Reversible strain induced by martensite variant rearrangement under magnetic field and mechanical loading of Fe–Pd single crystals

Tokujiro Yamamoto[a] and Minoru Taya[b]
Center for Intelligent Materials and Systems, Department of Mechanical Engineering, University of Washington, P.O. Box 352600, Seattle, Washington 98195-2600

(Received 15 January 2007; accepted 24 May 2007; published online 18 June 2007)

Reversible and repeatable strain without external bias stress was induced by applied magnetic field-induced martensite variant rearrangement (VR) and compressive stress-induced martensite VR for Fe–Pd single crystals. The amounts of the reversible strain induced by the magnetic field and the compressive stress were 0.4% and 5.0%, respectively, where the Fe–Pd specimen was martensitically transformed from austenite to martensite which consist of two large correspondence variants (CVs). The motion of the twinning boundary between the two CVs moved by applying the magnetic field or the compressive stress, and its movement was found to be reversible and repeatable. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2749718]

Shape memory alloys, such as TiNi intermetallic compounds, have been studied for the past several decades and they are considered to be candidates for actuator materials, because they can produce large recovery strain and force by martensitic phase transformation.[1] However, one of the bottlenecks for application of those conventional shape memory alloys to actuators is the fact that martensitic transformation is caused only by conduction of heat to use them and its speed of actuation is limited. On the other hand, ferromagnetic shape memory alloys, such as Fe–Pd, Fe_3Pt, and Ni–Mn–Ga, have also attracted strong interest among actuator designers as possible fast-responsive actuator materials. Although our previous studies[2–4] revealed that martensitic reverse transformation requires high intensity of magnetic field under which the induced strain remains modest, they are still attractive materials because single crystals of these alloys exhibit martensite variant rearrangement (VR) accompanied by large amount of strain by applying low intensity of magnetic field.[5–8] Reversible strain obtained in Ni–Mn–Ga ternary alloy single crystals by magnetic field is reported to exhibit as high as 2% under external bias stress, which helps converted variants return to initial ones upon removal of magnetic field; however, no reversible strain has been observed without bias stress.[9,10]

Fe–Pd austenite with face centered cubic (fcc) structure transforms to face centered tetragonal (fct) martensite with decreasing temperature as well as In–Tl binary alloys.[11–13] The VR is observed in Fe–Pd fct martensite specimens which transformed from fcc austenite single crystals. The VR is caused by twinning and detwinning of correspondence variants (CVs) in the fct martensite. The strain ε accompanied by the VR is geometrically calculated and expressed as a function of the c/a ratio of fct martensite.[14] The strain ε is usually irreversible without external bias stress. However, we found reversible VR without external bias stress in the previous study.[14] Such reversible strain is attractive for use in actuators. In the present letter, we studied the reversible VR and twinning pseudoelasticity of Fe–Pd fct martensite transformed from fcc austenite single crystals and measured the amount of the reversible strain without external bias stress.

The specimen used in this study was the same parallelepiped rectangular single crystal used in the previous study.[14] The specimen was cut from a single crystal ingot grown by the Bridgman method using Fe−30.5Pd (at. %) Ar arc-melted ingots. The dimension of the specimen is $2.0\times 2.2 \times 5.0\ \mathrm{mm}^3$ and all the edges are parallel to the $\langle 100\rangle$ directions of austenite. Martensite transformation start and finish temperatures, M_s and M_f, and reverse transformation start and finish temperatures, A_s and A_f, of the specimen are 6 and 0 °C, and 10 and 16 °C, respectively. Thus, according to the phase diagram of martensite of Fe–Pd system, it is estimated that the c/a ratio at −20 °C and the composition of the specimen are approximately 0.970 and Fe−30.0Pd (at. %), respectively.[12,13]

Magnetic field-induced strain was measured by using a laser displacement sensor at −20 °C, lower temperature than M_f. The experimental setup for the measurement is shown in Fig. 1. The specimen was located at the center of the gap between the yokes of an electromagnet. One end of the specimen was clamped and the other was contacted by a T-shaped lever made of aluminum. The specimen was indirectly cooled by pieces of dry ice, by way of a copper column. Constant magnetic field was applied along the longest side of the specimen by the electromagnet. To fix the copper

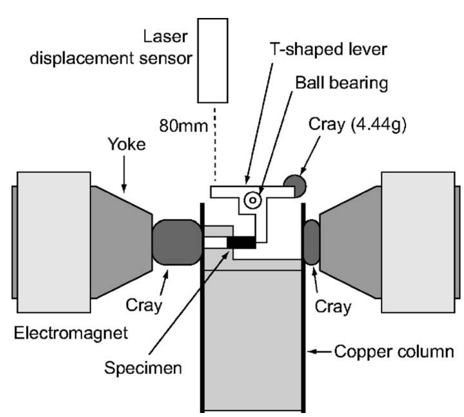

FIG. 1. Experimental setup for magnetic field-induced strain measurement.

[a]Present address: Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan; FAX: +81-22-215-2137; electronic mail: toku@imr.tohoku.ac.jp
[b]FAX: 206-685-8047; electronic mail: tayam@u.washington.edu

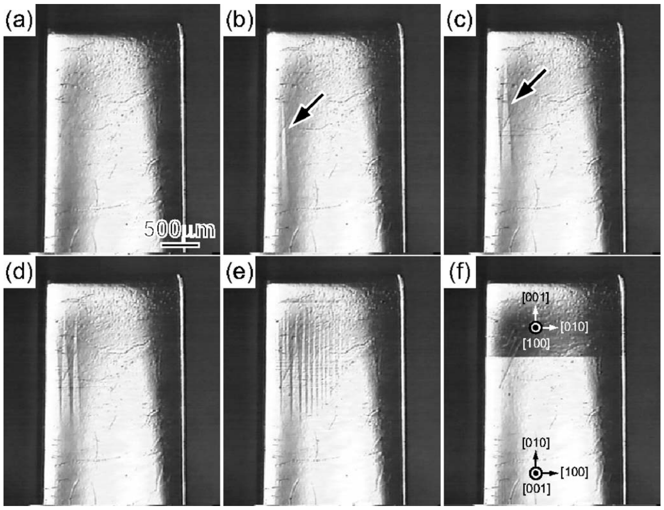

FIG. 2. Surface morphology change of the single crystal specimen during martensitic transformation. The arrows indicate growing wedge-shaped HPVs. The crystallographic orientations of the two fct martensite variants are shown in (f).

column under magnetic field, clay was placed between the column and the yokes of the electromagnet. A little clay (4.44 g) was put on the end of the lever to keep the lever contacting to the specimen by its rotation moment. The stress applied by the clay is less than 0.1 MPa, therefore, the influence of the stress on the measurement is negligible. The displacement induced by magnetic field was monitored every 0.2 s, with increasing and decreasing magnetic flux density. As one measurement was completed within 120 s, the influence of temperature change is considerably small.

Next, observation of surface morphology and measurement of stress-strain curves were performed while compressive stress was applied to the specimen along the longest edge by using an Instron machine at a strain rate of 10^{-4} s^{-1}. During this experiment, the specimen temperature was kept at −20 °C by flowing dry nitrogen gas which was cooled by liquid nitrogen and was introduced into a chamber with an observation window, whose outside was kept wet to prevent from getting the window fogged while the surface morphology was observed by a charge coupled device camera.

Surface morphology change was observed by the same experimental setup used in the previous study,[14] during a single crystal specimen being cooled. Figure 2 shows the sequence of the pictures taken during cooling of the specimen. Specimen temperature was 5 °C for Fig. 2(a) and 3 °C for Fig. 2(f), respectively. Martensitic transformation started from the left edge and wedge-shaped habit plane variants (HPVs) were grown and spread in the specimen. After the specimen was covered by HPVs, the specimen changed into a pair of dark and bright regions and clicking sound was heard. By trace analysis, it was found that the boundary between the two dark and bright regions corresponds to the {101} plane of fct martensite.

After the temperature was decreased to −20 °C and the specimen became the pair of CVs with a distinct twinning boundary, magnetic field was applied to the specimen along the longest edge. Although it was reported that application of external bias stress is required to induce twinning and detwinning,[9,10] this specimen exhibited reversible and repeatable strain without such bias stress. After several cycles of applying and removing the magnetic field, the strain induced

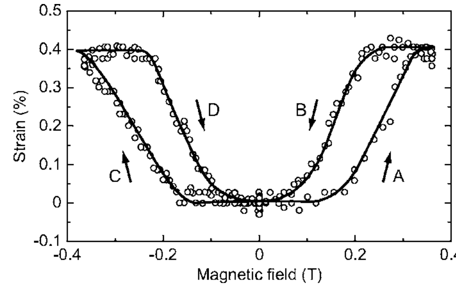

FIG. 3. Magnetic field-induced strain as a function of magnetic flux density measured in Fe–Pd single crystal. The magnetic flux density was increased and decreased in alphabetical order.

by the magnetic field was measured as a function of magnetic flux density and the results are shown in Fig. 3, where arrow sign shows the sequence of loading. In Fig. 3, negative magnetic flux density denotes the direction of the magnetic field being opposite to the initial loading direction. 0.4% of reversible and repeatable strain was obtained in this specimen by the magnetic field.

After the measurement of the reversible strain induced by the magnetic field at −20 °C, the single crystal specimen was once heated up to 50 °C, which is above A_f. Then, it was subjected to a compression test along the longest edge of the specimen at −20 °C after the boundary became distinct in order to measure the amount of the strain accompanied by stress-induced VR. Figure 4 shows the stress-strain curves for the first two cycles of loading and unloading, and the surface morphology change during the first loading is also depicted. For the first loading, the volume ratio of CV1 increased at the expense of CV2 with gradual increase in the compressive stress. When the stress reached 10 MPa, the whole specimen became a single variant of CV1 and the VR was completed [Fig. 4(e)]. After the strain reached 5.2%, the stress increased rapidly. For the first unloading cycle, the volume ratio of CV1 and the stress decreased with decreasing the stress. The stress during the first unloading was slightly lower than that during the first loading, but the unloading path is almost the same as the loading path. At the end of the first cycle of loading and unloading, 5.0% of

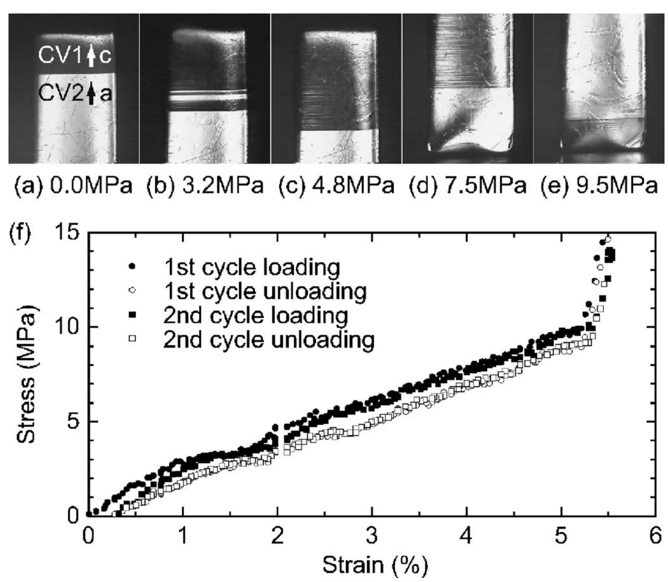

FIG. 4. [(a)–(e)] Change of volume ratio of CVs for the first loading and (f) stress-strain curves for the first two cycles of loading and unloading.

reversible strain and 0.3% of irreversible strain were observed in the specimen. The stress during the second cycle was almost the same as that during the first cycle for both loading and unloading. For the second cycle the strain caused by VR was completely reversible and the amount of the repeatable strain was 5.0%. It should be noted here that the hysteresis of the stress-strain curves during the loading and unloading cycles is considerably smaller than that of conventional shape memory alloys, because this reversible and repeatable strain is not accompanied by phase transformation but twinning. This repeatable strain under compressive stress could be utilized as a useful actuation mode if the magnetic flux gradient ∇B that provides the stress is applied to the specimen so as to induce the large strain by the above VR mechanism. This is similar to the hybrid mechanism used in fast actuation of polycrystalline Fe–Pd spring actuator.[15]

This work was supported by the National Science Foundation (CMS-0303536) where Jorn Larsen-Basse and Yip-Wah Chung are the program monitor. The authors would like to acknowledge helpful discussions with Setsuo Kajiwara, NIMS, Japan, Tsutomu Mori, UMIST, United Kingdom, Yuji Sutou, Tohoku University, Japan, and sample preparation of Fe–Pd single crystals by Thomas Lograsso, DOE Laboratory, AMES, Iowa.

[1] S. Miyazaki and A. Ishida, Mater. Sci. Eng., A **273-275**, 106 (1999).
[2] Y. Liang, Y. Sutou, T. Wada, C.-C. Lee, M. Taya, and T. Mori, Scr. Mater. **48**, 1415 (2003).
[3] T. Wada, Y. Liang, H. Kato, T. Tagawa, M. Taya, and T. Mori, Mater. Sci. Eng., A **361**, 75 (2003).
[4] H. Kato, T. Wada, T. Tagawa, Y. Liang, and M. Taya, Proceedings of International Symposia on Material Sciences for the 21st Century (ISM-21), Suita, Japan , 21–26 May, 2001, p. 296.
[5] K. Ullakko, J. K. Huang, C. Kantner, R. C. O'Handley, and V. V. Kokorin, Appl. Phys. Lett. **69**, 1966 (1996).
[6] T. Kakeshita, T. Takeuchi, T. Fukuda, M. Tsujiguchi, T. Saburi, R. Oshima, and S. Muto, Appl. Phys. Lett. **77**, 1502 (2000).
[7] T. Sakamoto, T. Fukuda, T. Kakeshita, T. Takeuchi, and K. Kishio, Appl. Phys. Lett. **93**, 8647 (2003).
[8] R. D. James and M. Wuttig, Philos. Mag. A **77**, 1273 (1998).
[9] S. J. Murray, M. Marioni, S. M. Allen, R. C. O'Handley, and T. A. Lograsso, Appl. Phys. Lett. **77**, 886 (2000).
[10] S. J. Murray, R. C. O'Handley, and S. M. Allen, J. Appl. Phys. **89**, 1295 (2001).
[11] T. Sohmura, R. Oshima, and F. E. Fujita, Scr. Metall. **14**, 855 (1980).
[12] R. Oshima, Scr. Metall. **15**, 829 (1981).
[13] R. Oshima, Proceedings of The International Conference on Martensitic Transformations (ICOMAT-86), Nara, Japan, The Japan Institute of Metals, 1986, pp. 971–978.
[14] T. Yamamoto, M. Taya, Y. Liang, T. Wada, and L. Sorensen, Acta Mater. **52**, 5083 (2004).
[15] T. Wada, M. Taya, H. H. Chen, and M. Kusaka, Proc. SPIE **5054**, 125 (2003).