Magnetic properties and magnetic transitions in rare-earth intermetallic compounds $(Tb_{1-x}Y_x)_3Co$

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The concentration dependence of the crystal lattice parameters, of the magnetic transition temperatures, of the molecular magnetic moment, of the effective magnetic anisotropy constant, and of the hysteretic magnetic properties is investigated for single crystals of the rare-earth intermetallic compounds $(Tb_{1-x}Y_x)_3Co$ $(0 \leq x \leq 1)$, in which the effective magnetic anisotropy field is comparable with or larger than the effective exchange-interaction field. A qualitative explanation of the observed regularities is given. Magnetically hard single crystals, with a gigantic value of the maximum energy product (up to 100 million G-Oe), are obtained.

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1. INTRODUCTION

Intermetallic compounds R_3T, where R is a rare-earth metal (REM) or yttrium and T is cobalt or nickel, have a crystalline structure of the Fe_3C type, of space group *Pnma*.[1] Depending on the kind of REM and 3*d* metal, some of them are ferromagnetic, others antiferromagnetic or paramagnetic. The metal T in these compounds has no magnetic moment[2] or a very small value of the moment.[3,4] The exchange interaction between the R ions is apparently indirect and takes place through the conduction electrons. Since it is, as a rule, weak, the magnetic ordering temperatures of the compounds are low (below 150 K[5]). Along with this, the magnetization of polycrystals does not reach saturation in pulsed fields up to 160 kOe[4]; this indicates an extremely high value of the magnetocrystalline anisotropy energy, comparable with the exchange-interaction energy. This can lead to a number of peculiarities of their magnetic properties: to the occurrence of noncollinear magnetic structures, of metamagnetism and of magnetic phase transitions induced by a magnetic field, of narrow (monatomic) domain walls, and consequently to peculiarities of the magnetization processes, producing high values of the coercive force H_c. Explanation of the physical nature of these peculiarities is not only of theoretical but also of practical interest. For these purposes, quasibinary compounds of the type $(R_{1-x}R'_x)_3T$ are especially suitable, since in them, by replacement of one R ion by another, it is possible to alter substantially the values of the exchange-interaction and magnetic anisotropy energies, by which the peculiarities mentioned above are principally determined.

The compound Tb_3Co has a noncollinear magnetic structure, with a ferromagnetic component along the *c* axis and antiferromagnetic along the *a* and *b* axes.[2] Taylor and Primavesi[4] measured the concentration dependence of the values of the molecular magnetic moment μ_m, the ordering temperature, and the coercive force of the compounds $(Tb_{1-x}Y_x)_3Co$. But these measurements were made only on polycrystalline specimens and in pulsed magnetic fields. In consequence of the high anisotropy and of the effects of aftereffect, these data, though of independent interest, conceal, as will be shown below, a number of peculiarities of the magnetic behavior of these materials.

Because of the facts set forth above, in the present research an investigation was made of the magnetic properties and crystalline structure of monocrystals of the intermetallic compounds $(Tb_{1-x}Y_x)_3Co$ in static magnetic fields, over a wide range of temperature and over the whole range of variation of the concentration $x(0 \leqslant x \leqslant 1)$.

2. EXPERIMENTAL METHOD

To obtain the alloys, Tb(99.8), Y(99.8), and Co(99.9) in appropriate proportions were fused in an arc furnace with a nonconsumable tungsten electrode on a water-cooled brass tray in helium. For the purpose of grain coarsening, the ingots were treated thermally in a manner similar to that used by Strydom and Alberts[1] for getting monocrystals of Gd_3Co. From coarse grains, monocrystalline specimens were prepared in the form of spheres of diameter 2–2.5 mm. According to data from metallographic and x-ray analyses, they contained no more than 3% of secondary phases. The angle of misorientation of subgrains within them did not exceed 3°. The crystal lattice parameters of the monocrystals were determined with accuracy ±0.005 Å on an x-ray diffractometer URS-50IM. Their variation with increase of the concentration of Y in the compounds $(Tb_{1-x}Y_x)_3Co$ is shown in Fig. 1.

The magnetic properties of the specimens were measured with a vibration magnetometer in static magnetic fields up to 40 kOe, produced with a superconducting solenoid. Orientation of the specimens along various crystallographic directions was accomplished by an x-ray method with accuracy no worse than 3°.

3. MAGNETIC TRANSITION TEMPERATURES

Figure 2 shows the temperature dependence of the specific magnetization σ of monocrystals of $(Tb_{1-x}Y_x)_3Co$, previously cooled from room temperature to 8 K in zero magnetic field, for various chemical compositions, in field 200 Oe along the *c* axis (solid line). The function $\sigma(T)$ has two maxima for compounds with $x \lesssim 0.4$ and one

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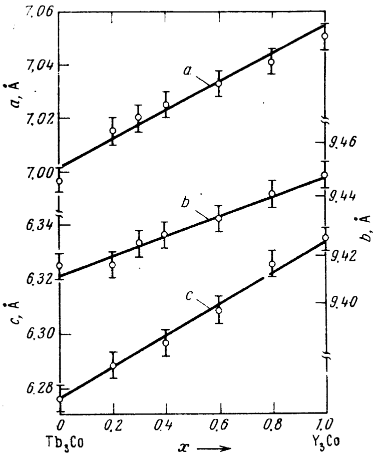

FIG. 1. Concentration dependence of the crystal lattice parameters of monocrystals of compounds $(Tb_{1-x}Y_x)_3Co$ at room temperature.

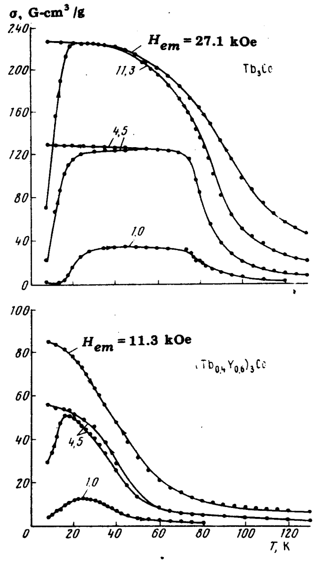

FIG. 3. Temperature dependence of the specific magnetization σ of $(Tb_{1-x}Y_x)_3Co$ monocrystals with $x=0$ and with $x=0.6$, at various values of the external field along the c axis.

for $0.4 \lesssim x < 1$. The high-temperature maximum for Tb_3Co, as was shown in Ref. 2 by comparison of magnetic and neutron-diffraction measurements and of heat-capacity measurements, is due to a transition from an antiferromagnetic state to the paramagnetic. Hence it is logical to suppose that for other compounds also ($x \lesssim 0.4$) it is due to the same cause and that the temperature of the maximum is the Néel temperature (T_N). The increase of σ in a constant field $H_{em} = 200$ Oe with increase of T in the low-temperature range (the low-temperature maximum) is due to a lowering of the value of H_c of the monocrystals. The decrease of σ with further rise of T is due to approach to the temperature T_t of transition from a ferromagnetic state to an antiferromagnetic. With increase of the measurement field H_{em}, the low-temperature maximum becomes less and less noticeable, and at fields H_{em} exceeding the value of H_c at the lowest temperatures it disappears completely; σ(T) becomes reversible (the thermal magnetic hysteresis disappears), and the transition from the antiferromagnetic state to the paramagnetic ($x \lesssim 0.4$) is smeared out (Fig. 3).

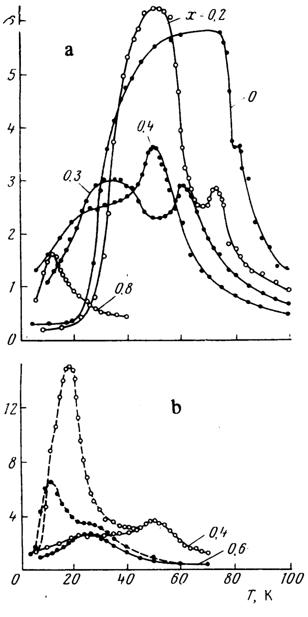

FIG. 2. Temperature dependence of the specific magnetization σ of $(Tb_{1-x}Y_x)_3Co$ monocrystals of various chemical compositions, in external magnetic field $H_{em} = 200$ Oe along the c axis. Solid curves: specimen cooled from room temperature to 8 K in field $H_{em} = 0$. Dotted curves: specimen first magnetized to saturation at 8 K and then demagnetized by a reversed field equal to the relaxational coercive force.

It is evident from Fig. 2 that the value of the low-temperature maximum (H_{em} = const) gradually decreases with increase of concentration, and for compounds with $0.4 \lesssim x < 1$ there remains only the high-temperature maximum. This means that compounds in this concentration range are apparently antiferromagnetic in the equilibrium state at $H_e = 0$. We noted, however, that after magnetization of them at $T = 8$ K in high fields (for example, 40 kOe) and demagnetization at this temperature by a reverse field equal in value to the relaxational coercive force ($H_r \approx H_c$), the low-temperature maximum of the function σ(T) again appears (Fig. 2b, dotted curves). This shows that under the influence of a magnetic field in monocrystals with $0.4 \lesssim x < 1$, ferromagnetic order is induced (or ferromagnetic domains originate), which now changes at $T = T'$ to antiferromagnetic Thus compounds $(Tb_{1-x}Y_x)_3Co$ with $0.4 \lesssim x < 1$ are metamagnetic; this, as is well known, [6] is the name applied to magnetic materials that have a value of the effective magnetic anisotropy field H_a^* equal to or greater than the value of the effective exchange-interaction field ($H_{ex}^* = kT_N/\mu_R$; k is Boltzmann's constant, μ_R the moment of the R ion). In fact, in our case, for example, for $x = 0.5$ the ratio $H_a^*/H_{ex}^* \approx 2.1$.

The concentration dependence of the phase transition temperatures T_N, T_t, and T_t' is shown in Fig. 4. The temperatures T_t and T_t' were determined from the steepest drop of the curve of the function σ(T). Here also, for comparison, are shown data from other papers. [2,4] It is evident that our results for Tb_3Co are close to the values obtained from the temperature dependence of the specific heat. [2] But the concentration dependence greatly differs (especially in the range of occurrence of metamagnetism) from that for the "order-disorder" temperature. [4] The reasons for the discrepancy are not clear. We note only that in Ref. 4, on variation of

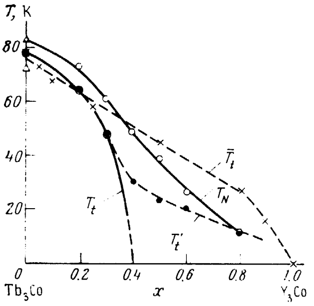

FIG. 4. Concentration dependence of the temperatures of magnetic phase transitions of monocrystals along the *c* axis; the Néel temperature T_N, the temperature of the ferromagnetic-antiferromagnetic transition T_t, and the temperature of transition of a ferromagnetic state induced by a field to an antiferromangetic, T_t'. Also shown here, for comparison, are data for the "order-disorder" transition measured on polycrystals, $\bar{T}_t$[4](x), and values of T_N and T_t for Tb_3CO according to data on the temperature dependence of the specific heat[2] (Δ).

temperature only one magnetic phase transition was observed; this does not agree either with our results or with the results of Ref. 2. It is possible that this is due to a certain difficulty in the separation of maxima on the temperature variation of the initial susceptibility measured on polycrystals by the transformer method.[4] Therefore the transition temperature measured by this method is an averaged value. Furthermore, the application of magnetic measurements both in our work and in Ref. 4 can hardly be considered sufficiently correct for a precision determination of the transition temperatures in magnetic materials with complicated magnetic structure and with a large value of the magnetic anisotropy, as is the case in the compounds $(Tb_{1-x}Y_x)_3Co$. Therefore the concentration variations of the magnetic transition temperatures in our case are, rather, of qualitative character.

The occurrence of a ferromagnetic-antiferromagnetic (more accurately, ferromagnetic-metamagnetic) concentration transition in the system of alloys $(Tb_{1-x}Y_x)_3Co$ is probably due to the different character of the exchange interactions between Tb ions located at different lattice sites, and to the weakening of the ferromagnetic interaction with replacement of Tb ions by nonmagnetic Y ions.

5. MAGNETIC MOMENT

Figure 5 shows magnetization curves along various crystallographic directions and hysteresis loops along the *c* axis, at 8 K. For $0 \leqslant x \lesssim 0.5$ saturation of σ along the *c* axis is attained in relatively small fields, whereas for $0.5 < x < 1$ saturation is not attained up to 40 kOe. The value of the molecular magnetic moment μ_m (the moment of a formula unit) was determined for $0 \leqslant x \lesssim 0.5$ by extrapolation of the linear section of $\sigma(H_i)$ to $H_i = 0$, and for $0.5 < x < 1$ by extrapolation of the linear section of the function $\sigma = f(1/H_i)$ to $H_i = \infty$. It was found that the function $\mu_m(x)$ is linear for all x ($u_{Co} = 0$), and the value of the mean magnetic moment $\bar{\mu}_{Tb}$ per Tb ion, within the limits of error, remains constant and $\sim 7\mu_B$. In view of the facts that the magnetic structure of Tb_3Co is noncollinear and that the measured value $\bar{\mu}_{Tb} = 7\mu_B$ is equal to the projection of the magnetic moment of Tb on the *c* axis, we find that the mean angle $\bar{\theta}_0$ between the Tb moment and the axis is 37–39°, since the value of the magnetic moment of the free Tb ion, *gJ*, is 9 μ_B, while according to neutron-diffraction investigations of Tb_3Co the moment $\mu_{Tb} = 8.8\ \mu_B$. The fact that $\bar{\mu}_{Tb}$ remains constant at all x is unexpected, since it indicates constancy of the mean angle $\bar{\theta}_0$, whereas it would appear that the quantities that determine this angle, i.e. the anisotropy and exchange-interaction energies, change considerably with increase of the yttrium concentration (see Figs. 4 and 7).

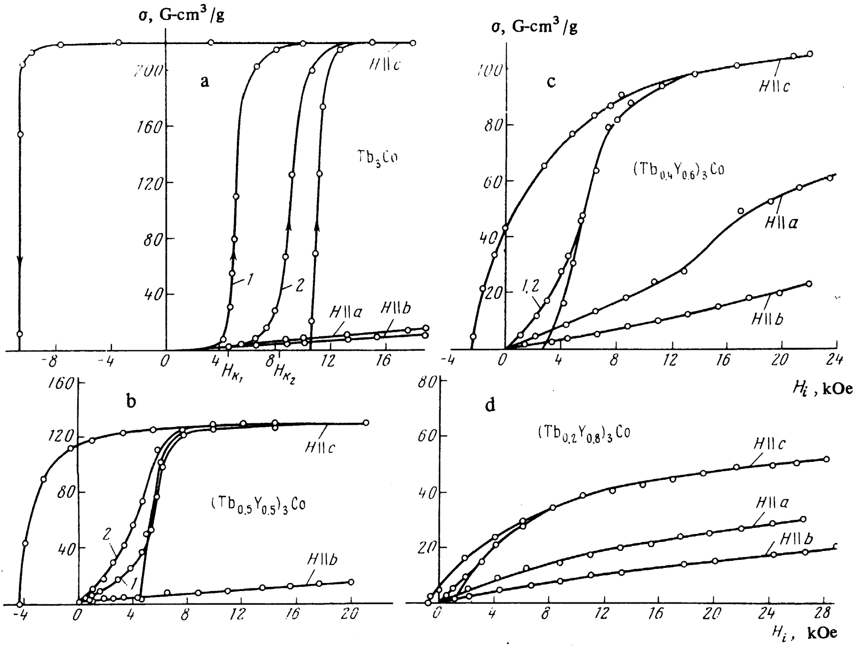

FIG. 5. Magnetization curves along the crystallographic directions *a*, *b*, and *c* and hysteresis loops along the *c* axis, for $(Tb_{1-x}Y_x)_3CO$ monocrystals of various chemical compositions at 8 K. a, $x = 0$; b, $x = 0.5$; c, $x = 0.6$; d, $x = 0.8$. Curve 1, specimen cooled from room temperature to 8 K in field $H = 0$; Curve 2, the same as Curve 1, but in addition the specimen was magnetized to saturation in the (+) direction and demagnetized by a reversed field equal in magnitude to the relaxational coercive force. (All experimental values were obtained 30 seconds after establishment of the appropriate value of the external magnetic field.)

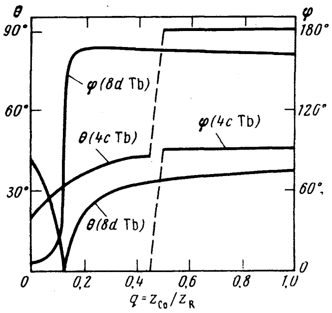

FIG. 6. Calculated variation of the angles θ and φ, which determine the orientation of the magnetic moment of the Tb ions (the local axis of easy magnetization) in Tb$_3$Co, with the ratio of the cobalt and terbium charges ($q=Z_{Co}/Z_{Tb}$), for crystallographic positions 4c and 8d.

6. MAGNETIC ANISOTROPY

The fact that the magnetization curves of $(\mathrm{Tb}_{1-x}\mathrm{Y}_x)_3\mathrm{Co}$ monocrystals along the a and b axes do not attain saturation in fields up to 40 Oe (Fig. 5) indicates the presence of large magnetocrystalline anisotropy, caused apparently by interaction of the anisotropic $4f$ electron shell of Tb with the crystalline field of the lattice, as in pure rare-earth metals.[7] Within the framework of this model, we calculated the lowest-order anisotropy coefficients k_q^2 in the expression for anisotropy energy of the R ion,

$$E_a(\theta,\varphi)=\sum_{q=-2}^{2}k_q^2C_q^2(\theta,\varphi), \tag{1}$$

where $C_q^2(\theta,\varphi)$ are renormalized spherical functions.[8]

The anisotropy coefficients, determined in a system of coordinates connected with the directions of the edges of the elementary cell, make possible a determination of the orientation of the axis of easy magnetization (AEM) and of the axis of hard magnetization (AHM) in the crystal from the extrema of (1). The description of the anisotropy energy is simplest in a system of coordinates connected with these axes:

$$E_a(\tilde{\theta},\tilde{\varphi})=\tilde{k}_0^2\cdot{}^1\!/_2(3\cos^2\tilde{\theta}-1)+\tilde{k}_2^2\cdot({}^3\!/_2)^{1/2}\sin^2\tilde{\theta}\cos^2\tilde{\varphi}. \tag{2}$$

The symmetry of a lattice of the Fe$_3$C type is such that together with ions with orientation (θ_0,φ_0) of the AEM (AHM), there are also in the lattice ions with orientation $(\theta_0,\pm\varphi)$ and $(\theta,\pi\pm\varphi)$ of the AEM (AHM); this leads to the existence of six noncollinear sublattices. The orientation of the AEM and AHM depends considerably (as also do, however, the coefficients k_q^2 themselves) on the ratio of the effective charges of the Co and Tb ions ($q=z_{Co}/Z_{Tb}$). Figure 6 shows this dependence for two crystallographic positions. The experimental mean value of the cosine of the angle of inclination of the AEM to the c axis of a Tb$_3$Co monocrystal is

$$\overline{\cos\theta_0}={}^1\!/_3(2\cos\theta_0[\mathrm{Tb}(8d)]+\cos\theta_0[\mathrm{Tb}(4c)])=0.78.$$

The closest calculated values are obtained for $q=0$ and $q=0.4$ ($\cos\theta_0=0.81$). For resolution of the question which of these cases is realized, we considered the magnetic susceptibility of the Tb ions in weak magnetic fields. The susceptibility is determined on the basis of (1) with allowance for the Zeeman energy. As a result, the following expressions are obtained:

$$\chi^a=\frac{M^2}{D}\left\{\sin^2\theta_0\sin^2\varphi_0\frac{\partial^2E_a}{\partial\theta_0^2}\right.$$
$$\left.+\frac{1}{2}\sin2\theta_0\sin2\varphi_0\frac{\partial^2E_a}{\partial\theta_0\,\partial\varphi_0}+\cos^2\theta_0\cos^2\varphi_0\frac{\partial^2E_a}{\partial\varphi_0^2}\right\},$$
$$\chi^b=\frac{M^2}{D}\left\{\sin^2\theta_0\cos^2\varphi_0\frac{\partial^2E_a}{\partial\theta_0^2}\right. \tag{3}$$
$$\left.-\frac{1}{2}\sin2\theta_0\sin2\varphi_0\frac{\partial^2E_a}{\partial\theta_0\,\partial\varphi_0}+\cos^2\theta_0\sin\varphi_0\frac{\partial^2E_a}{\partial\varphi_0^2}\right\},$$
$$\chi^c=\frac{M^2}{D}\frac{\partial^2E_a}{\partial\varphi_0^2}\sin^2\theta_0;\qquad D=\frac{\partial^2E_a}{\partial\theta_0^2}\frac{\partial^2E_a}{\partial\varphi_0^2}-\left(\frac{\partial^2E_a}{\partial\theta_0\,\partial\varphi_0}\right)^2.$$

Here θ_0 and φ_0 correspond to the orientation of the AEM. The susceptibility of the compound Tb$_3$Co determined from the expression (3) with $q=0.4$ differs substantially from the experimental values, whereas with $q=0$ and $Z_{Tb}=\frac{3}{4}|e|$ (e is the charge of the electron) good agreement with experiment is obtained (Table I). The values of $\tilde{k}_0^2$ and $\tilde{k}_2^2$ for Tb ions located at different crystallographic positions, for the latter case, are shown in Table II. These results were obtained without allowance for the exchange-interaction energy. Consequently they indicate an appreciable influence of the crystalline field of the lattice on the magnetic structure of Tb$_3$Co and on the magnetocrystalline anisotropy. Hence it should have been expected that the value of the effective anisotropy constant (k_{Tb}^*) at $T=0$ K, per ion of Tb, would remain constant with replacement of Tb ions by Y ions in the compounds $(\mathrm{Tb}_{1-x}\mathrm{Y}_x)_3\mathrm{Co}$, since it was assumed above that the anisotropy mechanism is the single-ion. But as is evident from Fig. 7, a, at 8 K the function $k_{Tb}^*(x)$ has a more complicated form. In particular, $k_{Tb}^*(x)$ and $H_a^*(x)$ along the b axis have a maximum at $x=0.2$ and thereafter, as along the a axis, decrease

TABLE I. Values of initial susceptibility of Tb$_3$Co monocrystals at $T=8$ K along crystallographic directions a, b, and c, for different values of $q=Z_{Co}/Z_{Tb}$.

	Value of susceptibility (10^{-4} cm^3/g)		
	Calculation ($Z_{Tb}=3/4\,|e|$)		Experiment
	$q=0.4$	$q=0$	
χ^a	3.0	7.3	7.6
χ^b	12.5	5.9	5.5
χ^c	1.3	4.4	4.5

TABLE II. Theoretically calculated values of the magnetic anisotropy coefficients $\tilde{k}_0^2$ and $\tilde{k}_2^2$ per Tb ion, and values of the critical field K_{crt}, at different crystallographic positions, for the compound Tb$_3$Co.

Position of Tb ion	$\tilde{k}_0^2$, 10^{-15} erg	$\tilde{k}_2^2$, 10^{-15} erg	H_{crt}, kOe
4c	−12	3	~140
8d	−9	5	~70

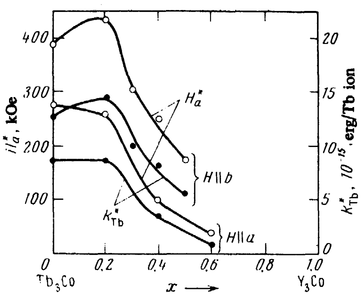

FIG. 7. Concentration dependence of the effective values of the anisotropy field H_a^* and the magnetic anisotropy constant per Tb ion (k_{Tb}^*), obtained from magnetization curves along the a and b axes at $T = 8$ K.

greatly. Although the measured concentration dependences may be influenced by many factors (change of the value and the symmetry of the crystalline field because of change of the lattice parameters or (and) a possible difference in the values of the effective electric charges of the Tb and Y ions, distortion of the magnetic structure under the influence of the magnetic field, effect of anisotropy of the exchange interaction[7]), we are inclined to suppose that the increase of k_{Tb}^* is most probably caused by the unequal probabilities of replacement of Tb by yttrium in the crystallographic positions 4c and 8d in which k_{Tb}^* has different values (see Table II). As for the subsequent decrease of k_{Tb}^*, it is probably produced by the large decrease of the magnetic ordering temperatures in yttrium-rich compounds and by their approach to the measurement temperature (8 K).

7. COERCIVE FORCE AND MAGNETIZATION PROCESSES

Figure 8 shows the concentration dependence of H_c, determined from the hysteresis loops in Fig. 5, of $(Tb_{1-x}Y_x)_3Co$ monocrystals along the c axis at 8 K. Here also, for comparison, is shown $\tilde{H}_c(x)$ measured on polycrystals in pulsed magnetic fields.[4] It is evident that the data in static and in pulsed fields differ greatly; this is probably due to the influence of aftereffect.

We have estimated (without allowance for exchange interactions) the critical fields for reorientation of the magnetic moments of isolated RE ions in Tb$_3$Co under the influence of an external magnetic field directed along the various crystallographic axes of the crystal. Along the c axis, the smallest of these is ~70 kOe (Table II), which is considerably larger than the experimentally observed value of H_c. Hence we may assume, with Taylor and Primavesi,[4] that magnetic reversal of the magnetic materials $(Tb_{1-x}Y_x)_3Co$ occurs by production of a domain structure and subsequent displacement of domain walls. The width of a domain wall, estimated by the formula

$$\delta=\pi(A/K)^{1/2}, \qquad (4)$$

where A is the exchange parameter, is 2 to 3 lattice parameters; but with allowance for the discreteness in the spin orientation in a wall, for $g(x) = a^2K^*/2A = 4$ to 6 ($K^* = H_a^*/M_s/2$), it is, according to Van den Broek and Zijlstra,[9] monatomic. In this case the intrinsic coercivity H_w of the wall may be quite high (~H_a) and responsible for the value of H_c:

$$H_w=\pi H_a\Delta\gamma/4dK. \qquad (5)$$

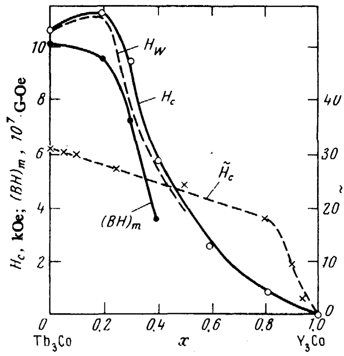

FIG. 8. Concentration dependence of values of the coercive force H_c and maximum energy product $(BH)_m$ in static fields, for $(Tb_{1-x}Y_x)_3Co$ monocrystals, along the c axis. Also shown here, for comparison, are the theoretically expected variation of the intrinsic coercivity of narrow domain walls, $H_w(x) \sim H_c(x) \sim H_a(x)(1-x)^{1/3}$, and the experimental variation of $\tilde{H}_c(x)$ in pulsed magnetic fields for polycrystals of the same compounds according to Ref. 4.

Unfortunately, it is difficult in our case to estimate the value of H_w accurately, since we do not know the energy barrier $\Delta\gamma$ for displacement of the wall or the value of the wavelength d of the Peierls potential, which is proportional to the distance between magnetically active ions. Therefore we shall restrict ourselves to analysis only of the concentration dependence of $H_w(x)$ and consequently of $H_c(x)$. For $g \geq \frac{2}{3}$, the value of H_w should according to Van den Broek and Zijlstra[9] be essentially independent of $(\Delta\gamma/K^*)$. Then

$$H_w(x)\sim H_c(x)\sim H_a(x)/d(x)\sim H_a(x)\,(1-x)^{1/3}. \qquad (6)$$

This dependence, reduced to H_c for Tb$_3$Co, as is evident from Fig. 8, is qualitatively close to the experimental. We note that experiments in pulsed fields[4] give instead of (6)

$$\tilde{H}_c(x)\sim(1-x)^{1/3}. \qquad (7)$$

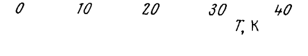

FIG. 9. Temperature dependence of the coercive force H_c along the c axis, for $(Tb_{1-x}Y_x)_3Co$ monocrystals of various chemical compositions, and effective magnetic anisotropy field H_a^* for $x = 0$, determined from magnetization curves along the c and b axes.

The temperature dependence of H_c of $(Tb_{1-x}Y_x)_3Co$ monocrystals is qualitatively the same at all x: H_c decreases rapidly with rise of temperature, according to the exponential law

$$H_c(T)=H_c(0)\exp(-kT/\alpha), \tag{8}$$

as is clearly evident from Fig. 9. Here also is shown, for comparison, the temperature dependence of the effective anisotropy field for Tb_3Co. It is evident that there is no direct relation between $H_c(T)$ and $H_a(T)$, as is often observed for ordinary ($H_a \ll H_{ex}$) high-anisotropy ferromagnets. The exponential character of the function $H_c(T)$ may be due either to change of wall thickness with change of T, for example because of temperature variation of the exchange parameter (A), as is seen in the example of Dy and Ho,[10] since[11]

$$H_c \sim \exp(-\pi\delta(T)/d), \tag{9}$$

or to thermal activation of the wall displacement. In the second case, the coefficient α in equation (8) has the meaning of the value of the energy barrier for displacement of domain walls and is proportional to $\Delta\gamma$.

We note some features of the magnetization processes. First, the value of the specific magnetization along the axis of easy magnetization of $(Tb_{1-x}Y_x)_3Co$ monocrystals with $0.5 \lesssim x < 1$, i.e., in the metamagnetic range of concentrations, does not reach saturation in fields significantly exceeding the values of H_c and H_{cr}. It may seem that this is due to a decrease of the angle θ under the influence of the magnetic field. But this is not so, since the value extrapolated to $H_i=\infty$ is $\mu_{Tb}=7\ \mu_B$; that is, it is equal to the value of μ_{Tb} for monocrystals with x in the ferromagnetic range of concentrations ($x \lesssim 0.4$), where technical saturation is attained in relatively weak fields. It is possible that the difficulty of magnetization is caused by difficulty of disappearance of remnants of domain structure or to the presence, in alloys rich in yttrium, of groups of atoms (clusters) that have weak exchange interaction with each other. Such clusters may behave during magnetization like single-domain, quasisuperparamagnetic particles, since the measurement temperature is close to T_t'.

Second, the value of the critical field H_{cr} strongly depends on the previous magnetic history of the specimens. In fact, in the concentration range $0 \leq x \lesssim 0.4$ the value H_{cr1}, determined from measurement of $\sigma(H)$ of a specimen cooled from room temperature to 8 K, at $H_c=0$ was significantly below H_c and H_{cr2}, obtained with repeated measurement of $\sigma(H)$ in the same direction when the specimen, after preliminary magnetization to saturation, was demagnetized by a reversed field equal to the relaxational coercive force. At $x=0.4$ the values of the critical fields coincide. In the range $0.4 < x \leq 0.8$ we have $H_{cr1} \geq H_{cr2}$.

In conclusion, we note that monocrystals of the intermetallic compounds $(Tb, Y)_3Co$ have gigantic values of the maximum energy product $(BH)_m$ (up to 100 million G-Oe; see Fig. 5), exceeding by almost one and one half times the highest hitherto known value of $(BH)_m$, for Dy_3Al_2 monocrystals,[12] with a record-high value, for magnetically hard materials, of the residual induction (up to 24 kG). This fact permits us to hope that the compounds $(Tb_{1-x}Y_x)_3Co$, especially in the form of textured polycrystals, may find application as sources of magnetic field at low temperatures.

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