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Magnetically Controlled Shape Memory Alloys: A New Class of Actuator Materials

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Materials that develop large strokes under precise and rapid control exhibit a great potential in mechanical engineering. Actuators made from those kinds of materials could replace hydraulic, pneumatic, and electromagnetic drives in many applications. However, no such materials are available to date. Piezoelectric and magnetostrictive materials exhibit rapid response, but their strokes are small. In shape memory alloys, strokes are large, but their control is slow due to thermomechanical control. Magnetic control of the shape memory effect was recently suggested by the present author for a principle of new kinds of actuator materials. These materials can develop strains of several percent, and their control is rapid and precise. Actuation of these materials is based on the reorienting of the twin structure of martensite or the motion of austenite-martensite interfaces by applied magnetic field. In the present report, magnetically induced motion of the austenite-martensite interfaces is demonstrated in an Fe-33.5Ni alloy.

Keywords

active material, actuator, adaptive, anisotropy energy, magnetically controlled shape memory effect, magneto-shape-memory material, magnetostriction, martensite interface, smart structure, twin boundary

1. Introduction

CONTROL of motion and force is one of the basic elements in mechanical engineering. Development of new materials has made it possible to produce motion and force using special functional materials called actuator materials. Employment of actuators based on these materials leads to simpler, lighter, and more reliable constructions than use of conventional technology. Actuators also can be integrated with sensing and control capabilities. Those systems, named adaptive, active, or smart structures, are becoming general in modern machine design. Sensing the operational parameters of a machine in real time and responding to the environmental or internal changes in a controlled manner make it possible to attain optimal operation, minimal energy consumption, enhanced lifetimes of the structures, and lower maintenance costs. The future trend is that advanced actuator and sensory materials integrated in smart structures will supersede conventional technology in machinery in a manner similar to how new electronic materials have replaced distinct components in electronic hardware. The roles of machine design, materials science, and control electronics overlap more.

The most important groups of actuator materials (Ref 1) are piezoelectric ceramics, magnetostrictive materials, and shape memory alloys. Piezoelectric ceramics develop mechanical deformation when subjected to an electrical field. Frequency response of these materials is fast, but strain amplitudes are very small, which limits their applicability. Magnetostrictive materials are strained when a magnetic field is imposed on them. This phenomenon is caused by the rotations of magnetic domains in the material, which are randomly oriented when the material is not subjected to a magnetic field. The orientation of the domains by external magnetic field results in the development of the strain. When the intensity of the magnetic field is increased, more magnetic domains orient themselves so that their magnetization vectors are parallel with the magnetic field in each region, and finally saturation is achieved. Elongation of the unit cells by the turning magnetization vectors is schematically presented in Fig. 1(a).

Figure 1(a) shows elongation of the unit cells by magnetic field in magnetostrictive materials; magnetization vector **M** turns parallel with the external magnetic field **H** in the unit cell, resulting in magnetostrictive elongation of the unit cell and a shape change of the material. Figure 1(b) shows turning of the unit cells by mechanical stress in conventional shape memory alloys; applied stress τ turns the unit cells of one twin variant into another resulting in twin boundary motion and a shape change of the material. Figure 1(c) shows turning of the unit cells by magnetic field in new magnetically driven shape memory materials; magnetic field **H** turns the unit cells of one twin variant into another and causes the shape change of the material. The easy magnetization direction is assumed to be parallel with the side of the unit cell.

Fe-Dy-Tb intermetallics, for example, Terfenol (Etrema Products, Inc., Ames, IA) (Ref 2), are commercially available magnetostrictive materials. Those materials offer strains up to 0.17%, which are an order of magnitude higher than those of the current piezoceramic materials. The forces developed by Terfenol are about 20 times higher than those of piezoceramics, and energy densities of Terfenol actuators are ten times higher than those attained in hydraulic machines. Actuators based on magnetostrictive strains of Terfenol were developed for active vibration control, sonic applications, and fuel injectors, and the number of new applications is rapidly increasing.

Shape memory metals (Ref 3) are materials that, when plastically deformed at one temperature, can recover their original undeformed state upon raising their temperature above an alloy-specific transformation temperature. In these materials, crystal structure undergoes a phase transformation into, and out of, a martensite phase when subjected to mechanical loads or

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temperature. The process when a mechanically deformed shape memory material returns to its original form after heating is called a one-way shape memory effect. Cooling the material subsequently will not reserve the shape change. The one-way shape memory effect is utilized in fastening, tightening, and prestressing devices. Strains of several percent can be completely recovered, and recovery stresses of over 900 MPa have been attained. Shape memory steels, especially high-strength nitrogen alloyed steels (Ref 4), are promising new developments due to their excellent performance and low cost. In the case of two-way effect, no deformation is required, and the material "remembers" two configurations that are obtained by heating and cooling to alloy-specific temperatures. The temperature difference between the two configurations can be as small as 1 to 2 K. Materials that exhibit a two-way shape memory effect are used to develop forces and displacements in actuators. Those actuators are applied in machinery, robotics, and biomedical engineering. The most extensively used shape memory materials are Ni-Ti and Cu-base alloys. A drawback of the shape memory actuators is their slow response due to the thermal control (especially in cooling) and low energy conversion, which is only a few percent.

1.1 *Principle of the Magnetically Controlled Shape Memory Effect*

An ideal actuator material for engineering applications would develop rapid strokes with large displacements and high forces under precise control. In addition, it should be economical enough to be used in mass products. No such material is available to date. Magnetic control of the shape memory effect has been suggested (Ref 5-8) for a principle of a new class of actuator materials, which can exhibit large strokes and high forces with rapid response. Actuation of these new materials is based on the control of the shape memory effect by the reorientation of martensite unit cells in an applied magnetic field. The motion of the martensite twin boundaries or austenite-martensite interface is controlled by the magnetic field in an analogous way as they are controlled thermomechanically in conventional shape memory alloys. Figures 1(b) and (c) show a two-dimensional illustration of the control of twin boundaries by stress in conventional shape memory alloys and by the magnetic field in the magnetically driven shape memory alloys.

In order for the shape memory effect to occur in conventional shape memory alloys, the martensite must exhibit a twinned substructure. The shape change of the shape memory material is based on the reorientation of the twin structure in an external stress field, which is illustrated in Fig. 1(b). Unit cells between two twin boundaries belong to the same twin variant. When stress is applied, some twin variants grow and some shrink to accommodate the shape change. Finally, the martensite plates can consist of only one twin variant. In some materials, applied stress induces formation of the martensite phase whose twinned substructure is preferentially oriented according to the applied stress. The principle of the new magnetically controlled shape memory materials, called magneto-shape-memory (MSM) alloys, is analogous to that of the conventional shape memory materials. The main difference is that in MSM materials, the motion of twin boundaries or the interfaces between martensite and the parent phase (austenite) is driven by the applied magnetic field. This principle is described here.

In crystalline ferromagnetic materials, magnetization vectors lie along certain definite crystallographic axes called directions of easy magnetization. Crystal anisotropy energy is an energy that directs the magnetization along these directions (Ref 9). When an external magnetic field is applied, the magnetization tends to turn from the easy direction of the unit cell to the direction of the external magnetic field (as shown for a magnetostrictive material in Fig. 1a). If the anisotropy energy is high, magnetic field strengths required to turn the magnetization are also high. If the energy of the motion of twin boundaries is low enough at the same time, magnetization can turn the unit cells as it turns to the direction of the external field. Magnetization then remains in the original easy direction in the turned unit cells. Figure 1(c) illustrates how the unit cells of one

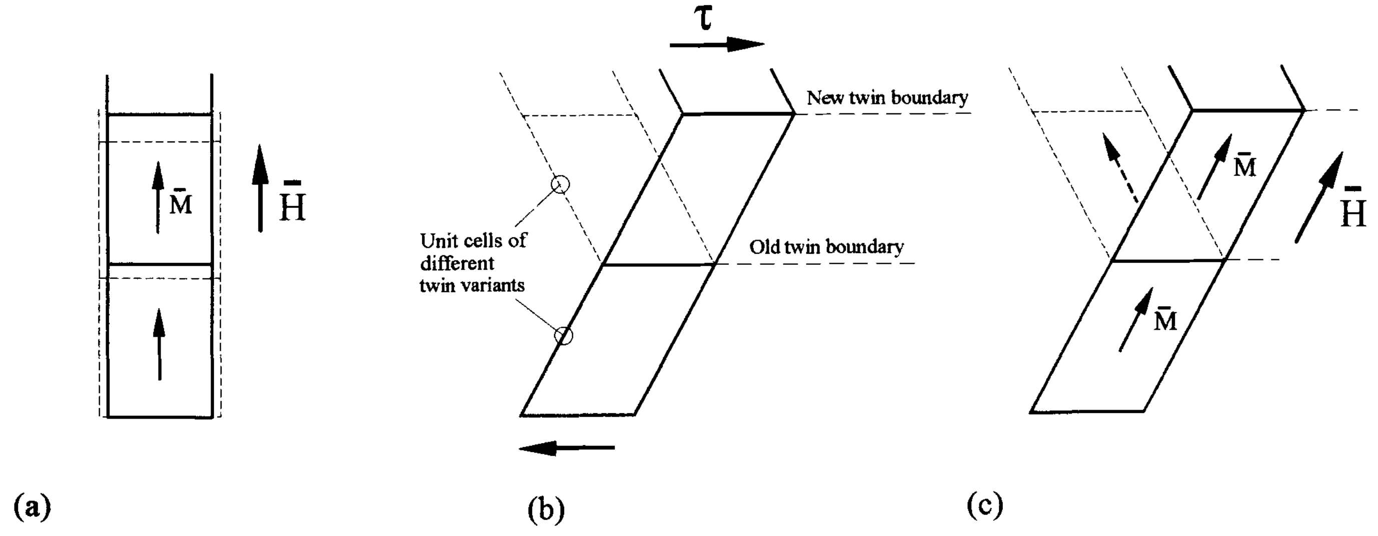

Fig. 1 Schematic presentations of the shape changes that cause the strokes in (a) magnetostrictive, (b) shape memory, and (c) new magnetically driven shape memory actuator materials (Ref 7, 8)

variant are turned into another by external magnetic field. As a result, twins in favorable orientation to the magnetic field grow at the expense of other twins. This causes the twin boundary motion and the shape change of the material, which finally results in the stroke of the actuator made from this material. The condition that makes possible the turning of the unit cells of one twin variant into another is expressed as:

$$U_K > E_t + W + E_0 \qquad \text{(Eq 1)}$$

where U_K is the anisotropy energy, E_t is the energy of twin boundary motion, W is the work done by the actuator material (if the turning is assisted by external stress, W is negative), and E_0 includes internal strain and other energy terms.

Effects of the external magnetic field on the orientation of the martensite unit cells can also cause the motion of martensite-martensite and austenite-martensite interfaces in an analogous way as applied stress causes the motion of those interfaces.

Because the reorienting of twins gives rise to recoverable strains of a few percent in conventional shape memory materials, the magnetic control of the shape memory effect should produce elongations of the same order. In some materials, twin boundaries or austenite-martensite interfaces are highly mobile under application of a mechanical stress. Very low stresses are then required to cause the movements of twin boundaries or austenite-martensite interfaces. Also magnetic fields, which can cause strokes in appropriate MSM materials, can be low if the energy terms on the right side of Eq 1 are small. Applied magnetic fields of only some tens of mT can cause strokes of a few percent in MSM materials. These strokes are more than an order of magnitude larger than those attained in high-magnetostrictive Terfenol. Because the maximal stresses produced by the MSM materials are mainly limited by the anisotropy energy, the stresses can be as high as those in Terfenol. If the magnetic straining of an MSM material is opposed by a high mechanical stress, the magnetically oriented twin structure could be recovered to the original structure under the stress, and the dimensions of the material that it had before magnetic straining are returned. The magnetization may, however, still remain in the direction of the external field under the load. As the external stress is removed, the twin variants turn again in such a way that their easy direction of magnetization is close to the external field. At the same time, the dimensions of the material that existed before the mechanical stress was applied are recovered. This recoverable strain, called "magnetosuperelasticity," can be a few percent in appropriate MSM materials.

Magnetic control of the shape memory effect should be possible in several ferromagnetic materials in which martensite interfaces or twin boundaries are glissile and magnetic anisotropy energy is high enough. Studies on Heusler alloys Ni_2MnGa (Ref 10) and other ferromagnetic shape memory materials are in progress. One important group of potential MSM materials is cobalt alloys. The close-packed hexagonal (cph) structure of cobalt exhibits high anistropy energy in the base plane direction (Ref 9). In some cobalt-base alloys, a martensitic transformation from face-centered cubic (fcc) to cph structure occurs, and the interfaces between austenite and the martensite phases are coherent and glissile (for example, in Co-32Ni, Ref 11). It is studied whether the motion of the austenite-martensite interfaces can be controlled by the magnetic field in appropriate Co-base alloys. Also such Co-alloys are being developed that exhibit twinned cph martensitic substructure. The strokes of these materials are based on the magnetically controlled reorientation of the twins. In the experimental part of this report, magnetic control of the motion of austenite-martensite interfaces is demonstrated in an Fe-33.5Ni alloy.

2. Experimental Results and Discussion

An alloy Fe-33.5%Ni (mass%) was induction melted in vacuum and chill cast. The ingot was hot forged and solution treated at 1473 K for 18 h. Specimens were prepared from a 1 mm thick sheet, which was made by cold rolling. Finally, specimens were annealed at 1473 K for 1 h in evacuated quartz capsules and water quenched. The samples were confirmed to be fully austenitic at room temperature by x-ray diffraction (XRD) and metallography.

Interfaces between the austenite and martensite phases in alloy Fe-33.5Ni were coherent and moved easily at low temperatures as mechanical stress was applied (Ref 12, 13). These interfaces also can be driven by the external magnetic field. Electrical resistivity, strain, and XRD measurements were performed in the magnetic field. Electrical resistivity was used to reveal the formation of martensite by mechanical strain in Ref 12 and 13. In the present study, resistivity measurements were made to demonstrate the formation of martensite by the applied magnetic field. The specimen was cooled first to liquid nitrogen temperature (77 K). An abrupt decrease in resistivity was observed at 125 K revealing a burst-like martensitic transformation. The transformation continued isothermally at 77 K. After the transformation was completed, the phase fraction of the α' martensite was about 75%. A perpendicular magnetic field of 230 mT was then applied on the specimen. Resistivity decreased 3.8% instantly, then a decrease of 1.9% occurred isothermally. The magnetic field induced the formation of new martensite, and the phase fraction of this martensite is 3.7% according to the relationship between the martensite amount and resistivity obtained from Ref 13. The result of this resistivity measurement is shown in Fig. 2(a). For comparison, decrease of resistivity due to the mechanical strain is shown in Fig. 2(b).

When the magnetic field was switched off and on, resistivity decreased and increased 0.9%, respectively. This effect was reversible. Application of the magnetic field of 50 mT aligned with the surface of the martensitic specimen at room temperature resulted in an increase of resistivity of 0.5%, which also was reversible. The increase of resistivity may be attributed to the internal strains caused by the structural changes of martensite in the applied magnetic field. XRD measurements at room temperature showed that the intensities and widths of the austenite and martensite peaks changed when the magnetic field was applied on the specimen. Those data reveal that internal strains are increased by the magnetic field. Further studies are required, however, to understand the mechanisms that give rise to the strains. The contribution of the changes in the magnetic domain structure to resistivity was measured on the (ferromagnetic) austenitic sample by applying a magnetic field of 230 mT perpendicular to the sample surface. This effect was

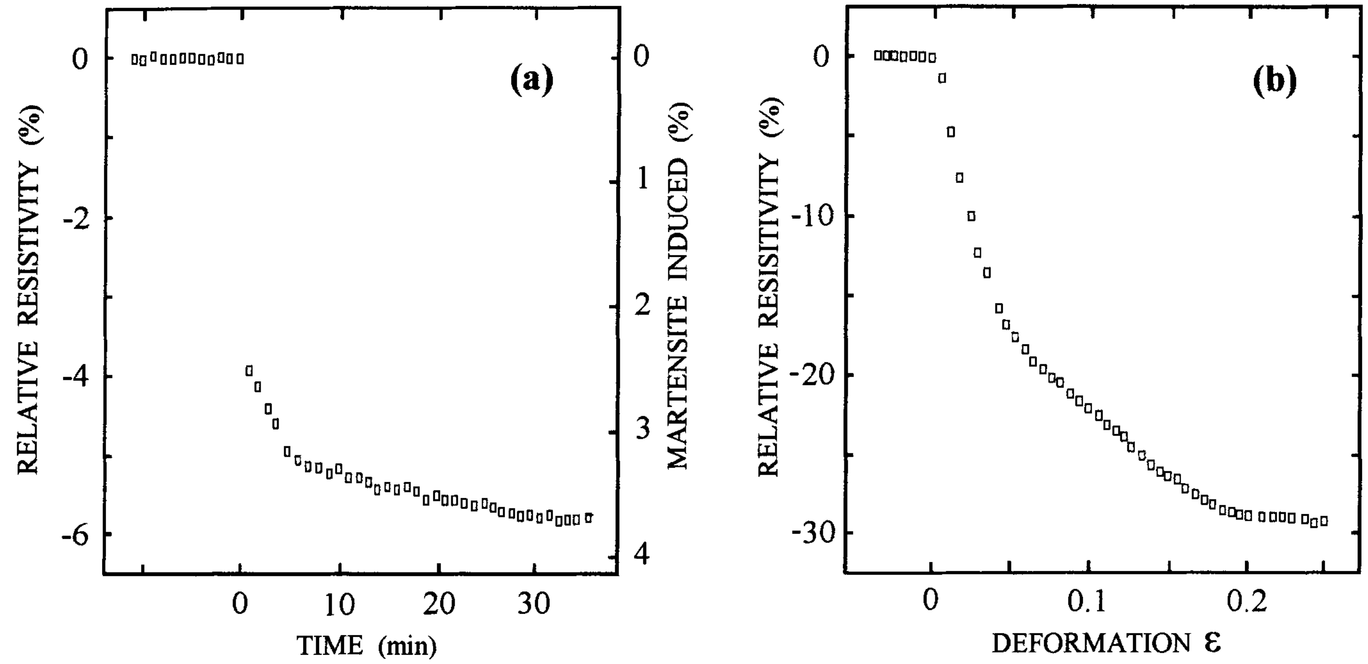

Fig. 2 (a) Formation of martensite by external magnetic field, evidenced by electrical resistivity. Magnetic field of 230 mT was applied at $T = 0$. (b) Resistivity change mainly caused by the formation of martensite as the material was mechanically deformed by twisting (Ref 13). Both measurements were made at 77 K.

only −0.05% and cannot explain the present phenomena (assuming the effect is of the same magnitude for martensite).

To study whether the martensite formed in the applied magnetic field prefers some orientations, a strain measurement was made. Strain was detected using a strain gage attached on the 12 × 12 mm^2 specimen. When the sample was quenched in liquid nitrogen, the martensitic transformation occurred. A volume change caused by the martensitic transformation induced a strain that was detected by the strain gage. After the transformation was completed at 77 K, a magnet whose field was 50 mT and aligned parallel with the surface of the sample was attached on the sample, opposite side to the strain gage. The magnet was then rotated around an axis perpendicular to the sample surface, and the strains were measured at different rotation angles. The strain increased when the magnetic field was parallel with the direction in which the strain was measured. This is attributed to the (isothermal) formation of new martensite, which was also evidenced by the resistivity measurements. When the magnetic field was turned perpendicular to the strain gage, the strain started to decrease. The decrease of the strain is caused by the reorientation of the martensitic structure in the applied magnetic field.

Martensitic transformations induced by pulsed high magnetic fields were previously observed in many alloys (Ref 14-16). Those transformations are based on phenomena other than that reported here. The pulsed magnetic fields were two orders of magnitude higher than the fields used in the present study, and they are too high to be employed in actuator applications. The present results show that low magnetic fields can induce the formation of martensite, and the orientation of this martensite is affected by the field. It does not seem probable that the magnetostrictive strains would induce the interface motion observed because the mechanical strains of the same magnitude used in the internal friction studies induced significantly smaller amounts of martensite (Ref 12) at the same temperature. Martensite of Fe-33.5Ni is consisted of plates that are partially twinned. The twin plane is $(112)_{\alpha'}$, and the mean thickness of the twins is about 14 nm according to the results obtained for alloy Fe-33Ni (Ref 17). Whether this twin structure can be reoriented by the magnetic field remains a topic for further studies. The anistropy energies of the Fe-Ni martensites are quite low. Therefore, Fe-Ni alloys are not optimal materials for actuator applications. The Fe-33.5Ni alloy was selected for the present study to demonstrate the magnetically driven growth of martensite at low temperatures.

3. Conclusions

Magnetic control of the shape memory effect was recently suggested for a principle of a new class of actuator materials. These materials may produce high stresses and strains as large as those developed by the conventional shape memory alloys (several percent). Their control is precise and rapid. Actuation of these materials is based on the reorientation of the twin structure of martensite or the motion of austenite-martensite interfaces by the applied magnetic field. The motion of the austenite-martensite interfaces at low magnetic fields was demonstrated using an Fe-33.5Ni alloy.

Acknowledgments

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