Effect of hydrostatic pressure on the giant magnetostriction of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$

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Giant magnetostriction (GMS) of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ single crystal has been measured at hydrostatic pressure up to 9 kbar. The electrical resistance and thermal expansion were also measured at low temperature down to 4.2 K to examine low temperature behavior. It is found that the magnitude of GMS increases with increasing pressure below 4 kbar but decreases above 6 kbar having a maximum near 5 kbar. The origin of maximum is discussed briefly the difference between hydrostatic pressure and uniaxial pressure is pointed out.

Key words: magnetostriction, hydrostatic pressure, thermal expansion

1. Introduction

It is well known that the ferromagnetic material including 3d or rare earth elements shows a magnetostriction, which is usually of the order of $10^{-5} \sim 10^{-6}$ at relatively high magnetic fields. Recently the giant magnetostriction (GMS) of 10^{-3} has been found for ferromagnetic RT_2 compounds (R: rare earth element, T: transition metal element) having C15 type crystal structure¹⁾. These magnetic materials have been extensively studied mainly for the wide range of application as an actuator. Among these materials the compound $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$ (Terfenol-D) shows the largest MS $\sim 1.6 \times 10^{-3}$ at low magnetic field less than 0.1 T. Furthermore it was revealed that the magnitude of MS is strongly dependent on uniaxial pressure along the measurement direction because the magnetization alignment is changed by applying pressure²⁾. The uniaxial pressure gives rise to a magnetization jump at several hundred Oe at room temperature, i.e., it extremely enhances the magnitude of MS.

In the present work we attempt to measure the magnetostriction of Terfenol-D under hydrostatic pressure up to 9 kbar in order to accumulate new informations to clarify the mechanism of GMS. The results are compared with those at uniaxial pressure. Electrical resistance and thermal expansion were also measured to examine the low temperature behaviors at ambient pressure.

2. Experimental procedure

The single crystalline $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ has a rod shape of $6 \text{ mm}\phi \times 20 \text{ mm}$ in length. The sample

was cut from this rod into a rectangular shape of $2.5 \times 2.5 \times 1.5 \text{ mm}^3$. The magnetostriction (MS) was measured by strain gauge method. The magnetic field H (kOe) was applied in the parallel direction of rod axis $[11\bar{2}]$. MS was measured both in the parallel ($\lambda_{\parallel}$) and perpendicular ($\lambda_{\perp}$) to H . Pressure up to 9 kbar was generated by using piston-cylinder apparatus. The pressure was clamped by tightening the screw and then transferred in the magnets to measure MS. The pressure was almost constant within an experimental error throughout the measurement (~ 1 day). The electrical resistance was measured by using standard four probe method.

3. Results and discussion

3.1 Electrical resistivity and thermal expansion at ambient pressure

Figure 1 shows the temperature dependent electrical resistivity $\rho(T)$ at ambient pressure in the current direction perpendicular to the rod axis, $j \perp [11\bar{2}]$. ρ increases with increasing temperature without any discontinuity in the temperature range $2 \leq T \leq 300 \text{ K}$. The residual resistivity ratio is relatively low 3.8, which may imply an existence of some kinds of disorder or impurity.

The thermal expansion is illustrated in Fig. 2 as a function of temperature. There is no discontinuity in the temperature dependence of the fractional change in length $(\Delta l/l)(T)$ which increases smoothly with temperature. From the results in Figs. 1 and 2, it is concluded that there is no phase transition in the temperature range $2 \leq T \leq 300 \text{ K}$. The magnitude of thermal expansion coefficient α is about $14 \times 10^{-6} \text{ K}^{-1}$ around 300 K, which is comparable to that of normal metals such as Cu ($\alpha \simeq 16 \times 10^{-6} \text{ K}^{-1}$). But at low temperatures α at 20 K is relatively large $\alpha \sim 1 \times 10^{-6} \text{ K}^{-1}$, which is larger than that of Cu, $\sim 0.3 \times 10^{-6} \text{ K}^{-1}$. This fact suggests that there is a disorder in the crystal lattice, which gives a small rrr value as mentioned above.

3.2 Magnetostriction at high pressure

Figure 3 shows a part of the results up to 4.5 kbar, in which $\lambda_{\parallel}$ is indicated as a function of magnetic field H to 4.3 kOe. At 0 kbar, $\lambda_{\parallel}$ increases with H having a large MS of the orders of 1×10^{-3} at 4.3 kOe. As pressure increases, $\lambda_{\parallel}$ is found to increase: the magnitude

Fig. 1: Electrical resistivity of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ as a function of temperature at ambient pressure.

Fig. 2: Thermal expansion of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ as a function of temperature at ambient pressure.

Fig. 3: Magnetostriction along the rod axis $[11\bar{2}]$ $\lambda_{||}$ at pressures below 4.5 kbar.

Fig. 4: $\lambda_{||}(H)$ above 6 kbar.

Fig. 5: $\lambda_{||}$ at 4.3 kOe as a function of pressure.

of $\lambda_{||}$ is 1.35×10^{-3} and 1.56×10^{-3} at 2 and 4.5 kbar, respectively. At 4.3 kOe $\lambda_{||}$ at 4.5 kbar is about 1.5 times larger than that at 0 kbar. At 4.5 kbar, $\lambda_{||}(H)$ increases more rapidly than those at 0 and 2 kbar around 1 kOe. This increase may correspond to the magnetization jumping between $[111]$ direction and the $[11\bar{1}]$ direction at a critical field H_{cr} which was observed at several hundreds Oe in $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ under the uniaxial pressure along the rod axis ²⁾. The jump occurs when the Zeeman energy exceeds the anisotropy energy. H_{cr} at 4.5 kbar may be around 1.5 kOe, which is several times larger than that under uniaxial pressure. By increasing H more than 3 kOe, $\lambda_{||}$ tends to be saturated with a rotation of magnetic moment towards the $[11\bar{2}]$ rod axis.

Figure 4 shows the $\lambda_{||}$ vs H curves in the pressure range of $6 \leq P \leq 9$ kbar. At 4.3 kOe, the magnitude of $\lambda_{||}$ is nearly the same as that at 4.5 kbar. But by increasing pressure above 6 kbar, $\lambda_{||}$ begins to decrease with pressure. Furthermore $\lambda_{||}$ above 8 kbar seems to have no magnetostriction jump. At 9 kbar, the $\lambda_{||}$ at 4.3 kOe is 1.02×10^{-3} .

Figure 5 shows the value of $\lambda_{||}$ at $H = 4.3$ kOe. $\lambda_{||}$

Fig. 6: $\lambda_{\perp}$ at 4.3 kOe as a function of pressure.

increases below 4 kbar but decreases above 6 kbar with a maximum near 5 kbar. GMS is expected to disappear above 10 kbar by extrapolating the present results.

On the other hand $\lambda_{\perp}$ at 4.3 kOe, the magnetostriction in the direction $\Delta l/l \perp H$, is shown in Fig. 6 as a function of pressure. It is found that $\lambda_{\perp}$ (4.3 kOe) is negative and almost independent of pressure below 9 kbar, which is in sharp contrast to the pressure dependence of $\lambda_{\parallel}$.

From the values of $\lambda_{\parallel}$ and $\lambda_{\perp}$, we calculate the volume magnetostriction $\omega = \lambda_{\parallel} + 2\lambda_{\perp}$. By using the results indicated in Figs. 5 and 6, ω at 0 kbar is estimated to be about -0.2×10^{-3} . The negative ω suggests the positive pressure dependence of ω because of the relation $(\partial\omega/\partial P) \propto -(\partial\omega/\partial H)$, which is derived by using the thermodynamical relations. This consideration explains qualitatively the increase of $\lambda_{\parallel}$ at low pressure below 4.5 kbar, which is shown in Fig. 5. However it

should be noted that there is a large difference between the results at hydrostatic pressure and that at uniaxial pressure. In the present work, $\lambda_{\parallel}$ at 4.5 kbar is about 1.5 times larger than that at 0 kbar. In the case of uniaxial pressure, it is enhanced about twice as large as that at 0 kbar by applying pressure of several hundreds bar. These facts indicate that the uniaxial pressure affects strongly the anisotropy energy of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ more than hydrostatic pressure³⁾.

It was pointed out that the magnetization and the magnetostriction jumps are enhanced by uniaxial pressure but become smaller at higher compressive load because of the small angle change of the direction of magnetization²⁾. The broad maximum observed in Fig. 5 may be originated from the same reason. To discuss more clearly the present data it is highly desired to observe the effect of pressure on the Curie temperature and the magnetization.

In conclusion, the magnetostriction of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.9}$ single crystal increases with increasing pressure below 4 kbar but decreases above 6 kbar. There is a large quantitative difference in the pressure dependence of the magnetostriction between at hydrostatic condition and at uniaxial condition. It is suggested that the peak in the λ vs P curve is associated with the volume dependence of the anisotropy energy.

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