Dependence of the magnetic-anisotropy energy in iron on the magnetic field

I. M. Puzeĭ and V. V. Sadchikov

Research Institute for Ferrous Metals

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The magnetic-anisotropy energy in a single crystal of pure iron is investigated at temperatures 4.2, 20, 77, and 298 K as a function of the external magnetic field up to 29 kOe. It is shown that the torques in various directions are linear in the field. The anisotropy constant is also linear in the field at these temperatures. The strong field dependence of the constant indicates that the anisotropy is of the band type.

1. INTRODUCTION

It is generally accepted at present that 3*d* metals are collectivized (band) magnets (see, e.g., Ref. 1). It had been assumed earlier, however, that iron is closer to being a localized 3*d* metal, and the magnetic anisotropy was calculated on the basis of this assumption.[2-7] It was found as a result that the temperature dependence of the first anisotropy constant is proportional to the tenth power of the saturation magnetization M_s. In experiment,[8] however, only a proportionality to $M_s{}^4$–$M_s{}^6$ was observed.

The anisotropy energy of iron was calculated in Refs. 9 and 10 on the basis of a band structure obtained for it in Ref. 11. The following were taken into account in these calculations: the spin-orbit interaction, the energy-level splitting along the ΓH axis of the Brillouin zone under the influence of this interaction and the crossing of these levels by the Fermi level, the contribution of the levels near the H-point and others, the direction and magnitude of the magnetization, and its influence on the redistribution of the conducting electrons.

The dominant contribution to the anisotropy energy was made by energy levels, split by the spin-orbit interaction along the ΓH axis. This calculation yielded for 0 K an anisotropy constant $K_1 = 6\cdot 10^5$ erg/cm^3. Calculations with our data in Sec. 2 give for $T = 4.2$ K a value $K_1 = 5.16\cdot 10^5$ erg/cm^3. The value of K_1 calculated in Refs. 9 and 10 is thus in good agreement with the experimental one.

The magnetic field is known to influence the electron structure of band magnets (e.g., the susceptibility of the paraprocess is large even at absolute zero), leading to a certain realignment of the band structure. It is therefore of interest to investigate the influence of a magnetic field on the magnetic anisotropy of iron. We know of no published data on this subject, but is has recently become of practical importance, particularly for electrotechnical steels.

2. EXPERIMENTAL RESULTS

We have carried out such an investigation on a single-crystal sphere of diameter 7.825 ± 0.001 mm, of pure iron obtained by recrystallizing polycrystalline iron. The single crystal composition was: 99.98% Fe—O, 0.008% C—O, 0.006% S—O, 0.003% P—O, 0.002% N_2—O and 0.001% O_2. The block misorientation did not exceed three degrees.

We measured in the (100) plane the torques in 15° intervals at eight values of the magnetic field from 13 to 29 kOe. Figure 1 shows the field dependences of the torque *M* and of its increment Δ*M* for various field-rotation angles θ about the ⟨100⟩ direction at 77 K. The ordinates on the left are the values of the torque *M* in a 13 kOe field. On the right are indicated the torque increments Δ*M* following an increase of the field from 13 to 29 kOe. The measurements were made at 77 K. It can be seen that the field dependence of the torque is linear in all directions. The torque at 30, 120, 210, and 300° is independent of the field and the correspond-

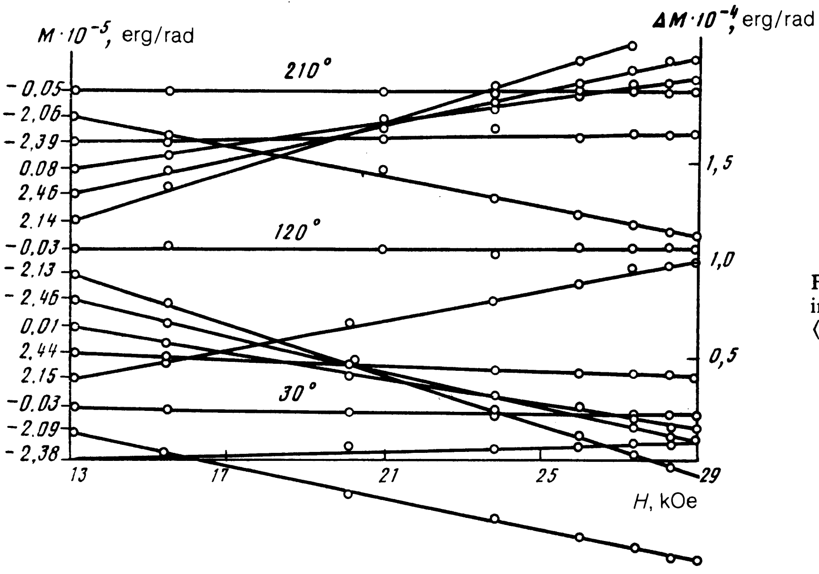

FIG. 1. Influence of magnetic field on the torque *M* and on its increment Δ*M* for various field-rotation angles θ about the ⟨100⟩ direction (see the text for explanations).

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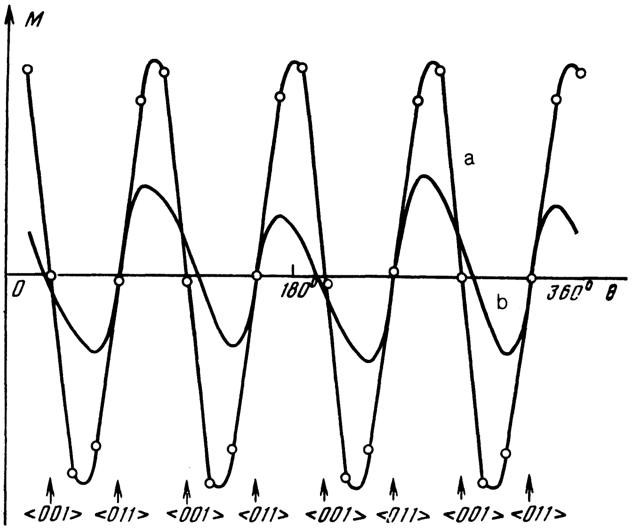

FIG. 2. Angular dependences of the torque M (a) and of its derivative $\Delta M/\Delta H$ (b) with respect to the field at 77 K.

ing straight lines are horizontal. The lines above and below them have a steeper field dependence. Figure 2 shows the angular dependences of the torque and of its derivative, illustrating the connection between the investigated directions and the crystallographic axes of the sample. The origins of the field-rotation angle (from left to right) are the same in Figs. 1 and 2. A characteristic feature of curve b in Fig. 2 (of the derivative $\Delta M/\Delta H$) is the change of its direction from an axis of type $\langle 100\rangle$ to one of type $\langle 110\rangle$. The regular form of curve a in Fig. 2 attests to a good structure of the crystal sample. The angular dependence of $\Delta M/\Delta H$ deviates from a regular sinusoid because the increment ΔM is smaller by 1.5 orders than the total torque M. A characteristic feature of the $\Delta M/\Delta H$ plot is that it is inscribed in the plot of the total torque. This is typical of pure metals and is important for the treatment of the field dependence of magnetic anisotropy in alloys.

The anisotropy constant K_1 of iron at temperatures 4.2, 20, 77, and 298 K is linear in the field in the investigated range 13–29 kOe (Fig. 3). The second anisotropy constant is nonlinear in the field (Fig. 4). We present below the values of the constant K_1, its derivative $\Delta K/\Delta H$ with respect to the field, and the relative derivative $K^{-1}\Delta K/\Delta H$ at 4.2, 20, 77, and 298 K:

T, K	$K_1\cdot 10^{-5}$, erg/cm^3	$\Delta K/\Delta H$, erg/cm^3 Oe	$K^{-1}\Delta K/\Delta H\cdot 10^{-6}$, Oe^{-1}
4.2	5.16	0.597	1.16
20	5.13	0.672	1.31
77	5.10	0.821	1.61
298	4.57	1.035	2.26

3. DISCUSSION OF RESULTS

The torque per unit volume of the crystal is $M = -dE/d\theta$, where E is the anisotropy energy and θ is the angle between the magnetization vector and the crystal axis. In a cubic crystal $M = \frac{1}{2}K_1 \sin 4\theta$ in the (100) plane. The torque M and the anisotropy constant K_1 have the same physical nature and differ only by a factor $(1/2)\sin 4\theta$.

A remarkable feature of the angular dependence of the derivative $\Delta M/\Delta H$ is its distinct inclination away from the $\langle 100\rangle$ axis towards the $\langle 110\rangle$ axis (see Fig. 2). The inclination makes the slope of this curve larger as it crosses the $\langle 110\rangle$ axis, and smaller when the $\langle 100\rangle$ axis is crossed. No such inclination is observed on the main $M(\theta)$ curve. It can therefore be assumed that the field dependence of the magnetic anisotropy is more sensitive to the energy structure of the system of valence electrons than the anisotropy of the iron itself. This dependence points clearly to an extremum of the energy, a maximum along the $\langle 110\rangle$ axis and a minimum along $\langle 100\rangle$. This agrees with the results of Refs. 9 and 10, where it is shown that the minimum of the valence-electron energy is along the ΓH axis in the Brillouin zone. The horizontal lines on Fig. 1 along 30, 120, 210, and 300° are the ΓH directions corresponding to the maximum energy of the valence electrons. The straight lines closest to them have the largest slope, indicating a strong decrease of the electron energy from its maximum along the $\langle 110\rangle$ direction. It must be noted that application of a magnetic field to the sample crystal redistributes the conduction electrons and displaces the Fermi level, increasing thereby the magnetic anisotropy of the iron. This is the main cause of the dependence of the anisotropy on the external magnetic field.

It can be seen from Fig. 3 that the first anisotropy constant has a strong field dependence at all temperatures, including $T = 4.2$ K. By analogy with the paraprocess in band magnets, this attests to the band nature of the magnetic anisotropy of iron.

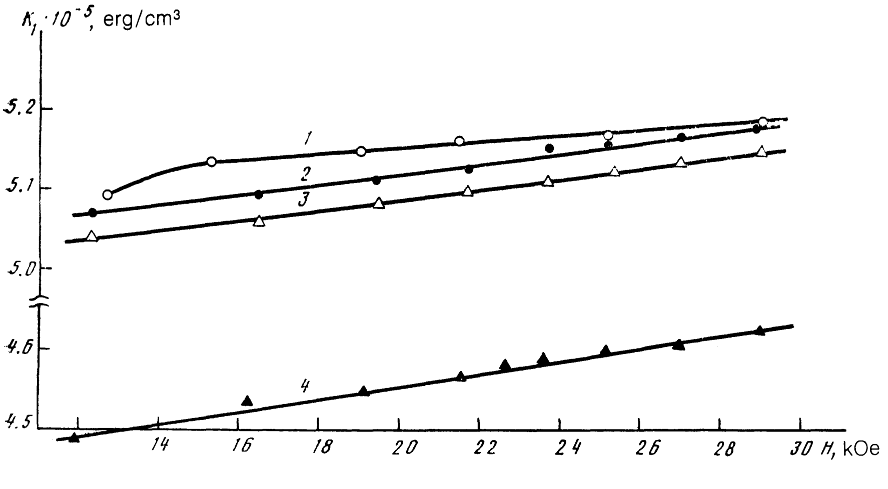

FIG. 3. Dependence of the anisotropy constant K_1 of iron on the magnetic field at temperatures 4.2 (1), 20 (2), 77 (3), 298 (4) K.

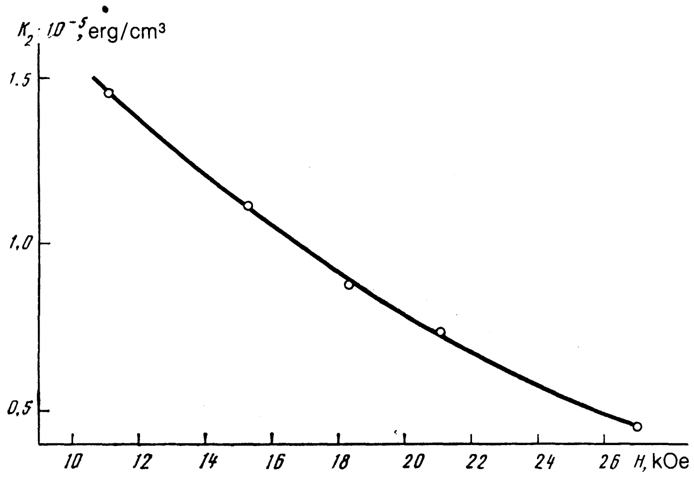

FIG. 4. Dependence of the anisotropy constant K_2 of iron on the magnetic field at 4.2 K. The measurements were made in the (111) plane.

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