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Local annealing of complex mechanical devices: a new approach for developing monolithic micro-devices

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Abstract

The concept of monolithic shape memory alloys (SMA) micro-devices is to integrate all device functions within the same piece of material. This is very interesting in the field of micro-systems, because assembly is avoided. In such devices, the main problem is to create a reversible motion. Recently, the use of the two-way shape memory effect has been investigated. A simpler solution could be to integrate a pullback spring within the monolithic structure. This implies introducing shape memory properties only in some predefined parts of the material. In this paper, an approach based on local annealing of the material is proposed. The annealed parts will exhibit a shape memory effect and the remaining non-annealed parts will have an elastic behavior. Two methods of local annealing have been investigated. The first one is done by an electrical current, which needs a special design of the electrical path. The second one is done by local laser heating, which allows complete freedom in choosing the 'memory regions' of the material. With these tools, complex mechanical devices with active and passive parts can be designed. To illustrate this idea, two mechanical structures containing locally annealed parts are presented.

Keywords: Shape memory alloys; Laser annealing; Local annealing; Monolithic design

1. Introduction

In the field of microsystems, one of the major technological problems is assembly, resulting in growing interest in monolithic design. In a previous paper, the concept of monolithic shape memory alloy (SMA) micro-devices has been introduced [1]. The basic idea is to integrate all functions of the devices like actuating parts, flexible hinges, fixation parts, etc. within the same piece of material. Some applications have already been developed based on these principles, such as a micro-gripper and translations stages [2]. However, the main problem in developing monolithic devices is to be able to obtain a reversible motion. Various solutions have been proposed: local heating inducing a phase transformation to austenite in a fully annealed material, SMA actuators working subsequently in opposite directions ('push-pull' design) and two-way shape memory effect [2].

In this paper, an approach based on local annealing of the material has been proposed. This means that only certain regions will exhibit a shape memory effect and the remaining non-annealed ones will have an elastic behavior. These non-annealed parts can be used for example as a pullback spring.

To obtain a locally annealed structure, two methods are proposed: the first one is a direct Joule heating of the material and the second one uses laser heating of the structure.

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2. Local annealing by Joule's effect

Most SMA actuators and devices are actuated by direct Joule heating. In the same way, with a higher current, the material can be heated up to the annealing temperature.

This idea has been applied to a one-axis translation stage (see Fig. 1).

The fabrication process is as follows:

1. The structure is cut out by laser from an 'as received' non-annealed SMA strip.
2. An electrical current is injected through the left springs (current path indicated in Fig. 1). The left springs are heated to the annealing temperature. The right springs nearly stay at room temperature.
3. After cooling down the whole structure to the room temperature, springs on both sides are prestrained along the X axis (see Fig. 1) and the stage is fixed.

The material used for the device was a Ni–Ti alloy with a small amount of Cu. The current passing through the left springs was 600 mA. The temperature was monitored by an infrared camera and the average temperature of annealing was about 500°C during 15 min. The annealed springs were quenched by a freezing spray. The annealing time was not yet optimized. Other experiments have shown that this time could be shorter (1–5 min) [3]. The actuating principle is the following: left springs ('the annealed springs') are heated above the transformation temperature (A_s: about 60°C) by a lower electrical current.

Left springs transform to austenite and recover their initial shape and pull the moving part to the left. On cooling, left springs go back to the martensitic state and the stage is pulled to the right due to the non-annealed springs elasticity ('the biais spring').

The behavior of this structure is exactly the same as the well-known design of SMA actuators including a SMA spring and a biais spring made out of a different kind of material. In this case, the biais spring and the actuating spring are integrated within the same piece of material. The response to a step current signal for various prestrain values is shown in Fig. 2. These results are compared with those of a fully furnace annealed structure (see Fig. 3). In the case of a fully annealed structure the working principle is slightly different and more complex: two electrical paths are required and the reversible motion is generated by heating subsequently left and right springs ('push–pull' design).

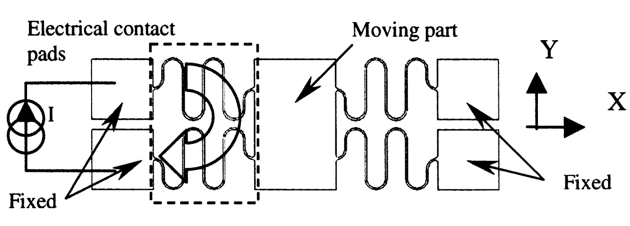

Fig. 1. One-axis monolithic translation stage with four leaf springs Dimensions: 6.5 × 20 mm^2, spring thickness: 60 μm, strip thickness: 150 μm.

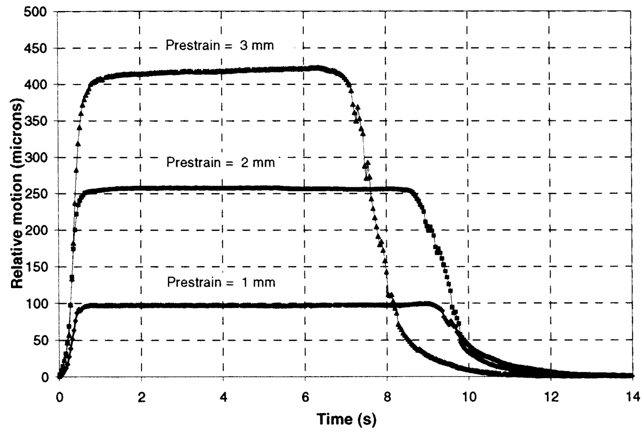

Fig. 2. Locally annealed translation stage: step response for the same current vs prestrain level.

In the case of a partially annealed stage, the time response is better than in the case of a fully annealed one. However, for the same prestrain, the range of motion is about six times smaller for the partially annealed stage (typically 250 vs 1550 μm). The non-annealed springs are stiffer than the annealed ones in martensitic state. The mechanical characteristic of the non-annealed springs is purely elastic. The range of motion could be increased by optimizing the thickness of the biais springs with respect to the thickness of the actuating springs.

These experiments show that direct Joule heating is an efficient local annealing method. However, a few limitations have to be mentioned:

- An electrical path must exist and must be adapted to the design.
- The cross-section of the structure has to be carefully designed with respect to the temperature distribution during heating. The thinnest section will be the hottest and as a consequence, will be annealed first.

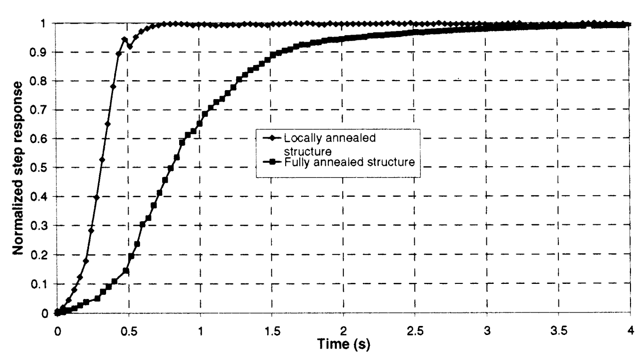

Fig. 3. Normalized step current response in the case of a fully and partially annealed stage.

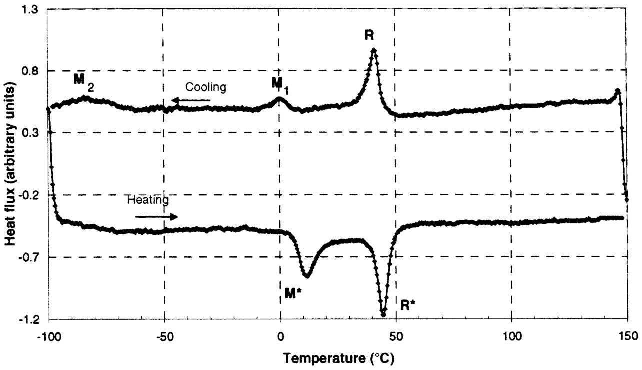

Fig. 4. Differential scanning calorimetry (DSC) measurements of a 10 μm thick laser annealed Ni–Ti film.

- The local temperature is *strongly* dependent on machining tolerances (the power dissipated in the structure is directly proportional to the resistance and thus, the cross-section).
- The resistivity of the SMA material varies with temperature and during the phase transformation.

3. Local annealing by means of a laser beam

The basic idea is to use a laser beam for local heating. The laser is focused on the point where annealing is required. An imaging system is used to control the position of the laser spot on the sample. The laser spot has a 500 μm long and 20 μm wide line shape. The maximum output light power is 0.7 W. Temperature measurements were done by infrared camera. The feasibility of laser annealing was first investigated by annealing a thin film and then the technology was applied to a micro-engineering device.

3.1. Laser annealing of a thin film

A 10 μm thick sputter-deposited Ni–Ti film was annealed by scanning a small area with the laser beam.

The average power per unit surface was about 70 W mm^{-2}. In order to evaluate the annealing quality, a differential scanning calorimetric measurement (DSC), shown in Fig. 4, was carried out.

In the heating curve, two endothermic peaks (M*, R*) were observed. In the cooling curve, three peaks (M_1, M_2, R) appeared. Due to the small hysteresis, peaks R* and R, can be attributed to an R-phase-austenite transformation and vice-versa. The M* peak in the heating curve might then be interpreted as a martensite to R-phase transformation. The two peaks M_1 and M_2 indicate a multiple transformation from R-phase to martensite probably due to an inhomogeneous microstructure of the film.

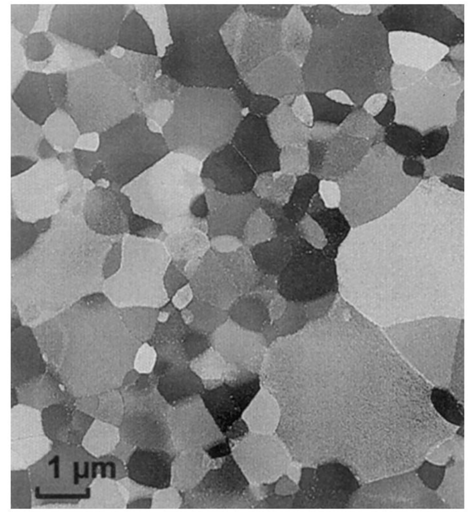

Fig. 5. Laser annealed film: grain structure at a distance of 400 μm from the center of the annealed region.

Initial investigations of the microstructure of a locally laser-annealed thin film were carried out by transmission electron microscopy (TEM). For these experiments, a small line shape area was annealed by single laser shots. Near the center of the annealed region, the material is crystallized in the austenite state with an average grain size of about 3 μm. The microstructure seems to be quite homogeneous. Fig. 5 shows the micrograph at a distance of about 400 μm from the center of the annealed area. In this intermediate region the grain size is rather inhomogeneous, typically ranging from 0.25 to 3 μm. At a distance of about 800 μm, the transition from the crystallized region to the amorphous zone can be observed. The corresponding micrograph in Fig. 6 shows single spherical austenite grains that are embedded in an amorphous matrix.

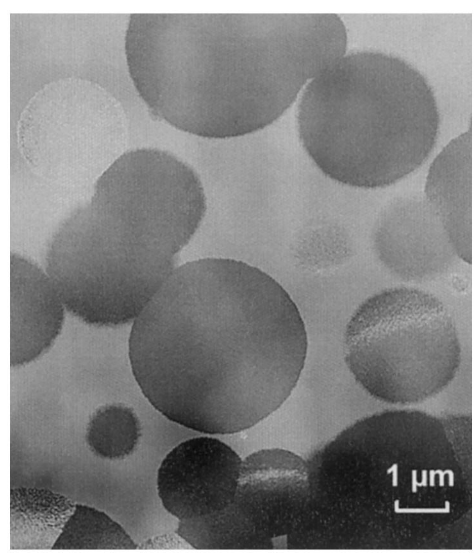

Fig. 6. Laser annealed film: grain structure at a distance of 800 μm from the center of the annealed region.

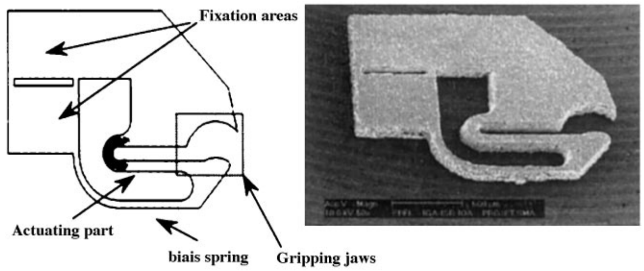

Fig. 7. Shape memory alloy (SMA) gripper: design and realization (the black area represents the locally annealed area); dimensions: 1.4×1.8 mm^2.

This experiment demonstrates the feasibility of laser annealing of a SMA material.

3.2. Local laser annealing of a micro-gripper

Local annealing was applied to a complex mechanical structure, consisting of a micro-gripper shown in Fig. 7.

The goal is to obtain an internal biais spring effect by annealing only one part of the gripper's moving arm. In order to obtain a reversible motion, the following process has been applied:

1. The gripper is cut out from a non-annealed work-hardened strip by a Nd-Yag Slab laser.
2. For local annealing, the laser is set on the semi circular hinge of the arm (see Fig. 7). The heating time is set to 1 s. The maximum monitored temperature on the actuating part was about 550°C whereas the biais spring only heats up to about 100°C.
3. At room temperature, the gripper arm is then deformed out of its elastic domain in order to define the open position.

During heating of the whole structure (by a Peltier element for example), the gripper closes due to the recovery force generated by the phase transformation in the annealed part. During cooling when the actuating part has returned to the martensite state, the elastic bias spring can pull the arm back in its open position (see Fig. 8).

Once again, the behavior of the structure can be compared to the well known SMA actuator working against an external biais spring.

The main advantages of local laser annealing are:

- Freedom in choosing the parts to be annealed
- Contactless technology
- Suitability for MEMS technology and MEMS fabrication environment (vacuum chamber, cleanroom, etc.)
- No particular design restrictions

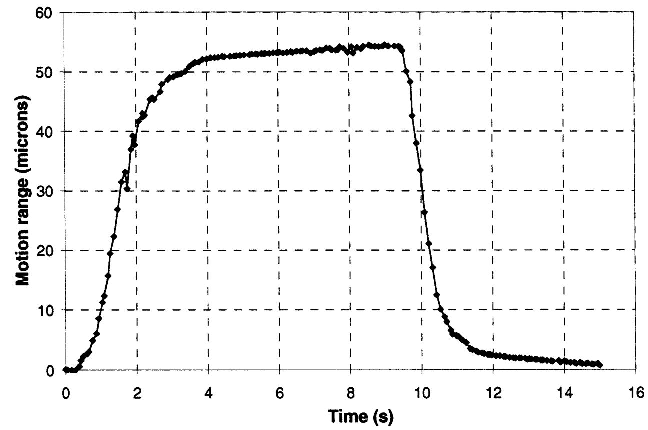

Fig. 8. Gripper arm motion on heating and cooling.

4. Conclusion

Local annealing of small SMA devices was presented. Two methods were investigated. The first uses an electrical current and was applied to a monolithic translation stage; the second uses a laser beam for local annealing and was applied to a thin film and a micro-gripper. The feasibility of local annealing of the material was demonstrated in both cases. Comparing the two methods, laser-annealing is the most promising. This is a flexible, contactless and cheap technology. Moreover, a kind of 'smart monolithic composite material' can be created by laser-annealing. Different mechanical properties can be introduced within the same part combining active and passive regions. Future work will be carried out to analyze in more detail the microstructure and the related mechanical properties of the locally annealed material as a function of laser parameters. Furthermore, new applications based on this technology will be developed.

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