Repeatable Shape Memory Effect and Mechanical Resonance of TiNiCu-Coated Magnetic Ribbons

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Abstract. This paper describes a new bimorph-type actuator composed of a shape-memory-alloy coated magnetic ribbon. A high magnetostrictive amorphous ribbon (Metglas 2605SC, 37 mm×6 mm×0.025 mm) coated with a 1.0 μm thick sputter-deposited Ti₄₈.₅Ni₃₃.₅Cu₁₈ film exhibited a repeatable shape memory effect in the temperature range from 10 °C to 70 °C; reverse martensitic transformation upon heating bent the ribbon and martensitic transformation upon cooling flattened it. Simultaneous application of AC and DC magnetic fields excited the longitudinal mechanical vibration which can be monitored wirelessly with a pickup coil. The resonance frequency was proportional to the displacement of the ribbon within an accuracy of 0.76 %. Consequently, it is confirmed that a TiNiCu-coated magnetic ribbon actuator with high positioning resolution can be realized by monitoring its resonance frequency and feeding back it to the heating and/or cooling power control algorithms.

1. Introduction

Recently, MEMS (Microelectromechanical System) technology is studied intensively. For an actuator in MEMS, large force and displacement are required. Shape-memory-alloy (SMA) is considered as a promising actuator material for MEMS because of its large force and displacement. The SMA films have been applied to various actuators such as micropump[1,2], microgripper[1,3] and positioner[4]. Ishida et al. reported that substrate temperature during sputtering process can be reduced by adding Cu in TiNi-alloy and that a TiNiCu-coated polyimide sheet shows repeatable shape-memory effect[5,6]. Since the repeatable shape-memory effect is based on the phase transformations, the displacement has large temperature hysteresis which results in large positioning error.

On the other hand, Shibata et al. have developed a wireless hydrogen sensor that uses the mechanical resonance of a PdNi-coated magnetic ribbon[7]. By applying AC and DC magnetic fields to a highly magnetostrictive ribbon, the ribbon vibrates mechanically. The behavior of the vibration can be detected wirelessly by monitoring the induced voltage on a pickup coil placed away from the ribbon. As hydrogen concentration is increased, the volume of the PdNi-film increases and the ribbon is bent remarkably. Because the curvature of the ribbon greatly affects the mechanical resonance frequency, the hydrogen concentration can be detected by monitoring the resonance frequency.

In this context, it is expected that a TiNiCu-coated magnetic ribbon also shows the repeatable shape-memory effect and that its mechanical resonance frequency changes with temperature. In order to achieve heat-driven SMA actuator with high positioning resolution, the relationship between...
displacement and mechanical resonance frequency was investigated for a TiNiCu-coated magnetic ribbon.

2. Experiments
Magnetic ribbons (Metglas 2605SC) which have high permeability (15000) and high magnetostriction (30×10^-6) were shaped into rectangular with length, width and thickness of 37 mm, 6 mm and 0.025 mm, respectively. In order to relieve the internal stress and introduce a transverse magnetic anisotropy, the ribbons were annealed at 410 °C for 10 min in N2 flow under a transverse magnetic field of 100 Oe. Films of Ti48.5Ni33.5Cu18 alloy with thickness of 1.0 μm were deposited on the ribbons with a carousel-type magnetron sputtering apparatus. Three targets of pure Ti (100 mm in dia.), Ni (100 mm in dia.) and Cu (75 mm in dia.) were used to obtain a desired composition. Sputtering conditions were as follows; Ar pressure was 0.2 Pa. Substrate temperature was 310 °C. The sputtering powers of Ti, Ni and Cu targets were 1000, 224 and 85 W, respectively. Sputtering duration was 18 min.

The phase transformation temperatures of the film peeled from the substrate were determined by differential scanning calorimetry (DSC) with a sweep rate of 1.0 °C/min¹. The peak temperatures of martensitic and reverse martensitic transformations were determined to be 43.8 °C and 54.9 °C, respectively.

Figure 1 shows a resonance frequency measurement setup. DC bias magnetic field (Hdc) was applied on a magnetic ribbon with Helmholtz coil. A pick-up coil was connected to port 1 of a network analyzer to measure reflection coefficient (S11). The mechanical resonance frequency (fr) was defined as the dip point of S11. The temperature of the sample was swept in a range of 0~100 °C by blowing a hot or cold air on the quartz tube in which the ribbon was placed. The temperature sweep rate was 2.5 °C/min¹.

Figure 2 shows a definition of displacement (h) of the magnetic ribbon. The h value was calculated by counting the number of the pixels in a digitized picture. The measurement accuracy of h was 0.02 mm.

3. Results and discussions
Figure 3 shows temperature dependencies of h upon heating (open circles) and cooling (open squares). Reverse martensitic transformation upon heating bent the ribbon and h increased from 1.0 mm at 0 °C
to 2.2 mm at 70 °C. In contrast, martensitic transformation upon cooling flattened the ribbon and $h$ decreased from 2.2 mm at 70 °C to 1.0 mm at 0 °C. The fact that $h=2.2$ mm at 70 °C means that internal stress introduced to the TiNiCu-film during sputtering process remains after deposition. The maximum temperature difference between the martensitic and reverse martensitic transformations was determined to be 7.3 °C by the displacement measurement. These features are consistent with the DSC measurements. As a result, it is proved that a TiNiCu-coated magnetic ribbon actuator can be driven by heating and/or cooling and that its displacement has large temperature hysteresis which results in large positioning error.

Figure 4 shows temperature dependencies of $f_r$ upon heating (open circles) and cooling (open squares). The bias magnetic field was 3.5 Oe at which the largest $\Delta E$ effect was attained. The temperature dependencies of $f_r$ are quit similar to those of $h$ as shown in figure 3; $f_r$ increased upon heating and decreased upon cooling. Moreover, $f_r$ had the maximum temperature hysteresis of 7.6 °C which is almost equal to that of $h$.

Figure 5 shows the relation between $h$ and $f_r$ upon heating (open circles) and cooling (open squares). The $f_r$ values are proportional to the $h$. Furthermore, there is no hysteresis during thermal cycling within an accuracy of 0.76 %. Consequently, it is confirmed that precise position control of a TiNiCu-coated magnetic ribbon actuator can be realized by feeding back the monitored $f_r$ values to the heating and/or cooling power control algorithms.

The mechanism of the change in $f_r$ with temperature is considered to be as follows; TiNiCu alloy film on magnetic ribbon expands on heating and bends the ribbon. Figure 6 shows the $H_{dc}$ dependencies of $f_r$ at (a) 25 °C and (b) 60 °C. The $f_r$ shows deep and shallow dips at 25 °C and 60 °C, respectively. Figure 7 shows the schematic drawings of the magnetic anisotropies for (a) flat and (b) bent magnetic ribbons. When the magnetic ribbon is flat and has single axis anisotropy in the width direction, large $\Delta E$ effect brings about the considerable decrease in $f_r$ at $H_{dc} = H_k$ as shown in figure 6(a). In contrast, as temperature is increased, the ribbon bends and the tension is introduced on the TiNiCu-coated side of the ribbon. This tension causes the longitudinal magnetic anisotropy due to the reverse magnetostriction effect. Accordingly, the average magnetic anisotropy becomes isotropic as shown in figure 7(b), which weakens $\Delta E$ effect and increases the $f_r$ at $H_{dc} = H_k$. This interpretation is consistent with the report on the PdNi-coated magnetic ribbon which was investigated as a hydrogen sensor[7].

![Figure 3](image-url)  
**Figure 3.** Temperature dependencies of displacement ($h$) upon heating (open circles) and cooling (open squares).

![Figure 4](image-url)  
**Figure 4.** Temperature dependencies of resonant frequency ($f_r$) upon heating (open circles) and cooling (open squares).
4. Conclusion
A high magnetostrictive amorphous ribbon (Metglas 2605SC, 37 mm×6 mm×0.025 mm) coated with a 1.0 μm thick sputter-deposited Ti$_{48.5}$Ni$_{33.5}$Cu$_{18}$ film exhibited a repeatable shape memory effect in the temperature range from 0 °C to 70 °C; reverse martensitic transformation upon heating bent the ribbon and martensitic transformation upon cooling flattened it. The temperature difference between the martensitic and reverse martensitic transformations was 7.3 °C. The resonance frequency of the longitudinal mechanical vibration excited by simultaneous application of AC and DC magnetic fields indicated the similar temperature dependence to the displacement. As a result, the mechanical resonance frequency was proportional to the displacement within an accuracy of 0.76 % and the relationship was not affected by the thermal hysteresis. Consequently, it was confirmed that a TiNiCu-coated magnetic ribbon actuator with high positioning resolution can be realized by monitoring its resonance frequency and feeding back it to the heating and/or cooling power control algorithms.

5. References
[1] Fu Y, Du H, Huang W, Zhang S and Hu M 2004 Sensors and Actuators A112 395
Acknowledgments
We thank Dr. Masaki Nakamura at Hitachi Metals, Ltd. (former Yamagata University) for his useful discussion on this study.