Ferroelastic properties of oriented $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ polycrystals

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The study of magnetostrictive and magnetomechanical properties of rare-earth–iron compounds has attracted much attention. Because of the giant magnetostriction, there has been interest in development of the magnetostrictive $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ alloys used as actuators, transducers, and sensors. Many advanced applications require either large actuator displacements or large forces. Such conditions may cause nonlinearity and permanent deformation, which can lead to degradation of the performance of the actuators. On the other hand, the $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ alloys are susceptible to brittle fracture that can lead to catastrophic failure. Therefore, it is important to understand their deformation as well as the effect of the mechanical stress on magnetic properties of the $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ alloys under coupled magnetomechanical fields. Domains exist in magnetостRICTIVE materials. External loads, such as magnetic field and stress, can cause domain state changing from one to another. Especially, the giant magnetostriction results from the domain discontinuously jumping between different easy axis. While the domain jumping occurs, the domain walls will move. This process of domain state changing is called as “domain switching.” Furthermore, the easy axis of $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ crystal is [111]. Therefore, there exist 180°, 109°, and 71° domain wall processes. To simplify formulation, it can be assumed that only 180° and 90° domain switching is considered. When used in engineering components, as the applied field becomes larger, the strain in the magnetostrictive $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ alloys deviates from linearity, and significant hysteresis appears because of the domain switching. The hysteresis limits the application of the magnetostrictive materials, especially under a large applied magnetic or stress field. The study on the hysteresis can expand the potential application of the materials.

In this investigation, the experiments were conducted to study the mechanical and magnetic properties of a $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$ alloy under coupled magnetomechanical loading. The coercive stress and Young’s modulus can be obtained from the measured stress–strain curves and demagnetization curves.

The pseudobinary compound $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.95}$ was produced with purities of the raw materials of Tb 99.9%, Dy 99%, and Fe 99.9%. The temperature gradient zone melting directional solidification device was used to obtain the oriented polycrystal rods. The grain growth axis is in [110]. The specimens were cut from these rods, and the diameter and length of the specimens are 10 and 30 mm, respectively. In experiments, both the magnetic field and the compressive stress were applied along the grain growth direction [110].

The saturation magnetization $M_s$ of measured specimens is about $0.7 \times 10^6 \text{ A/m}$. Figures 1 and 2 show the measured stress–strain curves and stress–magnetization curves, respectively. Clearly, the compressive stress is a function of strain and demagnetization under the different external magnetic fields. In Fig. 1(a), the stress at the point of inflection (Point C) is defined as the coercive stress $\sigma_c$, which is analogous to the coercive field $H_c$. Because the deformation is nonlinear, Young’s modulus is not constant. Therefore, the initial Young’s modulus $E_0$ is defined as the tangent of the segment A–B in the measured stress–strain curve during initial process [segment A–B in Fig. 1(a)]. The final Young’s modulus $E$ is designated as the tangent of the segment D–E in the curve after all domains have switched [segment D–E in Fig. 1(a)].

Figures 1(a) and 1(b) show the stress–strain curve and stress–magnetization curve under a zero magnetic field, respectively. In this measurement, without the external magnetic field, a compressive stress was applied along the grain growth direction, that is, in [110]. The nonlinear behavior of the $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.95}$ alloy is very similar to that of the piezoelectric materials. At the initial stage of the deformation, the strain is linear until the stress approaches 2 MPa [i.e., from point A to point B in Fig. 1(a)], while the coercive stress $\sigma_c$ of 2.5 MPa (at the point C) can be measured. With the increase of loading, domain switching can cause significant strain [from point B to point D in Fig. 1(a)], until all domains have switched. Another linear stage then occurs [from point D to point E in Fig. 1(a)]. At the stress of 60 MPa, the unloading process starts. During unloading, when the stress is greater than 8 MPa, the unloading curve is almost linear [from point E to point F in Fig. 1(a)]. However, after unloading to 8 MPa, the deformation turns to the non-
linear, which results from the domains partially switching back to their original direction. After the stress totally is removed, the specimen has a remnant strain of about 700 × 10^{-6}. At the same time, the piezomagnetic effect is examined, as shown in Fig. 1(b) in which there is a typical piezomagnetic curve. During loading, the magnetization increases with the increase of the applied compressive stress. The magnetization declines with the decrease of the stress during unloading. When the stress decreases to zero, the remnant magnetization of about 4 kA/m was measured. The hysteresis loop embraced by the loading curve and the unloading curve in both Figs. 1(a) and 1(b) reveal that there exists energy dissipation, and the area of the hysteresis loop represents the dissipated energy that is associated with magnetic domain switching.

To investigate the influence of the magnetic field on the mechanical properties, different magnetic fields, such as $H=39.8$, 79.8, 119.4, and 198.9 kA/m, were applied along the grain growth direction (i.e., in [110] direction), and kept constant during the entire measurement process. After the magnetic field was applied, a compressive stress was loaded and unloaded. The results are shown in Figs. 2(a) and 2(b), respectively. Under the applied magnetic field, the domains are fixed against the compressive stress in their original orientation. In this case, therefore, higher stresses are needed to induce domain switching. From Fig. 2(a) it can be found that the higher the applied magnetic field, the higher the stress needed to switch the magnetic domains, and also the higher the initial Young’s modulus $E_0$. That is, the material seems to become “harder” with the increase of the magnetic field. Figure 2(b) indicates that the compressive stress also causes the demagnetization $\Delta M$, which is defined as

$$\Delta M = M_0 - M_1,$$

where $M_0$ is the original magnetization before a stress is applied and $M_1$ is the magnetization after the stress is applied. Obviously, $\Delta M$ is the function of the applied stress. However, since a stress usually can cause the 90° domain switching, the compressive stress makes domain switch to the direction perpendicular to the loading direction (i.e., [110] direction), which can weaken the magnetization. During the unloading stage, when the compressive stress decreases to zero, the switched domains switch back to their original direction again with the aid of the external magnetic field. Then the magnetization reverts to the original value, and there is almost no remnant strain in the specimens.

From the measured curves in Figs. 1 and 2, the coercive stresses under various coupled magnetomechanical loadings can be obtained. Figure 3 shows that the coercive stress increases almost linearly with the increase of the magnetic field. This linear dependence can be explained by considering the change of energy density during domain switching. In the domain switching process, the total change of energy density must be equal to the critical energy density $w_s$:

$$\sigma \cdot \varepsilon + H \cdot (\Delta B) = w_s.$$  

The first term in the left side of Eq. (2) is the change of mechanical energy density, while the second term,
$H \cdot (\Delta B)$, corresponds to the change of magnetic energy density. When the domain switches, the coercive stress can be expressed as

$$\sigma_c = -\frac{\Delta B_r}{\varepsilon_r} H + \frac{w_s}{\varepsilon_r}.$$  (3)

When the stress is equal to the coercive stress $\sigma_c$, the overall value of the coefficient $-\Delta B/\varepsilon$ is nearly equal to that of $-\Delta B_r/\varepsilon_r$, which has been verified by our measurements. $\Delta B_r$ is the remnant magnetic induction and $\varepsilon_r$ is the remnant strain, which are both material constants. Therefore, the coercive stress $\sigma_c$ is a linear function of $H$.

The comparison of the initial modulus and final modulus is illustrated in Fig. 4. The initial changes of $E_0$ and $E$ are slight, but both $E$ and $E_0$ change dramatically once the magnetic field exceeds 40 kA/m, which implies that a larger amount of domains switch at this point. Therefore, a large amount of domains switching makes the modulus change dramatically. When the magnetic field increases to 160 kA/m, $E_0$ is almost equal to $E$. It is interesting to note that the changes of $E$ and $E_0$ are almost symmetric. Under a constant magnetic field applied in the direction parallel to the direction of the applied compressive stress, the domains are still aligned in their magnetized orientation when the applied compressive stress is small. To switch the domains from their initial aligned direction (i.e., [110]), higher stresses are needed. That is, when the external magnetic field is larger, a higher compressive stress is needed to induce the domain switching. Therefore, the initial modulus $E_0$ increases with the increase of the magnetic field. However, when all domains have switched, the relatively lower stresses can lead to the switching deformation with the aid of magnetostriction induced by the magnetic field, which makes the final modulus $E$ decrease with the increase of the magnetic field.

In summary, the nonlinear behavior of compressive strain and demagnetization of the oriented Tb$_2$Dy$_{1-x}$Fe$_2$ polycrystalline alloy can successfully be explained by domain-switching mechanisms. The compressive strain and demagnetization have been measured as a function of compressive stress applied parallel to the external magnetic field. The final Young’s modulus declines and coercive stress increases as the constant magnetic field increases.

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