Two-Way Shape Memory Effect and Micromachine of Rapidly Solidified Ferromagnetic Fe–Pd Ribbon

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Ferromagnetic Fe–Pd alloy is a magneto-thermoelastic actuator material that has a large magnetostriction and the shape memory effect. In order to use the Fe–Pd alloy for a micromachine, we investigated the behavior of the shape memory effect for rapidly solidified Fe–29.6 at% Pd alloy ribbons. From the results, the ribbon exhibited a reversible two-way shape memory effect (TWSME) in the temperature range of 273 to 403 K, where the transformation from the martensite phase to austenite phase is found. On the basis of the development of an actuator of rapidly solidified Fe–29.6 at% Pd ribbon, a small simple-structured micromachine system was fabricated. A wireless micromachine is controlled remotely by an alternating magnetic field: it is able to swim in a fine liquid pipe with the aid of the gripping motion of a small ball. The ball is released by heating it to 340–350 K. This unique fishlike swimming micromachine will be applicable to medical curing devices in the body and as a nondestructive investigation tools for industrial machines and structures.

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1. Introduction

The ferromagnetic shape memory alloy (FSMA) Fe–Pd is expected to be useful as a magnetic-field-drive sensor/actuator material for micromachines and intelligent/smart material systems. The FSMA exhibits a large strain caused by the initiation of martensitic twining and its movements.1) Although Fe2Pd3 single-crystal2,3) and Fe2Pd3 polycrystalline bulk4) samples exhibit large magnetostriction, their face-centered tetragonal (FCT)-face-centered cubic (FCC) transformation temperatures are lower than room temperature.

In previous studies5,6) we showed that a rapidly solidified Fe–29.6 at% Pd alloy ribbon prepared by the melt-spinning method has a stronger crystal anisotropy and a large magnetostriction of 1.0 × 10−3 with a good shape memory effect in a wide temperature range of 300 to 380 K. Furthermore, the data obtained with the elastomometer shows the two-step (low and high temperature) FCT-FCC phase transformations.7)

Here, in order to use the Fe–Pd alloy for a micromachine, we investigated the behavior of the shape memory effect in more detail for rapidly solidified Fe–29.6 at% Pd alloy ribbons. They exhibited the reversible two-way shape memory effect in a wide temperature range of 273 to 403 K.

Next, we tried to develop a new type of wireless micromachine that would be controlled remotely by an alternating magnetic field and that would move in a fine pipe just like the fry of an eel. This prototype micromachine is made from a simple-structured shape using only the Fe–29.6 at% Pd ribbon.

The two-way shape memory effect is utilized for self-gripping motion.

2. Experimental Procedure

Ingots of Fe–29.6 at% Pd alloy were prepared from electrolytic iron (99.98%) and palladium (99.998%) metals by arc-melting in an argon atmosphere. Ribbon samples 60 μm thick were produced from these ingots using the single-roll melt-spinning apparatus, which is designed in this laboratory,5,6) on condition of the rotational surface speed of 31.4 mps. The sample was spun onto an iron wheel in an argon atmosphere. The composition of the ribbon was checked with an electron probe microanalyzer. The structure of the ribbon was analyzed by X-ray diffraction (XRD). The variation of magnetization in an applied magnetic field of 50 mT was measured by VSM. The two-way shape memory effect for the as-spun Fe–29.6 at% Pd ribbon was investigated in a wide temperature range of 293 to 403 K.

The size of the prototype micromachine [shown in Fig. 1(b)], which was made from a simple-structured shape using a only Fe–29.6 at% Pd ribbon, is 3.8 mm in length, 0.62 mm in width and 60 μm in thickness, respectively. The top-end part is locally curved for gripping a very small ball and the bottom-end part is thin and flat where a part of the material is locally twisted at an angle of about 70° in order to obtain fluctuations similar to fin movements under an alternating magnetic field [see Fig. 1(b)]. In addition to this, a part of the fin (i.e., the shadowed area) was locally annealed at about 1200 K for 30s to create an austenite phase with a high magnetic susceptibility.7) A transparent polymer-pipe filled with static water was encircled around the concentric electromagnetic coil and the micromachine was able to move in the pipe, as shown in Fig. 1(a). In this case, an alternating magnetic field was applied perpendicular to the length of the micromachine, and it was movable horizontally around the coil. The micromachine’s motion in the pipe (diameter = 3 mm) filled with static water was observed experimentally through an enlarged view by a digital video camera under an alternating magnetic field of 1.5 mT and a frequency from 0 to 30 Hz.

A grip is in the deformed-martensitic phase at a starting temperature of 300 K. When this micromachine approached the target point, microwave (2.45 GHz) radiation was applied outside of the liquid pipe. As the temperature of the micromachine increased up to 340–350 K, the grip in the austenite phase was opened and the ball was released.
3. Results and Discussion

3.1 Two-way shape memory effect of Fe–29.6 at% Pd ribbon

Figure 2 shows XRD patterns of Cu-Kα, with a cutting of Kα1, for (a) an as-spun ribbon and (b) a shortly annealed one. The XRD peaks in Fig. 2(a) show that the as-spun ribbon consists of FCT (martensite phase) and FCC (austenite phase) structures. On the other hand, XRD peaks in Fig. 2(b) obtained from the annealed ribbon exhibit the FCC structure.
Figure 3 exhibits the two-way shape memory effect of the as-spun Fe–29.6 at% Pd ribbon. The ribbon, which has a lightly curved shape, was deformed in a circular shape at room temperature, as shown in Fig. 3(a). As temperature increased up to 403 K, the curled ribbon returned almost to its original shape [Fig. 3(c)]. It was found that the shape recovery ratio of the as-spun ribbon at 403 K is about 100%. During the cooling process, the ribbon curled again as shown in Figs. 3(d, e, f). However, the curvature of Fig. 3(f) did not recover to the one of Fig. 3(a). On the other hand, in the 2nd and 3rd heating and cooling processes from this state [Fig. 3(f)], the ribbon changes its shape reversibly [(f) → (b) → (c) → (d) → (e) → (f)].

Figure 4 shows temperature $T$–strain $\varepsilon$ curves obtained from the shape change, as shown in Fig. 3, and a temperature-magnetostriction $\lambda$ curve. The strain of the outer surface was estimated by $\varepsilon = (D/2)/R$, where $D$ is the thickness of the ribbon and $R$ is the radius of curvature for the ribbon at each temperature, as shown in Fig. 3(b) in which the circle fits almost to the curve of the ribbon. The strains of (a)–(f) in Fig. 4 correspond to the curvatures of the ribbon in Fig. 3. The strain decreases rapidly in the temperature range of 303 to 323 K and then slowly from 353 to 403 K. On the other hand, the magnetostriction of this ribbon, which is caused by the rearrangement of the activated martensitic twin variants responding to magnetic field, at first increases until it reaches a maximum of 700 ppm at 373 K, and finally decreases suddenly over 373 K. From these results, it is thought that the transformation temperature of the martensite phase to the austenite phase for the as-spun ribbon is in these two temperature ranges of 303 to 323 K and 353 to 403 K, where the strain decreases from 1.4 to 0.4 and 0.4 to 0.2, respectively. On the cooling process, it also increases on two steps, from 0.2 to 0.65 and from 0.65 to 1.0 in temperature ranges of 333 to 303 K and 293 to 278 K, respectively. It is difficult to determine exactly at what temperature of the as-spun ribbon the austenite phase starts ($A_S$) and finishes ($A_f$) because of local residual strains caused by rapid solidification. We determined the values $A_S \sim 295$ K and $A_f \sim 313$ K using DSC and another high-temperature FCT-FCC transformation ($A_S \sim 400$ K, $A_f \sim 420$ K) using the acoustic elastometer method for as-spun ribbon. These two-step phase transformations are explainable the temperature-strain curve in Fig. 4.

Figure 5 shows the magnetization $M$ vs. temperature $T$ curve of the as-spun ribbon in an external magnetic field of 50 mT at a temperature range of 200 K (FCT martensite phase) to 473 K (FCC austenite phase).
3.2 Swimming micromachine

It was experimentally confirmed that this micromachine swam between the walls of a water tube, which differs from the formerly proposed system that consisted of a few swimming machines using the friction force by fin-kicking the wall of the machine. Moreover, it was found that this micromachine could move forward or backward by changing the frequency of the applied alternating magnetic field. Figure 6(a) shows the moving speed $v$ of the micromachine vs. the magnetic field frequency $f$. It moves backward at a low frequency range of 3 to 7 Hz: a maximum speed of 1.5 mm s$^{-1}$ arises at $f = 5$ Hz. On the other hand, it moves forward at a high frequency range of 10 to 30 Hz: a maximum speed of 6.3 mm s$^{-1}$ arises at $f = 20$ Hz. The shortly annealed fin consists of a FCC austenite phase with a high susceptibility and has a lower demagnetizing field than that of the top-end part (grip) because the fin-plane is parallel to the field. Consequently, since the fin fluctuates widely under a low alternating magnetic field [see, Fig. 6(b)], the water in the tube is stroked forward, that is, the micromachine moves backward. On the other hand, since the fin fluctuates fast and narrowly under a high alternating magnetic field [see, Fig. 6(c)], the micromachine swims forward. The maximum backward and forward speeds arise due to the resonance frequency effect against the sizes of the micromachine and tube.

Lastly, it was also confirmed that the behavior of gripping and releasing a small polymer ball (the diameter, $\varphi = 0.5$ mm) occurred by supplying microwave energy from the outside of the water pipe. Figure 7(a) shows the micromachine that grips the ball in the water tube. When 2.45 GHz microwaves were irradiated outside of the tube, the water was heated up and the grip opened automatically. Finally, the grip released a small ball at a water temperature of 340–350 K, as shown in Fig. 7(b).

TWSME can work to simplify the mechanism of the gripping actuator part and the machine structure, which will markedly contribute to downsizing against the assembled parts system in a conventional micromachine.

Therefore, it is thought that this unique simple-structured fishlike swimming micromachine with a grip will be applicable to medical curing devices and nondestructive investigation tools in the liquid pipes in industrial machines and structures.

4. Conclusions

We investigated the two-way shape memory behavior of rapidly solidified Fe–29.6 at% Pd ribbon. Based on the development of an actuator of this ribbon, a small simple-structured micromachine system was fabricated. The main results are summarized as follows:

(1) As-spun ribbon exhibits a reversible two-way shape memory effect in the temperature range of 273 to 403 K.

(2) The wireless micromachine can be controlled remotely by an alternating magnetic field: it swims in the fine liquid pipe backward at a low frequency range and forward at a high frequency range.

(3) The micromachine is aided by the gripping motion of a small ball that is released by heating to 340–350 K.

(4) This unique fishlike swimming micromachine will be applicable to medical curing devices in the body and to nondestructive investigation tools for industrial machines and structures.

REFERENCES