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Magnetic field-induced reversible actuation using ferromagnetic shape memory alloys

Yuanchang Liang *, Yuji Sutou [1], Taishi Wada, Cheng-Chun Lee, M. Taya, T. Mori

Department of Mechanical Engineering, Center for Intelligent Materials and Systems, University of Washington, Seattle, WA 98195-2600, USA

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Abstract

This paper presents a simple method to examine whether a ferromagnetic shape memory alloy can be used as an actuator by controlling the transformation temperature by magnetic field. Both Fe–Pd and NiAlCo alloys are studied. The analysis results show the recently discovered alloy of NiAlCo cannot be used. Although an Fe–Pd alloy can be used, in principle, for magnetic field actuation, the work extracted by magnetic actuation is small.
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Keywords: Ferromagnetic shape memory alloy; FePd; NiAlCo; Magnetic field; Actuator

1. Introduction

Ferromagnetic shape alloys are currently studied for possible applications of actuation controlled by magnetic field. One application focuses on the martensite variant change induced by magnetic field [1–3]. The other utilizes the forward and reverse martensitic transformation controlled by the magnetic field. This note is concerned with the latter subject. The note proposes a simple method to quickly see whether a ferromagnetic shape memory alloy can be used as reversible actuator manipulated by magnetic field. It also provides a method to evaluate the work extracted by this magnetic actuation. Of course, the alloy does not provide the work, but transmits the magnetic energy as energy converter. If austenite and martensite differ in magnetic properties, transformation temperature changes when magnetic field is applied. Consider the case that martensite is more strongly magnetized under a magnetic field than austenite as in NiAlCo. NiAlCo may exhibit magnetic field-induced actuation in the martensite phase, since it shows 0.06% strain after a suitable heat treatment [4]. The present paper will also examine the case of Fe–Pd alloy which has the opposite property. However, the identical discussion is given for this type of alloy, too. By measurements of standard and simple experiments, we can

* Corresponding author. Tel.: +1-2066856722; fax: +1-2066164088.
E-mail address: yliang@u.washington.edu (Y. Liang).
[1] Permanent address: Department of Materials Science, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan.

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evaluate the actuation capacity of the alloy in a straightforward way.

2. Analysis and conclusion

First, consider an ideal case that the forward and reverse transformation occurs at the same temperature with no hysteresis. Fig. 1(a) is the amount of transformation vs. temperature curve. Under no magnetic field, the transformation occurs at T_0, while it does at T_0' under a magnetic field. Only between T_0 and T_0', the magnetic field can supply work by a cycle of the application and removal of the field. Fig. 1(b) is the corresponding free energy–temperature curve. The free energy of martensite is shifted (relatively) downwards by W_M when the magnetic field is applied. The work extracted by one cycle of the field application is maximum (W_M) at T_0 and minimum (0) at T_0'. W_M is calculated from the magnetization curves of martensite and austenite.

Next, we examine another ideal case: Fig. 2. The transformation is complete at the martensite start temperature (M_s and M_s') which is assumed to be the same as martensite finish temperature and this holds also for the reverse transformation (A_s and A_s') at austenite start temperature which is also assumed to be equal to austenite finish temperature. However, the transformation involves hysteresis. Work can be extracted in case (a), but not in case (b) by a cycle of magnetic activation. Hysteresis means that a certain amount of energy is dissipated for the martensite plates to grow or shrink. When the dissipation energy is small, case (a) is observed. When it is large, case (b) occurs. This point is discussed in more detail later.

Fig. 3 is for a case close to actual transformation, which has a temperature range of the transformation and hysteresis. To conduct a simple examination, the amount of the forward and reverse transformation is assumed to linearly depend on temperature change from the start of forward or reverse transformation. If an alloy belongs to category (a), we can use reversible magnetic actuation. If an alloy has the transformation characteristic of (b), the reversible magnetic actuation is not achieved. Thus, this alloy cannot be used as a component of a reversible actuator. Fe–Pd belongs to case (a) and, thus, can be used for reversible magnetic actuation. A recently developed alloy of NiAlCo [5] shows the characteristic of (b). These points will be discussed later.

Let us estimate the amount of work extracted by reversible actuation in case (a). Our experience in thermoelastic shape memory alloys indicates that a

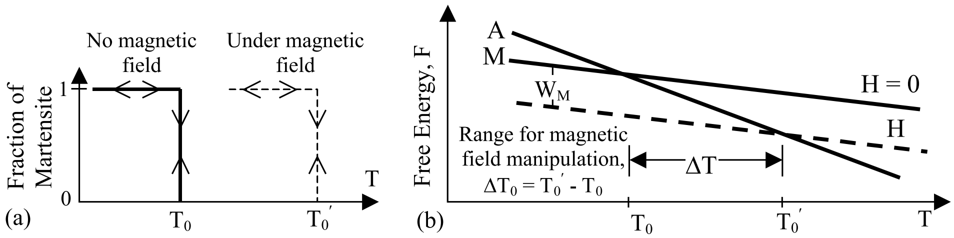

Fig. 1. Ideal case of (a) martensite fraction–temperature curve and (b) free energy–temperature curve where A and M denote austenite and martensite, respectively.

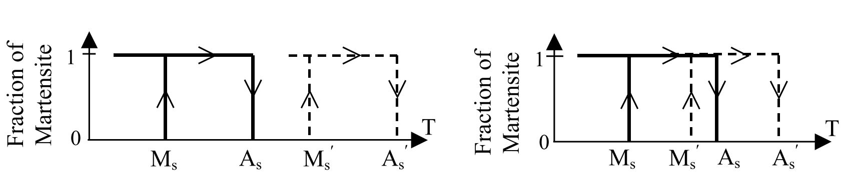

Fig. 2. Actual case of martensite fraction–temperature relation with some idealization. (a) No overlapping case where reversible actuation is possible between A_s and M_f' and (b) overlapping case where no reversible actuation is achieved.

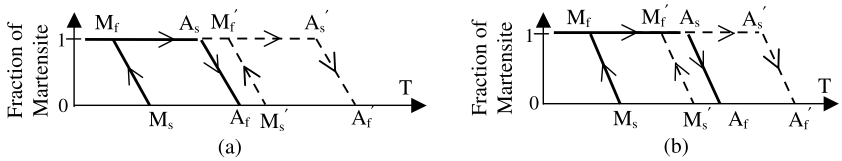

Fig. 3. More realistic case of martensite fraction–temperature relation. (a) No overlapping case where reversible actuation is possible between A_s and M_f' and (b) overlapping case where reversible actuation is not possible.

particular martensite plate always appears at an identical temperature and disappears at another identical temperature. For this martensite plate, we shall use the case of slightly idealized curves, Fig. 4. Fig. 4(b) is the free energy–temperature curve, where the energy supplied by a magnetic field (W_M) and dissipation energy (W_D) are also shown. When actuated at A_s, we can extract the work given by

$$W_E(A_s) = W_M - 2W_D. \tag{1}$$

When the actuation is done at M_s', no work is extracted because all energy supplied by magnetic field is consumed by the dissipation energy,

$$W_E(M_s') = 0. \tag{2}$$

Between A_s and M_s', it is

$$W_E = \{(M_s' - T)/(M_s' - A_s)\}(W_M - 2W_D). \tag{3}$$

Thus, between A_s and M_s', the average work of

$$\overline{W}_E = (W_M - 2W_D)/2 \tag{4}$$

can be extracted by a cycle of magnetic actuation.

We propose that the overall transformation of a more realistic case shown in Fig. 3 originates from the existence of the distribution T_0. In this case, the temperature range usable for magnetic actuation is between A_s and M_s'. The work extracted depends on the subranges of temperature.

$$W^* = \{(M_s' - T)/2(M_s' - M_f')\}(W_M - 2W_D) \quad \text{for } A_f \leqslant T \leqslant M_s'. \tag{5}$$

The term in the first brackets is the fraction of martensite which appears by the application of the field and disappears by the removal of the field. The term in the second brackets is 4. The average (5) is

$$\overline{W}^* = \{(M_s' - A_f)/4(M_s' - M_f')\}(W_M - 2W_D). \tag{6}$$

In the central temperature range, i.e. between A_f and M_f', the extracted work does not depend on the temperature. It is given by

$$W^* = \{(M_s' - A_f)/2(M_s' - M_f')\}(W_M - 2W_D) \quad \text{for } M_f' \leqslant T \leqslant A_f, \tag{7}$$

since the fraction of martensite controlled by the magnetic field is $(M_s' - A_f)/(M_s' - M_f')$ in this temperature range. In the third range,

$$W^* = \{(T - A_s)/2(A_f - A_s)\}(W_M - 2W_D) \quad \text{for } A_s \leqslant T \leqslant M_f', \tag{8}$$

the average of which is equal to (6).

It is of course assumed that the temperatures characterizing the transformation such as M_s and M_f are experimentally determined. W_D is simply estimated from

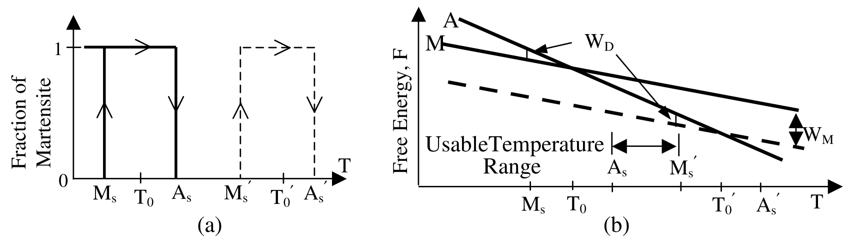

Fig. 4. Transformation of a single martensite plate. (a) Martensite fraction–temperature curve (the solid line is under no magnetic field, while the dashed line is under magnetic field). (b) Free energy–temperature curve.

$$W_D = S(A_f - M_s)/2, \quad (9)$$

where S is the entropy increase from martensite to austenite, and given by $S = H/T_0$ where H is the enthalpy of the transformation obtained by standard thermal analysis such as a DSC measurement, T_0 is the temperature at which the free energy of austenite is equal to that of martensite under no magnetic field. The above analysis assumes that A_f is higher than M'_f. The case that A_f is lower than M'_f can be similarly analyzed. In this case, more energy can be extracted for reversible magnetic actuation, since this means that more magnetic work is supplied for transformation or larger amount of martensite has the same transformation temperature.

Fig. 5 shows that Fe–30.5%Pd belongs to the category described by Fig. 3(a), where the definition for the solid and dotted lines are exchanged. When a specimen was slowly heated under no magnetic field after the completion of the transformation and the reverse transformation partially progressed as shown in (a), a magnetic field of 8×10^5 A/m (1 T) was suddenly applied at 2 °C. Then, some martensite plates, which had still remained at the last stage, disappeared, as shown in (b). When the field was removed, the same martensite plates reappeared as in (a). This is consistent with the magnetization of the alloy in the austenite and martensite shown in Fig. 6. It is clear that the austenite is more stable under a magnetic field. As seen in Fig. 6, the effect of magnetic field should not differ much between 4×10^5 and 8×10^5 A/m. This point was examined using a field of 4×10^5 A/m. The reversible change between Fig. 5(a) and (b) was confirmed. A possible effect of magnetic force caused by non-uniform magnetic field and producing a stress in a specimen is ruled out. For the specimen was a polycrystal. Thus, whether this stress was tensile or compressive, the same stress could promote the forward transformation in some grains, even if the stress helped the reverse transformation in a certain grain. We have never seen an increase in the amount of martensite in Fe–Pd when a magnetic field is applied in a similar experiment to the present one.

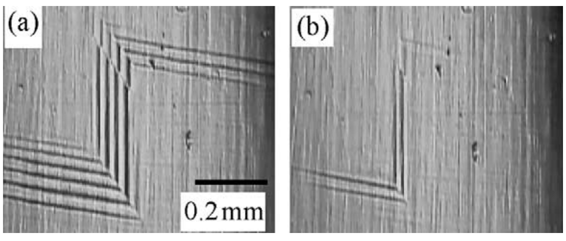

Fig. 5. Metallographic observation of magnetic field-induced reverse transformation (martensite to austenite) in Fe–30.5%Pd at 2 °C. (a) Martensite plates under no magnetic field. (b) Some plates disappear when a field of 8×10^5 A/m (1 T) is applied.

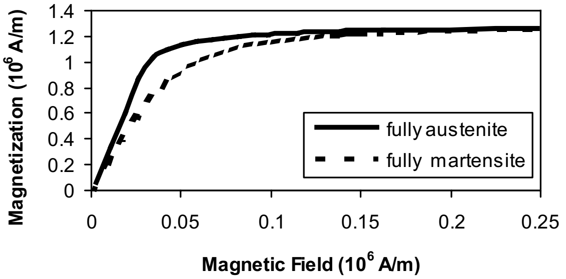

Fig. 6. Magnetization curves of Fe–30.5%Pd. The solid line is for austenite at 23 °C, while the dashed line is for martensite at −23 °C.

Fig. 6 exhibits the magnetization curves measured by a SQUID magnetometer (in NIST Magnetics Lab, Boulder, Colorado) of both the austenite (23 °C) and martensite (−23 °C) phases of an Fe–30.5%Pd sheet, $10 \times 2 \times 0.5$ mm, having M_s of 3 °C and A_f of 5.5 °C. Using these curves, we will calculate the work extracted by the application of a magnetic field. W_M is calculated as 27 kJ/m^3 [6] when the magnetic field is 8×10^5 A/m. It is assumed that the magnetization does not sensitively change near the transformation temperature. H has been reported to be 4.2×10^6 J/m^3 and T_0 is approximately 300 K [8]. $A_f - M_s$ is approximately 1 K [7]. The transformation vs. temperature curve is approximated as in Fig. 3 and $M_s - M_f$ is approximately 5 K. Thus, the maximum work extracted by one cycle of the application and removal of this magnetic field is $W^* = 1.3$ kJ/m^3. Here, (7) is used. Similar to the result reported by Koeda et al. [9], the initial magnetization shown in Fig. 6 is smaller in the martensite state than in the austenite state.

The strain achieved by forward or reverse transformation is of the order of $\varepsilon_a \cong 10^{-2}$ [6,7],

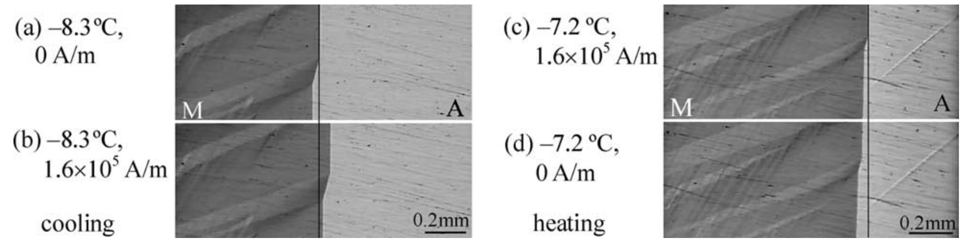

Fig. 7. Effect of magnetic field 1.6×10^5 A/m (0.2 T) on transformation in NiAlCo. The dark area is martensite and the bright area is austenite. When the field is applied, the transformation front advances from (a) to (b) during cooling. When the field is removed, the transformation front retreats from (c) to (d) during heating.

when the complete transformation is fully used. Here, ε_a is the transformation strain along the a-axis in martensite. Thus, in the above temperature range, the strain is roughly $\varepsilon \cong \varepsilon_a(M'_s - A_f)/(M'_s - M'_f)$. This means that the stress of the order of $\sigma \cong W^*/\varepsilon = (W_M - 2W_D)/2\varepsilon_a$ is realized by the magnetic actuation. This is calculated as 0.65 MPa. If we use the average transformation strain, $(2\varepsilon_a + \varepsilon_c)/3 = 2.2 \times 10^{-3}$ [8], 3 MPa is obtained. (ε_c is the transformation strain along the c-axis of martensite.) Thus, the magnetic actuation using the transformation provides a very small stress.

Fig. 7 is for Ni–30%Al–34.5%Co. This specimen is in β single phase with large grains, prepared by secondary recrystallization at 1350 °C. Then, a single crystal specimen with a size of about 5 mm × 5 mm × 2 mm was obtained from specimen with a large grain size. A magnetic field of 1.6×10^5 A/m was applied during cooling and the front of the transformed region advanced as shown in Fig. 7(a) and (b). When the field was removed, no change occurred. When the field was applied during heating, the interface between the austenite and martensite did not move. Also, if the field was immediately removed, no change in the position of the interface was observed. However, when the field was removed after some time, during which the temperature was raised slightly under the field, the interface moved to decrease the amount of martensite. The structural change during heating is shown in Fig. 7(c) and (d). These are all consistent with the behavior described in Fig. 3(b). It also has been confirmed that the reversible actuation does not occur even if magnetic field of 8×10^5 A/m is applied. That is, NiAlCo cannot be used as a magnetic actuator, if the austenite–martensite transformation is to be used.

In conclusion, a simple method to see whether a ferromagnetic shape memory alloy can be used as actuator by controlling the transformation temperature by magnetic field is presented. Also, the amount of work extracted by magnetic actuation is estimated for an Fe–Pd alloy, which can, in principle, be used for magnetic field actuation. A recently discovered alloy of NiAlCo cannot be used.

Acknowledgements

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