi alloys. Measurements were performed at room temperature.

applied electrical power [4–7]. For comparison, devices made of both amorphous and aged TiNi were studied. Typical dependences on applied power of the room-temperature mechanical displacement (δL) of both the amorphous and the aged micro-tweezers and the corresponding normalized electrical resistance (Z/Z_0) of the aged device are presented in figure 4, where Z_0 is the resistance measured at room temperature. Originating solely from thermal expansion or contraction during power cycling, a nearly linear dependence of δL on the applied power is observed for an amorphous TiNi device. No hysteresis was observed during power cycling.

Compared with δL of a device made of amorphous TiNi, that of the device made of aged TiNi is much larger at any equivalent power level and exhibits hysteresis typical of force-loaded SMA subjected to temperature cycling. With an increase in electric power, δL increases linearly at first, then saturates before taking off rapidly when the power is increased beyond $\sim 2 \text{ mW}$. Concomitantly, Z decreases rapidly [2–4, 6, 7]. This is induced by an *R*- to *A*-phase rather than an *M*- to *R*-phase transformation [2, 4, 7]. This is because the *M*- to *R*-phase transformation temperature (figure 3) for the TiNi alloy studied in this work is below room temperature. When the applied power is reduced, δL decreases linearly at the beginning as a result of regular thermal contraction of the actuator beams. When the applied power is reduced to $\sim 3.2 \text{ mW}$, the decrease in δL saturates, though at a level higher than that observed during the power ramp-up. Reverse phase transformation from *A*- to *R*-phase occurs. Concomitantly, Z increases rapidly. When the applied power is further reduced to $\sim 1.4 \text{ mW}$, δL quickly decreases again. Both δL and Z return to their initial values when the applied power is finally shut off.

Since the *R*- to *M*-phase transformation temperature upon cooling is below room temperature, micro-tweezers were cooled using liquid nitrogen to generate the *M*-phase and to study the effects of *M*- to *R*-phase transformation on δL . Two plateau separated by a region of relatively faster increase can be observed in the heating portion of the δL -power characteristics shown in figure 5. These are related to the

Figure 5. The δL -power characteristics of a micro-actuator measured at room temperature after it was first cooled down using liquid nitrogen.

Figure 6. The δL -power characteristics of devices A ($d_A = 30 \mu\text{m}$) and B ($d_B = 12 \mu\text{m}$) measured at room temperature.

two-stage phase transformation from *M*- to *R*-phase and from *R*- to *A*-phase, associated with the plateau at lower and higher power levels, respectively. The first plateau ends at a power level of ~ 12 mW and the second plateau ends at ~ 40 mW.

When the power was subsequently reduced and the device cooled to room temperature, it can be seen that δL would not return to zero as in the case shown in figure 4. A residual displacement $\delta L'$ appears. This is because the actuator beams cannot recover the original *M*-phase shape formed at the lower liquid-nitrogen temperature.

The relationship between δL and the beam offset (d) is investigated using different devices. As an illustration, the δL -power characteristics of two micro-tweezers (A and B) with different beam offsets are shown in figure 6. The beam offsets of devices A and B are $d_A = 30 \mu\text{m}$ and $d_B = 12 \mu\text{m}$, respectively. It can be seen that the appearance of the hysteresis loops is different for the two devices. Compared with δL of device A, δL of device B is much smaller at equivalent power

Figure 7. Frequency response of a micro-actuator operating at room temperature and ambient.

levels. This is consistent with the dependence of stress on d [2, 3, 12, 14, 16, 17]. When d is small, the necks of beams B_L and B_R will significantly overlap with that of beam B_C . In the case of device B, the neck width is $20 \mu\text{m}$ and d_B is $12 \mu\text{m}$, giving rise to an overlap of $\sim 8 \mu\text{m}$. When the actuator beams extend due to thermal expansion and phase transformation, the stresses provided by beams B_L/B_R and B_C act against each other [12] in the overlap area, thus reducing the torque and the rotational displacement (equation (2)). Consequently, δL of device B is smaller.

Finally, the frequency response of the micro-tweezers was measured at room temperature. The dependence of δL on the frequency of an applied voltage pulse is shown in figure 7. The maximum frequency response is about 8 Hz. This relatively slow response is consistent with the slow cooling rate due to thermal conduction/convection and with the long transient associated with the phase transformation process [5].

5. Conclusions

Thermal and intrinsic residual stress has been explored productively to realize TiNi thin-film shape-memory alloy micro-actuators requiring no individual manual training. The contribution of shape-memory effect to actuation is verified by the hysteresis loops present in both displacement-power and electrical resistance-power characteristics. The behavior of the micro-actuators agrees qualitatively with the theory governing the mechanical behavior of beam-actuated micro-rotators. The operation frequency of the micro-actuators is ~ 8 Hz.

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