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Magnetic-field-induced actuation of Ni-Mn-Ga micropillars

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Abstract:
We report on magnetic-field-induced actuation of $Ni_{50}Mn_{28.5}Ga_{21.5}$ single crystalline micropillars. Focused ion beam (FIB) milling technology was used to machine 45×45×120 μm³ cuboid pillars. The removal of about 2 μm of ion-beam-damaged surface layer enabled magnetic field actuation in pillars. Our results demonstrate the feasibility of manufacturing of microns-sized magnetic shape memory actuators by using Xe plasma source FIB technique.

Keywords: Magnetic Shape Memory, Twinning, Ni-Mn-Ga, Focused Ion Beam, Micro-scale Magnetic Actuation

Introduction

Magnetic shape memory (MSM) alloys are known for exhibiting large reversible magnetic-field-induced strain (MFIS) in the martensite phase [1, 2]. MSM alloys offer prospects for novel applications and embody a unique mechanism for magnetic-to-mechanical energy conversion. Therefore, they were under the scope of scientific research during the past decades [3 – 6]. The mechanism behind the MSM effect is the magnetically induced reorientation (MIR) of the crystal lattice by twin boundary (TB) motion [7, 8]. High velocities of TBs discovered in MSM materials [9] are important for new applications, especially in microscale devices. Thus, scaling down is a natural step in the evolution of MSM actuation devices. Similar to microelectromechanical systems (MEMS), here the key idea is to replace existing complex multi-component systems by magneto-mechanically active materials.

The operation of MSM alloys as shape memory material was previously shown in micro- and nanoactuators: Ni-Mn-Ga beams exhibited reversible thermal and thermomagnetic shape memory effect down to 100 nm [10 – 12]. The operating principle there was based on the martensite-austenite phase transformation induced by heating and/or by magnetic field application. However, to obtain the true advantage of the MSM effect, especially the fast and large actuation simultaneously, MIR must be employed. Thus, MSM microactuators should be based on the single-crystalline material.

Recently, we have shown the feasibility of creation of a magnetically active micropillar by FIB milling technology followed by electro-chemical etching [13]. In the present study, we report on the reversible actuation of MSM micropillar. Bulk Ni-Mn-Ga single crystal used for the pillars milling exhibited five-layered modulated martensite structure at room temperature.

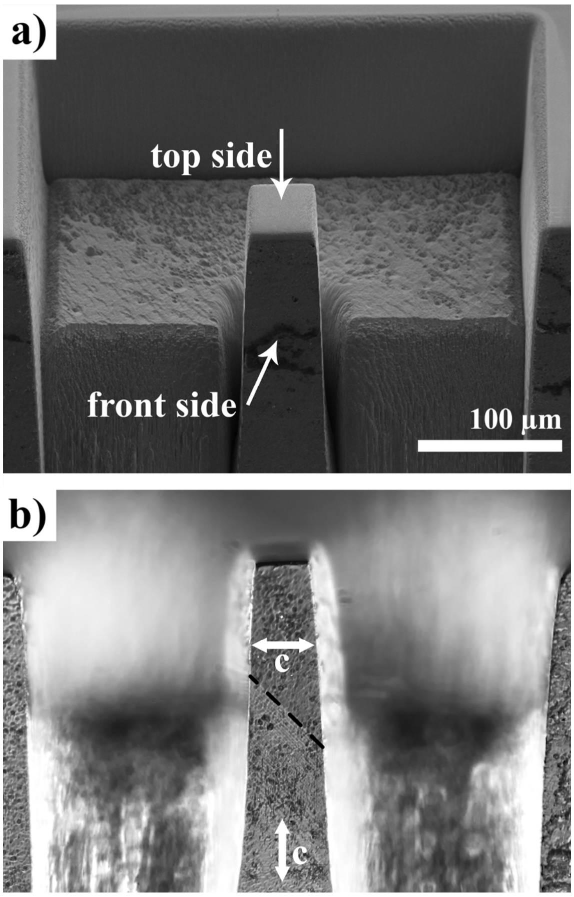

Fig. 1: *(a) Top-front view of the pillar captured by SE detector in SEM after FIB milling procedure and (b) optical micrograph of the side of fully actuated pillar in polarized light. In (a), the top and front sides of the pillar are marked with arrows. In (b), easy magnetisation c-axis orientations of twin variants are denoted by arrows, TB is marked by dashed line. Both images are equally scaled.*

Martensite transformation and Curie temperatures of the crystal were $T_M = 321$ K, $T_A = 327$ K and $T_C = 371$ K, and maximum possible MFIS derived from the lattice parameters was $1 - c/a = 6.3\%$ [14]. Thus, our goal was to achieve strains of more than 6% by application of a magnetic field. Ultimately, the reverse actuation must not involve a mechanical force application to the material.

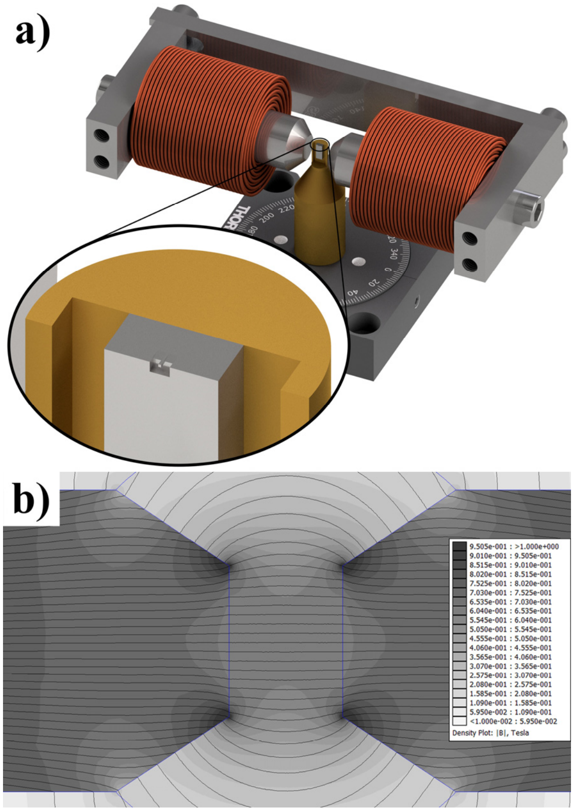

Fig. 2: *(a) Schematic view of the in-house built rotatable sample holder setup equipped with an electromagnet. (b) Magnetic field distribution within the air-gap calculated in Finite Element Method Magnetics package [15].*

Experimental

Fig. 1(a) shows the SEM image of the micropillar after FIB milling with the size of approximately $45\times45\times120$ μm^3. The electro-chemical removal of about 2 µm of ion-beam-damaged surface layer enabled magnetic field actuation of the micropillar [13]. The side view of the sample with magnetically induced twin variant in first possible TB orientation is shown in Fig. 1(b), from which the active length of the pillar was found to be about 100 µm.

Fig. 2(a) represents the schematic view of the in-house built rotatable sample holder setup equipped with an electromagnet. The setup was designed for the direct observation of the pillar response to the applied magnetic field. An electromagnet was capable of creating magnetic fields up to $\mu_0H = 0.65$ T within 6 mm long cylindrical air-gap between the concentration poles of 8 mm in diameter. Fig. 2(b) shows the magnetic field distribution at 5 A current within the air-gap calculated in Finite Element Method Magnetics package [15].

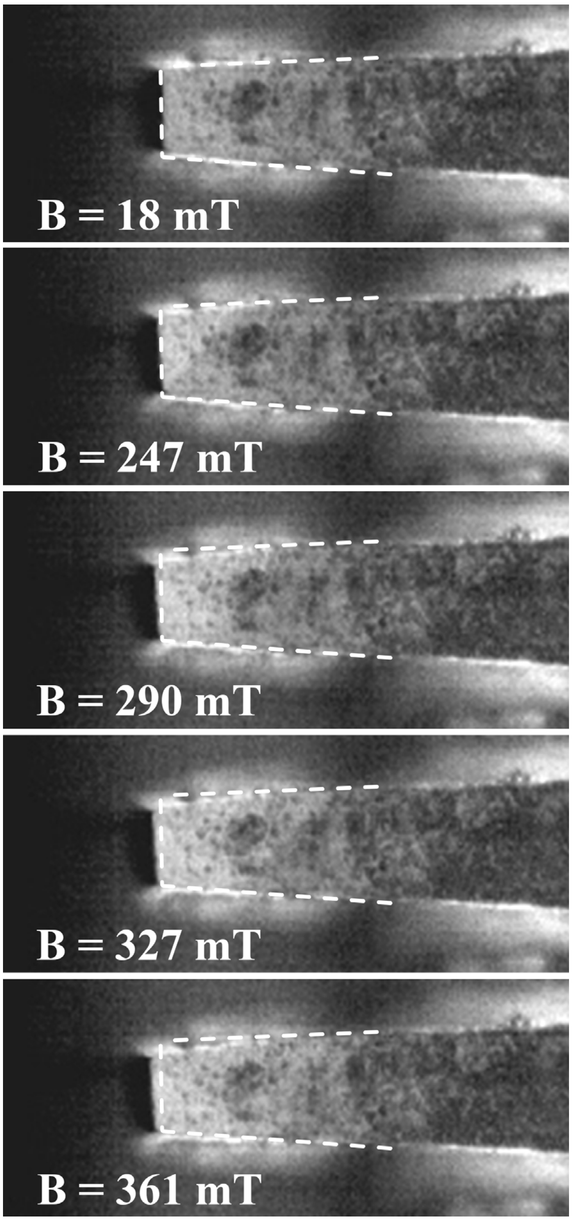

Fig. 3: *Temporally ordered optical micrographs of the MIR of the pillar during the magnetic field sweep. Dashed line denotes initial pillar shape on each frame for the reference.*

Prior to the MIR investigation, the sample with the milled pillar was reoriented to the single-variant state in saturating magnetic field ($\mu_0H = 1.5$ T) applied along the pillar longest dimension. It was then glued with a super glue onto the sample holder to ensure that TBs will move only within the pillar and will not be driven by the MIR of twin variants in the bulk. Then the sample holder was oriented in a way that the magnetic field will be applied perpendicularly to the pillar, see Fig. 2(a). The MIR of the pillar was recorded at 30000 frames per second by Photron FASTCAM SA5 model 775K-M2 monochrome video camera temporally synchronized with the magnetic field sweep from remanent field of 0.02 T to 0.65 T. Polarized light contrast was used to distinguish TB position.

Results and Discussion

Fig. 3 represents the indicative frames of the footage with corresponding values of applied magnetic field. The TB motion occurs in steps, which is explained by the non-uniform field distribution within the sample [16]. To retrieve the initial state of the pillar (fully contracted) the sample holder was rotated 90°. During the magnetic field sweep TB moved through the entire pillar within less than 0.1 ms when the field reached value of 0.12 T.

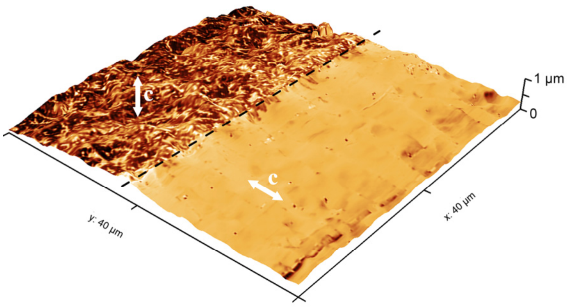

Fig. 4: *AFM image of the region of the pillar with the TB, mapped by MFM image. Arrows indicate easy magnetisation c-axis orientation in twin variants. Dashed line denote TB position.*

The second possible TB orientation variant was induced by repeated magnetic field application in another pair of perpendicular directions (a normal to the front and a normal to the top sides of the pillar). Fig. 4 shows Magnetic field microscopy image of the front side of the pillar with the TB in the middle. We observed a branched magnetic domain (MD) structure in the martensite variant with the easy magnetisation axis perpendicular to the surface and a 'needle-like' MD structure in the variant with the c-axis laying in the surface plane [17]. The observed MD structure is inherited from the bulk material [18]. This confirms that magnetic properties of the studied object are similar to those of the bulk.

Conclusions

We presented for the first time the magneto-mechanically active micropillars manufactured from the bulk Ni-Mn-Ga single crystal using standard techniques. The thickness of ion-beam-damaged layer was found to be smaller than 2 μm. Fully reversible MIR of the pillar was shown to be possible. The magnetic fields required for magnetic actuation are below 0.4 T. These important results indicate that FIB milled structures with the scale of several micrometres based on the MSM alloys could be used as micro-magneto-mechanical devices.

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