MAGNETOSTRICTION OF A GADOLINIUM SINGLE CRYSTAL

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The magnetostriction of a gadolinium single crystal in various crystallographic directions has been measured as a function of the magnetic field strength and of the temperature. It was found that the paraprocess magnetostriction along the hexagonal axis is large not only in the vicinity of the Curie temperature, as was shown in [2], but also at lower temperatures (beginning at 180°K). The spontaneous magnetostriction λ'_s caused by the change of exchange energy on passage through the Curie point was calculated by the method of thermodynamic coefficients [8] and was found to be sharply anisotropic. The temperature-variation curves of the saturation magnetostriction λ_s, obtained after subtraction of the paraprocess magnetostriction, have a complicated form. Some of these curves have maxima in the temperature interval 200 to 250°K.

1. Investigations of polycrystalline gadolinium have shown that in it there are complicated dependences of the magnetization, magnetostriction, and galvanomagnetic and other phenomena on the temperature [1]. For understanding of these phenomena, careful magnetic investigations of single crystals of gadolinium are necessary. Recently there have appeared several papers devoted to the investigation of the magnetostriction [2,3], magnetic anisotropy [4], magnetization [5], and other properties [6] of single crystals of gadolinium. The present article presents our data on measurement of the temperature dependence of the magnetostriction of a single crystal of gadolinium.

2. The magnetostriction measurements were made by a tensometer method in fields up to 15 000 Oe in the temperature interval 78—350°K. The gadolinium single crystal was grown in the laboratory of E. M. Savitskiĭ and contained less than 0.2% impurities. From the single crystal, two specimens were cut (5 × 5 × 1 mm); one of them contained the a and b axes, the other the a and c axes.

For a crystal of hexagonal symmetry, the analytic expression for the saturation magnetostriction λ_s due to magnetic forces has a complicated form. If, however, the direction of easy magnetization coincides with the hexagonal axis c, this expression is considerably simplified. Mason [7] showed that in this case

$$\begin{aligned}\lambda_s = {} & \lambda_A[(\alpha_1\beta_1+\alpha_2\beta_2)^2-(\alpha_1\beta_1+\alpha_2\beta_2)\alpha_3\beta_3] \\ & +\lambda_B[(1-\alpha_3^2)(1-\beta_3^2)-(\alpha_1\beta_1+\alpha_2\beta_2)^2] \\ & +\lambda_C[(1-\alpha_3^2)\beta_3^2-(\alpha_1\beta_1+\alpha_2\beta_2)\alpha_3\beta_3] \\ & +4\lambda_D(\alpha_1\beta_1+\alpha_2\beta_2)\alpha_3\beta_3,\end{aligned}$$

where λ_s is the saturation magnetostriction; λ_A, λ_B, λ_C, and λ_D are magnetostriction constants; α_i are the direction cosines of the saturation-magnetization vector; and β_i are the direction cosines of the measurement direction with respect to the axes a, b, and c of the hexagonal crystal (the indices 1, 2, 3 correspond to the axes a, b, c respectively).

According to Graham [4], the direction of easy magnetization of a gadolinium single crystal depends on temperature, and above 250°K it is parallel to the hexagonal axis. In this case it is not possible to determine the magnetostriction constants by direct use of the expression cited above and given by Mason. Therefore in our measurements we used the scheme presented in the table.

Bozorth [2], to measure the magnetostriction constants, turned the direction of the magnetic field (usually of magnitude 10 kOe) from an initial position to the final one shown in the table. We measured magnetostriction isotherms by applying a field up to 15 kOe first in the initial position and then in the final one, according to the scheme of the table. By extrapolation of the resulting magnetostriction isotherms λ(H) to zero field, we

Direction of gauge on crystal	Axes contained in crystal	Direction of saturating magnetic field		Magnetostriction constants observed
		Initial	Final	
‖ *a*	*a* and *c*	‖ *c*	‖ *a*	λ_A
‖ *a*	*a* and *b*	‖ *a*	‖ *b*	$\lambda_B-\lambda_A$
‖ *c*	*a* and *c*	‖ *c*	‖ *a*	λ_C
At 45° to c axis	*a* and *c*	‖ *c*	At 45° to c axis	λ_D

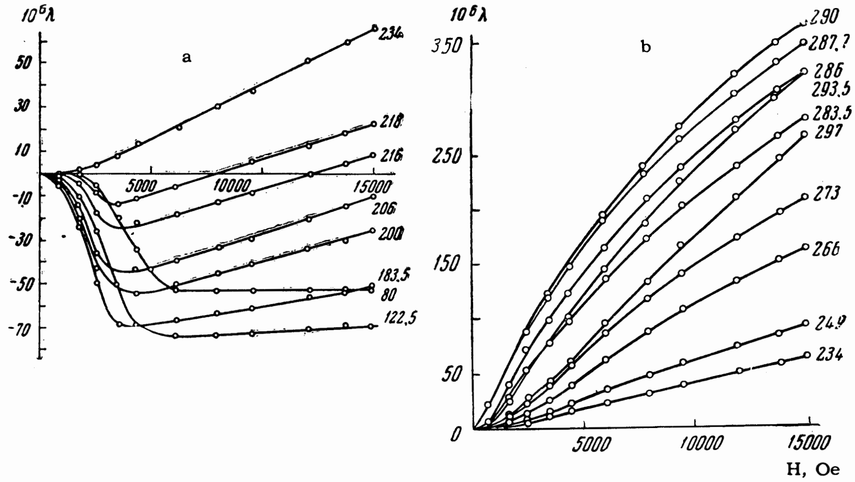

FIG. 1. Isotherms of longitudinal magnetostriction of a single crystal of gadolinium along the c axis (numbers on the curves are degrees Kelvin)

separated out the paraprocess magnetostriction and found the saturation magnetostriction λ_s, due to magnetic lattice forces, at a given temperature.

The difference between the saturation magnetostriction measured in the initial and in the final positions made it possible to estimate the corresponding magnetostriction constants and their temperature behavior. Such a method of measurement of the magnetostriction also enabled us to explain some new peculiarities of its behavior in a single crystal of gadolinium.

3. The measurements of magnetostriction isotherms $\lambda(H)$ showed that the longitudinal magnetostriction of a gadolinium single crystal along the c axis, above temperature 120°K, has no saturation in fields up to 15 kOe (Fig. 1a, b), whereas the longitudinal magnetostriction along the a axis (Fig. 2a, b) reveals saturation in fields of order 5 kOe up to temperature 270°K. The absence of saturation magnetostriction along the c axis (and along the a axis above 270°K) is explained by the influence of the paraprocess.

Figure 3 gives the temperature dependence of the value of $d\lambda/dH$, measured by change of the field from 10 to 15 kOe. This quantity can serve as a numerical characteristic of the paraprocess magnetostriction. Figure 3 shows that at the Curie point the paraprocess magnetostriction in the direction of the c axis is positive and about 25 times larger than the paraprocess magnetostriction in the direction of the a axis, where it has a negative sign. This phenomenon was first observed by Bozorth [2], who determined the value of $d\lambda/dH$ only in the Curie-point region. From our measurements, however, it follows that the value of $d\lambda/dH$ along the c axis is large not only in the vicinity of the Curie point, but also at considerably lower temperatures. The paraprocess magnetostriction of a gadolinium single crystal along the c axis has the character of the paraprocess magnetostriction of Invar alloys.[8]

The spontaneous magnetostriction λ_s' caused by change of the exchange energy on passage through the Curie point can be determined by the thermodynamic coefficients [8] from the curves of λ as a function of σ^2. Here λ is the magneto-

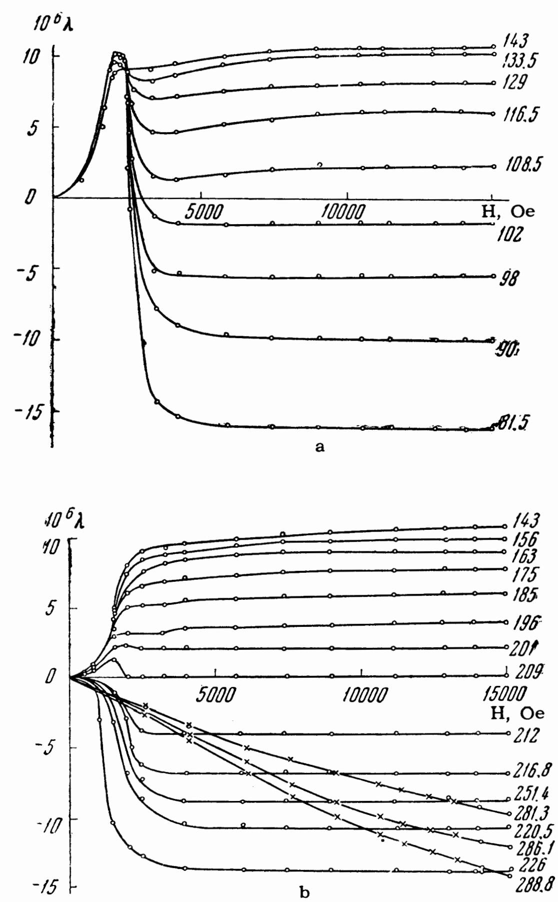

FIG. 2. Isotherms of longitudinal magnetostriction of a single crystal of gadolinium along the a axis (numbers on the curves are degrees Kelvin).

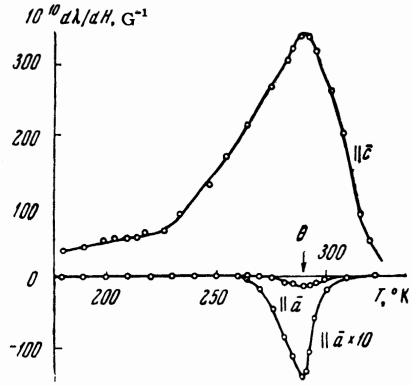

FIG. 3. Change of the paraprocess magnetostriction with field for a single crystal of gadolinium, along the a and c axes.

striction near the Curie point, and $\sigma = \sigma_s + \sigma_i$, where σ_s is the specific spontaneous magnetization and σ_i is the specific true magnetization.

Figure 4 gives the temperature dependence of the spontaneous magnetostriction λ_s' of a gadolinium single crystal, obtained by the method mentioned, for the a and c axes. Obviously it is sharply anisotropic. It is known that the anomaly of the coefficient of thermal expansion at the Curie point is equal to $d\lambda_s'/dT$. We calculated from our data the value of the anomaly of the coefficient of thermal expansion; along the c axis it is equal to $\Delta\alpha_c = -70 \times 10^{-6}$ deg^{-1}, and along the α axis to $\Delta\alpha_a = +5 \times 10^{-6}$ deg^{-1}. These values agree with the directly measured coefficients of thermal expansion [9] and lattice parameters [10] of a gadolinium single crystal.

4. Figure 5 shows $\lambda_s(T)$ curves obtained by extrapolation of the $\lambda(H)$ isotherms to zero field. The magnetostriction λ_s determined in this way is related to the fact that the vector saturation magnetization, without changing its magnitude, changes its direction with respect to the crystallographic axes. The figure shows that the $\lambda_s(T)$

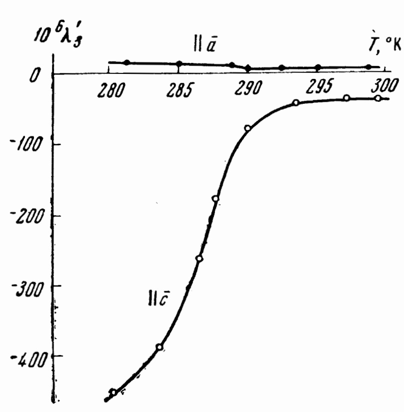

FIG. 4. Spontaneous magnetostriction λ_s' of a single crystal of gadolinium in the vicinity of the Curie point, along the a and c axes.

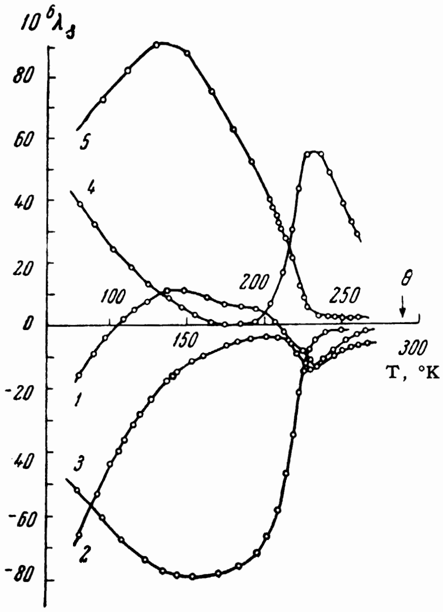

FIG. 5. Saturation magnetostriction λ_s of a single crystal of gadolinium: 1, longitudinal along the a axis (specimen contains the a and c axes); 2, transverse along the a axis (specimen contains the a and b axes); 3, longitudinal along the c axis (specimen contains the a and c axes); 4, transverse along the c axis (specimen contains the a and c axes); 5, transverse along the a axis (specimen contains the a and c axes).

curves have a complicated form. In the vicinity of 220 to 230°K, maxima of λ_s occur for the longitudinal and transverse magnetostriction measured along the a axis (on a specimen containing the a and b axes), and for the transverse magnetostriction along the c axis (on a specimen containing the a and c axes).

The temperature dependences of the magnetostriction constants λ_A, λ_B, λ_C, λ_D were obtained from the $\lambda_s(T)$ curves according to the scheme shown in the table. Figure 6 shows the temperature behavior of these constants, and also the temperature behavior of the longitudinal saturation magnetostriction measured along the c axis and the transverse saturation magnetostriction measured along the a axis, when the external field was directed along the hexagonal axis. Following Bozorth [2], we denote these by λ_{0e} and λ_{0a} respectively. The temperature behavior and values of the magnetostriction constants, and also of the magnetostrictions λ_{0c} and λ_{0a}, as shown in Fig. 6, agree basically with the data of [2]. It can be shown that the magnetostrictions λ_{0c} and λ_{0a} are related to the half-angle θ of opening of Graham's cone [4] and to the magnetostriction constants by the following expressions:

$$\lambda_{0c} = -\lambda_C \sin^2\theta,$$

$$\lambda_{0a} = -(\lambda_A + \lambda_B)\sin^2\theta / 2.$$

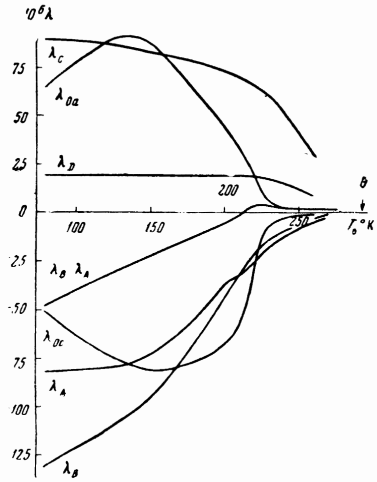

FIG. 6. Temperature behavior of the magnetostriction constants λ_A, λ_B, λ_C, and λ_D and of the magnetostrictions λ_{0c} and λ_{0a}.

Bozorth, by use of these relations and of Graham's data on the change of the angle θ with temperature, showed that the experimental λ_{0c} and λ_{0a} curves are well described by these formulas down to temperatures below 200°K. At higher temperatures there is a deviation between the calculated and the experimental curves.

We, by use of our data on measurements of λ_{0c} and λ_{0a}, have constructed the temperature behavior of θ, the half-angle of opening of the cone of directions of easy magnetization (Fig. 7). These curves agree qualitatively with the results of Graham's work [4], but the temperature interval in which the directions of easy magnetization lie in the basal plane is somewhat displaced toward the low-temperature region; it occurs at temperatures ~145–210°K. It should be mentioned that the curves derived from the formulas for λ_{0a} and λ_{0c} agree in the temperature interval from 80 to 200°K and diverge somewhat at higher temperatures.

The facts stated above enable us to conclude that the behavior of the magnetostriction λ_s of gadolinium in the temperature interval 200–250°K

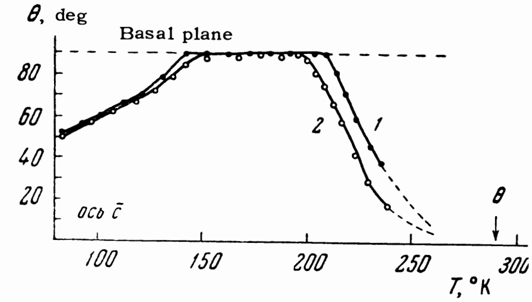

FIG. 7. Angle between the directions of easy magnetization and the hexagonal axis: 1, λ_{0a}; 2, λ_{0c}.

can apparently not be explained solely through processes of rotation of the vector σ_s against magnetic anisotropy forces.

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