Effect of Uniaxial Compression on Exchange Interaction in SmCo and NdFeB Permanent Magnets

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The dependence of the magnetization of a SmCo magnet on the uniaxial pressure up to 6.2 MPa was measured at $T = 300$ and 77 K. A diminishing of the magnetization was observed. The results obtained for the SmCo and NdFeB permanent magnets qualitatively correspond to the slope of the Berthe–Slater curve.

topics: SmCo magnets, elastic properties, magnetic properties, exchange interaction

1. Introduction

As is well known [1], the ferromagnetism of $3d$-metals is determined by the exchange interaction. The exchange integral is proportional to the overlap of d-orbitals of neighbour atoms and strongly depends on the distance between them.

Many years ago, this dependence was described by the Berthe–Slater curve (see §56 in [2]), in which the exchange interaction was plotted as a function of the ratio the interatomic distance (d) to the d-shell radius (r_d) for metallic Mn, Fe, Co, and Ni (see Fig. 4.1.1 in [1]).

The curve begins from a negative value of the exchange interaction for Mn, crosses zero before Fe, reaches a maximum near Co, goes down for Ni, and diminishes asymptotically to zero.

Later, the theoretical background of the Bethe–Slater curve has been criticized by several authors (see Ch. 19, §1.3 in [3]).

However, the last *ab initio* calculations of the exchange interaction for $3d$-metals are in a good agreement with the Berthe–Slater curve [4].

In a recent paper [5], we investigated the influence of uniaxial compression on the magnetization of a NdFeB magnet. The observed diminishing of magnetization was explained by the position of iron on the rising part of the Berthe–Slater curve.

Cobalt has a position near the top of this curve. Hence, it was of interest to make the same measurements with a SmCo magnet.

In $Nd_2Fe_{14}B$, the average distance between nearest neighbouring iron atoms is $d = 0.251$ nm [6], the radius of the d-shell is $r_d = 0.153$ nm (see Table II part(d) in [7]), and the relative interatomic distance is $d/r_d = 1.64$.

In $SmCo_5$, the average distance between nearest neighbouring cobalt atoms is $d = 0.246$ nm [8], the radius of the d-shell is $r_d = 0.138$ nm, and the relative interatomic distance is $d/r_d = 1.78$.

The contribution of rare-earth elements to the magnetization of these magnets is rather small.

The magnetic moments of cobalt and samarium in $SmCo_5$ determined at $T = 5.4$ K by neutron powder diffraction measurements [9] are $m_{Co} = 2.23\mu_B$ and $m_{Sm} = 0.99\mu_B$. Therefore, the contribution of samarium to the total magnetic moment is 8%.

For $Nd_2Fe_{14}B$, we used the results of magnetic measurements on a single crystal [10] and estimated the contribution of neodymium to the total magnetization at $T = 4.2$ K as 16%. Summing up the *ab initio* calculations, the authors of a recent work [11] noted the decisive role of iron in the properties of the $Nd_2Fe_{14}B$ magnet.

2. Experiment

The experiments were done with commercial SmCo (nominal composition $SmCo_5$) cylindrical magnets. Their dimensions ($l = 5$ cm, $2a = 1.2$ cm) were the same as the previously investigated NdFeB magnets and the same device was used (see Fig. 1 in [5]). In this device, the radial magnetic field B_r, which is proportional to the magnetization, was measured by a Hall sensor glued at a distance 4.5 mm from the lower end of the magnet.

The elastic parameters necessary for estimating the resulting deformation were obtained from the pulse ultrasonic measurements described in [12]. Earlier similar measurements were done only at room temperature [13].

3. Results

The results of the pulse ultrasonic measurements are given in Table I.

It was determined that the transverse sound velocity c_t is independent of the direction of propagation and the direction of polarization $c_{t\mathrm{II}}$ or perpendicular $c_{t\perp}$ to the direction of the magnetization. The anisotropy of the longitudinal sound velocity c_l does not exceed 4%, so for the target estimation of the Young modulus E and the Poisson's ratio σ, the following equations, valid for an isotropic case, were used (see Eq. (22.4) in [14])

$$c_l = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}, \quad c_t = \sqrt{\frac{E}{2\rho(1+\sigma)}}, \qquad (1)$$

where $\rho = 8.345\ \mathrm{g/cm^3}$ is the measured SmCo magnet density (see Table II).

The relative change in volume under the applied force F was calculated as

$$\frac{\Delta V}{V} = (2\sigma - 1)\,\frac{F}{s\,E}, \qquad (2)$$

where s is the magnet cross-section area.

Figure 1 shows the measured dependencies of the relative change of the radial magnetic field on an applied force. From comparison with the results obtained in [5] for NdFeB magnet, it follows that for SmCo magnet the effect of uniaxial compression is an order of magnitude smaller.

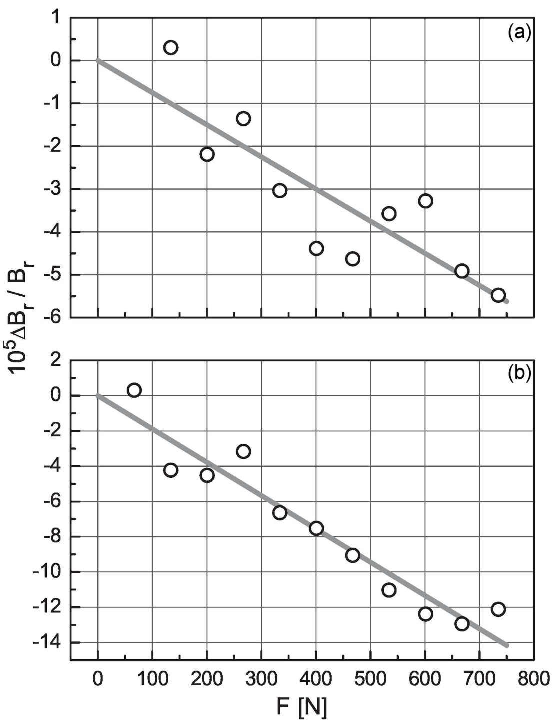

Fig. 1. Dependence of the change of the radial magnetic field $\Delta B_r/B_r = [B_r(F) - B_r(0)]/B_r(0)$ on the compressive force F at: (a) $T = 300$ K, (b) $T = 77$ K.

4. Discussion

Because the deformation of the magnet under uniaxial compression is anisotropic (its length diminishes and diameter increases), it is reasonable to characterise it by the relative change in the volume, $\Delta V/V$, which may be calculated from the measured force F and the elastic moduli E and σ. Then, the experimental results for the NdFeB magnet (shown in Fig. 2 in [5]) and the results for the SmCo magnet (shown in Table II) have been summarized in Table III.

TABLE I

Longitudinal and transverse sound velocities [km/s] in a SmCo magnet.

T [K]	$c_l^{\parallel}$	$c_l^{\perp}$	$c_t^{\parallel}$	$c_{t\parallel}^{\perp}$	$c_{t\perp}^{\perp}$
300	5.15	4.96	2.59	2.59	2.56
77	5.22	5.06	2.61	2.61	2.61

TABLE II

Elastic properties of SmCo magnet.

T [K]	E [GPa]	σ
300	148	0.332
77	153	0.332

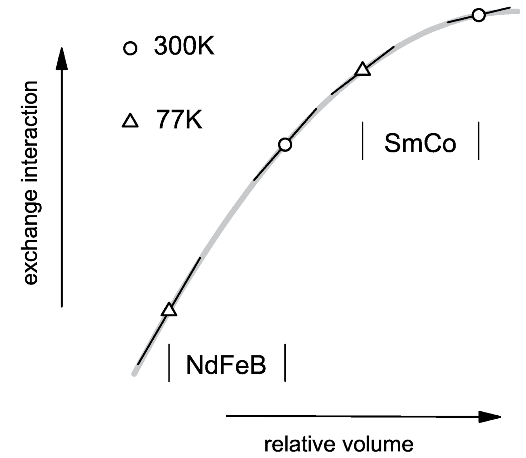

Fig. 2. Schematic volume dependence of the exchange interaction.

It is possible to redraw the Berthe–Slater curve, substituting the relative interatomic distance with the relative volume $(d/r_d)^3$.

Figure 2 shows a fragment of the Berthe–Slater curve related to iron and cobalt. In these coordinates, the data given in Table III multiplied by the value of the exchange interaction is equal to the slope of the tangent at the corresponding point.

The circle near the top of the curve corresponds to cobalt in a SmCo magnet at $T = 300$ K. The tangent (short straight line segment) has a small

TABLE III

Ratio of the relative change in magnetization $\Delta B_r/B_r$ to the relative change in volume $\Delta V/V$.

T [K]	NdFeB	SmCo
300	18.1	3.7
77	80.2	9.8

slope. Decreasing the temperature to 77 K results in a decrease in the volume and an increase in the slope of the tangent.

The same increase in the tangent slope takes place in the case of iron in an NdFeB magnet.

Thus, the obtained results may be qualitatively described by the Berthe–Slater curve.

The earlier experimental conformation of this curve was found in the dependence of the Curie temperature T_{C} on the interatomic distance of ferromagnetic alloys (see Table 4.1.1 in [1]).

Very important results were obtained in the investigations of T_{C} under high pressure [15]. From these rather complicated measurements, $\mathrm{d}T_{\mathrm{C}}/\mathrm{d}p$ was obtained for iron, cobalt, nickel, and their alloys. For cobalt — $\mathrm{d}T_{\mathrm{C}}/\mathrm{d}p = 0$, hence it is at the top of the Berthe–Slater curve. For nickel, $\mathrm{d}T_{\mathrm{C}}/\mathrm{d}p$ is positive, whereas for the Ni(30%)–Fe(70%) alloy, $\mathrm{d}T_{\mathrm{C}}/\mathrm{d}p$ has large negative value, in a full agreement with the Berthe–Slater curve (surprisingly, it is not mentioned in that article).

Our very simple method allows one to obtain similar information for permanent magnets.

5. Conclusions

In the present work, the influence of uniaxial compression on the magnetization of a SmCo magnet was measured. Diminishing of magnetization under compression was observed.

Elastic parameters necessary for estimating the resulting deformation were obtained from pulse ultrasonic measurements.

The results obtained for NdFeB [5] and SmCo magnets, presented as the ratio of the relative change in magnetization to the relative change in volume, qualitatively correspond to the slope of the Berthe–Slater curve.

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