MAGNETOSTRICTION OF Tb AND Ho

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The magnetostriction of Tb and Ho was measured in magnetic fields up to 15 000 Oe. The magnetostriction of Tb at low temperatures, where it is in the ferromagnetic state ($T < \Theta_1 = 219°K$), is very high ($\chi_{||} = 750 \times 10^{-6}$, $\lambda_\perp = -460 \times 10^{-6}$ at $T = 85°K$). In the region of the antiferromagnetic-paramagnetic transition ($\Theta_2 = 230°K$) the para-process magnetostriction was observed and was anisotropic. At temperatures at which Ho is antiferromagnetic and in magnetic fields not exceeding the critical value, the magnetostriction of Ho was very low ($\lambda_{||} \simeq 7 \times 10^{-6}$), anisotropic ($\lambda_{||} > 0$, $\lambda_\perp < 0$), and decreased monotonically on approaching $\Theta_2 = 133°K$.

STUDIES of the magnetic properties of Ho and Tb [1,2] have indicated that these rare-earth metals are ferromagnetic below a temperature Θ_1, which is 20°K for Ho and 219°K for Tb, and paramagnetic above a temperature Θ_2, 133°K for Ho and 230°K for Tb. In the intermediate temperature range, from Θ_1 to Θ_2, Ho and Tb are antiferromagnetic but the antiferromagnetic state can be destroyed by a magnetic field that exceeds a certain critical value H_{cr}. Neutron diffraction studies [3] have established that Ho has helical magnetic structure in the temperature range 35—133°K: the magnetic moments of atoms lying in the basal plane of hexagonal Ho crystals are parallel but the magnetic moments of atoms in neighboring layers meet at an angle. It is probable that a similar magnetic structure exists also in Tb in the temperature range 219—230°K.

Measurements of the magnetostriction of dysprosium were reported earlier. [4,5] The present paper reports experimental data on the magnetostriction of Tb and Ho.

The magnetostriction was measured with wire tension gauges on samples in the form of disks (the measurement technique was described in greater detail in [5]).

The magnetostrictions of Dy, Ho, and Tb have different temperature and field dependences in fields up to 15 000 Oe. This is because a field of 15 000 Oe is sufficient to destroy the helical magnetic structure in Dy and Tb but is lower than H_{cr} in the case of Ho and consequently Ho retains its helical structure.

In the case of dysprosium $H_{cr} \simeq 10^4$ Oe; this value of H_{cr} corresponds to quite a high energy of interaction between the layers, which depends on the angle between the magnetic moments of neighboring layers. When the helical structure is destroyed the interaction energy changes and this is the cause of the strong magnetostriction. [5]

In the case of Ho the applied magnetic fields were lower than H_{cr}, which exceeds 17 000 Oe in the range of temperatures employed in our tests, and therefore the 15 000-Oe field produced only a small deformation of the helical magnetic structure. Consequently the magnetostriction of Ho is of the same type (Fig. 1) as the magnetostriction of a normal antiferromagnet, for example NiO. [6] The magnetostriction of Ho is seen to be low ($\lambda_{||} = 5 \times 10^{-6}$ at 80°K and H = 15 000 Oe), its magnitude is proportional to the square of the field (H^2) and decreases monotonically on approaching $\Theta_2 = 133°K$ (with $\lambda_{||} > 0$ and $\lambda_\perp < 0$).

Figures 2 and 3 show the dependence of the magnetostriction of Tb on the field H and on temperature. Since Tb is in the ferromagnetic state below $\Theta_1 = 219°K$, the magnetostriction should be, in general, due to the usual processes of displace-

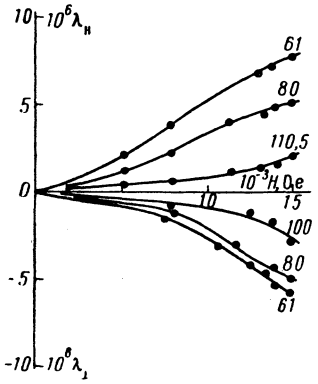

FIG. 1. Isotherms of the logitudinal $\lambda_{||}$ and transverse $\lambda_\perp$ magnetostriction of Ho; the numbers at the curves denote temperatures in deg K.

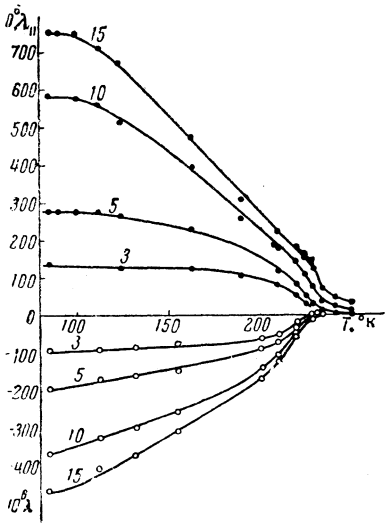

FIG. 2. Temperature dependence of the longitudinal $\lambda_{\parallel}$ (black dots) and transverse $\lambda_{\perp}$ (open circles) magnetostriction of Tb; the numbers at the curves denote the magnetic field in kOe.

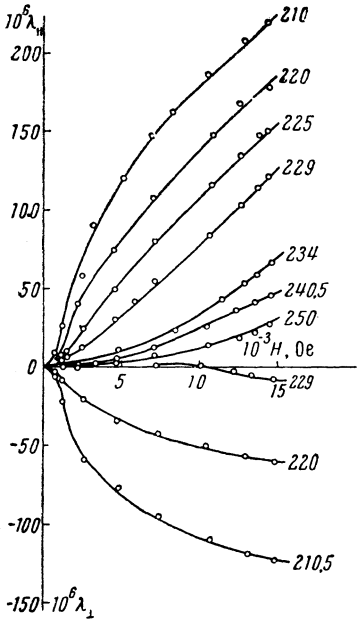

FIG. 3. Isotherms of the longitudinal $\lambda_{\parallel}$ and transverse $\lambda_{\perp}$ magnetostriction of Tb; the numbers at the curves denote temperatures in deg K.

ment and rotation, with $\lambda_{\parallel} > 0$ and $\lambda_{\perp} < 0$. This magnetostriction decreases monotonically on approaching Θ_1. In the range between Θ_1 and Θ_2 we were unable to separate out in Tb the magnetostriction accompanying the destruction of the helical magnetic structure, such as was found in Dy.[5] This may be because the low H_{cr} ($\simeq 10^2$ Oe) of Tb[2] corresponds to a small change of energy on destruction of the helical structure and the magnetostriction is therefore weak. The magnetostriction corresponding to rotation of the magnetic moments of the layers is obviously much stronger than the "helical" magnetostriction in the temperature range Θ_1—Θ_2 and the latter is therefore difficult to observe.

Figures 2 and 3 indicate that the transverse magnetostriction $\lambda_{\perp}$ almost vanishes in the region of Θ_2 while the longitudinal effect $\lambda_{\parallel}$ is still strong. Thus at 250°K, which is 20 deg higher than Θ_2, we have $\lambda_{\perp} < 2 \times 10^{-7}$ and $\lambda_{\parallel} = 27 \times 10^{-6}$ (in H = 15 000 Oe). The sample lengthens considerably along the field and the transverse effect is practically negligible. Our measurements showed that the longitudinal magnetostriction of Tb at Θ_2 is proportional to $H^{2/3}$ in sufficiently strong fields, while above Θ_2 but still close to it this magnetostruction is proportional to H^2. This dependence on the field in the region of the Curie point is known to occur in the case of the para-process magnetostriction in normal ferromagnets. It follows that near Θ_2 Tb exhibits mainly the para-process magnetostriction.

The magnetization curves were obtained near Θ_2 on the same sample of Tb as was used to measure the magnetostriction. This enabled us to determine the dependence of magnetostriction on the square of magnetization near Θ_2. Figure 4 shows that the dependence of $\lambda_{\parallel}$ on σ^2 consists of two linear regions. A similar dependence of magnetostriction on σ^2 near the Curie point was found by Belov and Panina[7] for Invar alloys. Belov and Panina found that one of the linear regions of the $\lambda = \lambda(\sigma^2)$ curve is due to technical magnetization, while the second linear region corresponds to magnetization in strong fields and is due to the para-process. A similar interpretation should, obviously, apply to Tb. In Fig. 4 the first region of the $\lambda_{\parallel} = \lambda_{\parallel}(\sigma^2)$ curves corresponds to processes of rotation of the magnetic moments of the layers, while the second linear region corresponds to magnetization in strong fields and is due to the para-process. However, the transverse magnetostruction curves of Tb, $\lambda_{\perp} = \lambda_{\perp}(\sigma^2)$, do not have linear regions corresponding to the para-process (Fig. 4) since there are no kinks on these curves at values of the magnetization corresponding to strong fields. Thus it follows that the transverse

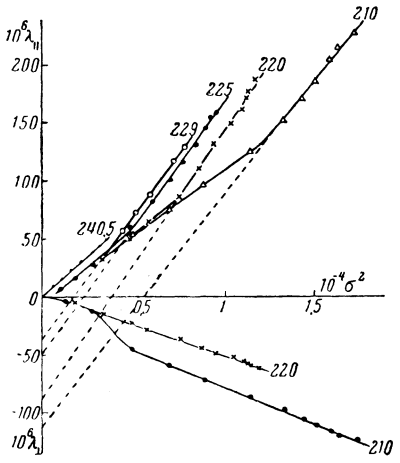

FIG. 4. Dependence of the longitudinal $\lambda_{\parallel}$ and transverse $\lambda_{\perp}$ magnetostriction of Tb on the square of the specific magnetization σ^2.

magnetostriction of the para-process is practically zero in polycrystalline Tb.

Our results indicate that Tb exhibits anisotropic magnetostriction of the para-process in the region of Θ_2.

The published measurements of magnetostriction near the Curie point were carried out on ferromagnets with cubic structure. In such materials the magnetostriction is strictly a volume effect ($\lambda_{||} = \lambda_{\perp}$) and is independent of the direction of the magnetization in the lattice. The spontaneous magnetostriction of such crystals (or the ferromagnetic anomaly of the thermal expansion) near the Curie point is also isotropic.[8] This is due to the isotropic nature of the exchange energy in ferromagnets with cubic structure.

In hexagonal crystals of rare-earth metals the exchange interaction (especially due to their layered magnetic structure) is anisotropic. Therefore near Θ_2 the spontaneous magnetostriction due to exchange forces is also anisotropic, i.e., it varies with the crystallographic direction. This is manifest as an anisotropy of the thermal-expansion anomalies of the lattice parameters below Θ_2.[9] On spontaneous magnetization the increase of the exchange interaction energy alters the anisotropic spontaneous magnetostriction. This change is the para-process magnetostriction which varies with the crystallographic direction.

Our measurements show also that the para-process magnetostriction in Tb depends on the direction of the magnetization in the lattice. In fact, in the absence of such a dependence the geometrical shape of a polycrystalline sample would not change on spontaneous magnetization because the changes in the dimensions would be the same along all directions ($\lambda_{||} = \lambda_{\perp}$), owing to averaging over all grains. This averaging would lead to unaltered geometrical shape of a polycrystalline sample on thermal expansion although individual grains of the sample have anisotropic thermal expansion.

Since the para-process magnetostriction of Tb varies with the crystallographic direction and depends on the direction of magnetization in the lattice, the major axes of the magnetostriction "ellipsoids" of grains should lie along the field if the latter is sufficiently strong. This should alter the shape of a polycrystalline sample since then the longitudinal magnetostriction is stronger than the transverse, as observed in our experiments on Tb.

This dependence of the para-process magnetostriction on the direction of the magnetization in the lattice has not so far been observed in ferromagnets, and is due to the fact that Tb, Dy, and other rare-earth metals have hexagonal structure with a strong anisotropy of the exchange interaction, because of their layered magnetic structure.

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