Influence of Uniaxial Compression on Magnetization of NdFeB Magnet

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The dependence of the magnetization of the NdFeB magnet on uniaxial pressure up to 6.2 MPa was measured at $T = 300$ and 77 K. A decrease in magnetization was observed. The change in the magnetic free energy was much smaller than the change in the elastic free energy. Relations with the anomalous thermal expansion are discussed.

topics: NdFeB magnets, elastic properties, magnetic properties

1. Introduction

In a recent paper [1], we have investigated strain resulting from interaction of NdFeB magnets. The interpretation was based on measured magnetic field distribution, magnetization, elastic properties, and magnetostriction. The experiments were done with commercial NdFeB cylindrical magnets (length = 5 cm, diameter = 1.2 cm).

For the positive direction of an external magnetic field, the magnetostriction resembled deformation under compression along the magnet axis — its length diminished and radius increased (see Fig. 6 in [1]). At the same time, the magnetization grew (see insert in Fig. 3b in [1]).

In the present work, we have performed direct measurements of the magnetization as a function of longitudinal compression.

2. Experiment

The measuring device is shown in Fig. 1. Compression was created by a screw and measured with a mechanical dynamometer (panel a). The radial magnetic field B_r, which is proportional to the magnetization M, was measured by a Hall sensor glued at a distance of 4.8 mm from the lower end of the magnet (panel b).

Measurements were performed at temperatures above (300 K) and below (77 K) the spin-reorientation transition (about 130 K).

Experimental results are shown in Fig. 2. As can be seen, uniaxial compression results in a diminishing of the magnetization.

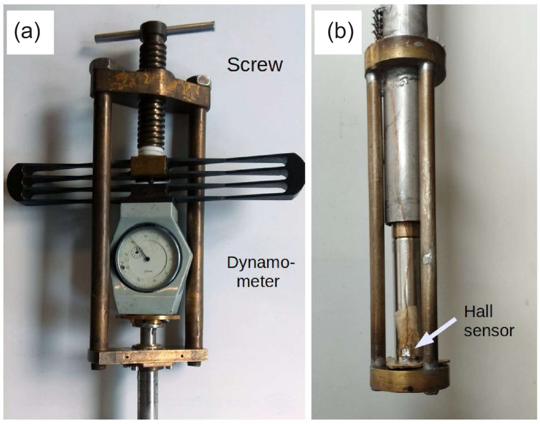

Fig. 1. Photo of measuring device.

In Fig. 2, the dashed lines show the change in the radial magnetic field resulting from the change in the magnet dimensions under uniaxial compression.

This dependencies were calculated using equations (1)–(3) and (6) from [1] and data for the Poisson ratio. The results for B_r at the Hall sensor position as a function of the relative change in the magnet length $\delta l/l$ for $M =$ const are:

- $T = 300$ K

$$B_r(\delta l/l) = B_r(0)\big[1 - 0.284(\delta l/l)\big], \quad (1)$$

- $T = 77$ K

$$B_r(\delta l/l) = B_r(0)\big[1 - 0.317(\delta l/l)\big]. \quad (2)$$

As can be seen in Fig. 2, this contribution may be neglected.

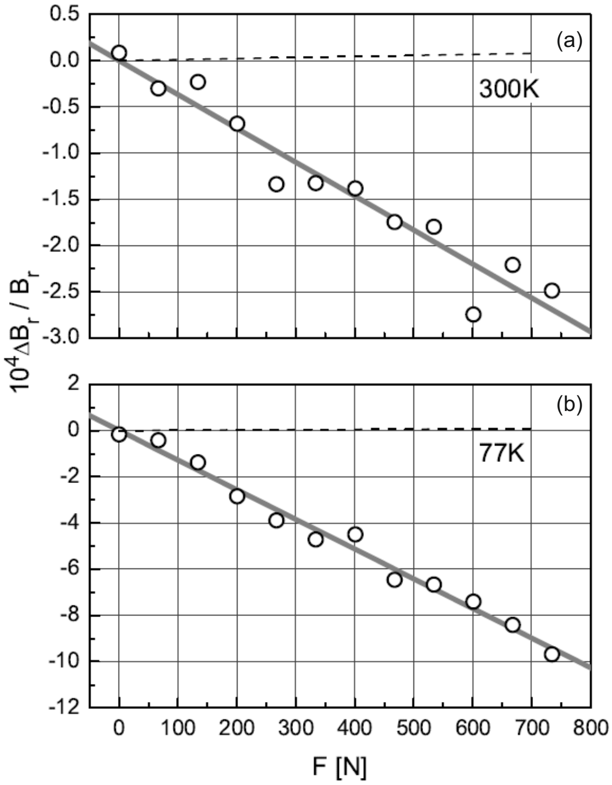

Fig. 2. Dependence of the change in the radial magnetic field $\Delta B_r/B_r = [B_r(F) - B_r(0)]/B_r(0)$ on the uniaxial stress.

TABLE I

Parameters used to calculate the free energy of anomalous thermal expansion.

T [K]	μ [GPa]	λ [GPa]	$\lambda_\parallel$ ($\times 10^3$)	$\lambda_\perp$ ($\times 10^3$)	F_e [J/cm^3]
300	90	86	3.2	5.0	12.9
77	100	117	3.3	5.7	20.9

TABLE II

Magnetic free energy.

T [K]	M [kA/cm]	F_m [J/cm^3]	F_e/F_m
300	9.73	0.54	23.1
77	11.8	0.79	25.6

TABLE III

Parameters used to calculate the change in elastic free energy under applied force $F = 700$ N.

T [K]	$\delta l/l$ ($\times 10^5$)	$\delta r/r$ ($\times 10^5$)	δF_e [mJ/cm^3]
300	-2.76	0.67	-19
77	-2.44	0.66	-20

3. Discussion

It should be pointed out that deformation due to the magnetostriction is different from that resulting from the uniaxial compression. From results for the magnetostriction presented in [1] in Fig. 6 and by Eqs. (11) and (12), it follows that the ratio of $-\delta r/r$ to $\delta l/l$ is about 0.7. This ratio (the Poisson ratio) should be < 0.5 in the case of homogeneous deformations; see §5 in [2].

For the positive direction of the magnetic field, magnetostriction leads to an increase in the volume of the magnet, whereas uniaxial compression diminishes it.

As in the preceding work [1], it was of interest to compare magnetic free energy F_m and free energy of anomalous thermal expansion F_e observed below T_c (spontaneous magnetostriction).

The elastic free energy F_e was calculated for $T = 300$ and 77 K using Eqs. (17) and (18) from [1]. The Lamè coefficients μ and λ were obtained from experimental values of the Young modulus E and Poisson's ratio σ given in Table II in [1]. Values of anomalous thermal expansion along ($\lambda_\parallel$) and perpendicular ($\lambda_\perp$) to the magnet axis were estimated from experimental results shown in Fig. 3 in work [3]. For this purpose, the lattice contribution to the thermal expansion at low temperatures was calculated from the high-temperature (above 800 K) experimental data using Debye's interpolation formula (see §66, §67 in [4]) with $\Theta_\mathrm{D} = 420$ K [5]. Results of the calculation are given in the last column of Table I[†1].

The density of the magnetic free energy (see Table II) was calculated using a thin substitutional coil model

$$V F_m = \frac{L\,(l\,M)^2}{2}, \qquad (3)$$

where M is the magnetization determined from the experiment, l — magnet length, and V — magnet volume. The inductance of substituting coil $L = 2.573$ nH was calculated with Eq. (14) from [1].

From the last column of Table II, it can be seen that elastic free energy is much greater than magnetic free energy.

A similar ratio was obtained for changes in the elastic and magnetic free energies due to uniaxial compression.

The change in the elastic free energy (Table III) was calculated using Eq. (19) from [1] with strains $\delta l/l = -F/(sE)$, $\delta r/r = -\sigma \delta l/l$, where s is the magnet area.

From (3), the change in the magnetic free energy is

$$V \delta F_m = L(l\,M)^2 \Delta B_r/B_r. \qquad (4)$$

[†1] In the previous work [1], the interpolation of high-temperature data to low temperatures was done "by eye."

TABLE IV

Parameters used to calculate the change in the magnetic free energy under applied force $F = 700$ N.

T [K]	M [kA/cm]	$\Delta B_r/B_r$ ($\times 10^4$)	δF_m [mJ/cm^3]	$\delta F_e/\delta F_m$
300	9.73	-2.6	-0.61	31.1
77	11.8	-9	-1.27	16

The parameters used for the calculation of the change in the magnetic free energy and the results obtained for $F = 700$ N at $T = 300$ and 77 K are listed in Table IV.

The last column of Table IV shows that under uniaxial compression, the change in elastic free energy is much larger than the change in magnetic free energy.

Anomalous thermal expansion results in an increase in elastic free energy and magnetic free energy.

Uniaxial compression results in a decrease in elastic free energy and magnetic free energy.

From the comparison of the last columns of Tables II and IV, it follows that in both cases, the ratio of $\delta F_e/\delta F_m$ is approximately the same, i.e., the effect of lattice strain on magnetization is reversible.

The dependence of magnetization on lattice strain may be explained by the dependence of the exchange interaction on the distance between Fe atoms. According to the Berthe–Slater curve (see Fig. 4.1.1 in [6]), the exchange interaction between the moments of two Fe atoms increases with distance. Thus, the increase in the volume due to the anomalous thermal expansion will increase the exchange interaction between Fe atoms, whereas diminishing volume under uniaxial compression will decrease it.

4. Conclusions

In the present work, the influence of uniaxial compression on the magnetization of the NdFeB magnet was measured at temperatures above and below the spin-reorientation transition. Diminishing of magnetization under compression was observed.

The changes in the elastic and magnetic free energies due to anomalous thermal expansion and uniaxial compression were estimated.

The obtained results were ascribed to the dependence of the exchange interaction on distance.

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