Magnetic hysteresis in terbium–yttrium rare earth alloys near the antiferromagnetic-ferromagnetic phase transition

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The magnetic hysteresis of terbium–yttrium single crystal alloys has been investigated. Hysteresis loops associated with the antiferromagnetic-ferromagnetic phase transition were observed near the critical magnetic field strengths. It is shown that the phase transition is of the first order. The width of the hysteresis loop depends nonmonotonically on the composition of the alloy. It was found that the concentration dependence of the critical magnetic field strength in terbium–yttrium alloys has a maximum at 70 at.% Y.

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Studies of the magnetic hysteresis of rare-earth metals (REM) and their alloys, which have a helicoidal antiferromagnetic structure in a certain temperature range, are of scientific interest from two points of view: first, to elucidate the complex magnetization processes in helicoidal magnets, and second, to obtain information on the nature of the phase transitions.

REM and their alloys exhibit complex magnetic transitions between ferromagnetic, helicoidal antiferromagnetic, and paramagnetic phases.[1] Up to now polycrystalline specimens have been used to investigate the magnetic hysteresis in the vicinity of these transitions,[2] and this is inadequate since the results are very difficult to interpret because of the very large magnetic anisotropy and magnetostriction.

In the work reported here we investigated the magnetic hysteresis of terbium-yttrium alloy single crystals. The techniques used in growing the crystals and monitoring their quality have been described elsewhere.[3] Neutron-diffraction data[4] show that these alloys have a helicoidal antiferromagnetic structure in a certain termperature range Θ_1–Θ_2, the magnetic moments of the atoms then lying in the basal plane of the hexagonal dense-packed lattice. A magnetic phase diagram for terbium-yttrium alloys has been constructed[5] on the basis of studies of the magnetostrictive[5] and electrical[3] properties.

Figure 1 shows magnetization and magnetic hysteresis curves for Tb+37 at.% Y and Tb+50 at.% Y alloys measured along the b axis in the basal plane at a temperature (4.2 °K) at which the helicoidal magnetic structure exists in the absence of a field. As the magnetic field is increased the magnetization first rises linearly, and then, at a critical field strength $H=H_{cr1}$, it rises discontinuously and reaches saturation. The sudden decrease of the magnetization on reducing the field strength takes place at a different critical field strength $H=H_{cr2}$.

We note that the saturation magnetization of the Tb+37 at.% Y alloy at 4.2 °K amounts to $\sigma=260$ G·cm³/g, which corresponds to a magnetic moment of $\mu_0=9.8\ \mu_B$ for the Tb ion. This value of μ_0 exceeds the magnetic moment of the free trivalent terbium ion ($\mu_0=9\ \mu_B$). On the basis of this we can say that the present alloy is a ferromagnet having its magnetic moments aligned parallel at 4.2 °K when $H>H_{cr}$. The spin polarization of the conduction electrons due to s–f exchange also makes an appreciable contribution to the magnetic moments.

Thus, the helicoidal structure is destroyed when the field strength rises above the critical value H_{cr}, i.e. a phase transition from helicoidal antiferromagnetism to ferromagnetism takes place. The large magnetic hysteresis accompanying this transition doubtless indicates that the transition is of the first order. This conclusion is confirmed by measurements of the magnetocaloric effect[6] and the magnetostriction,[5] since there is an entropy discontinuity as well as discontinuities in the linear dimensions and volume of the specimen at $H>H_{cr}$.

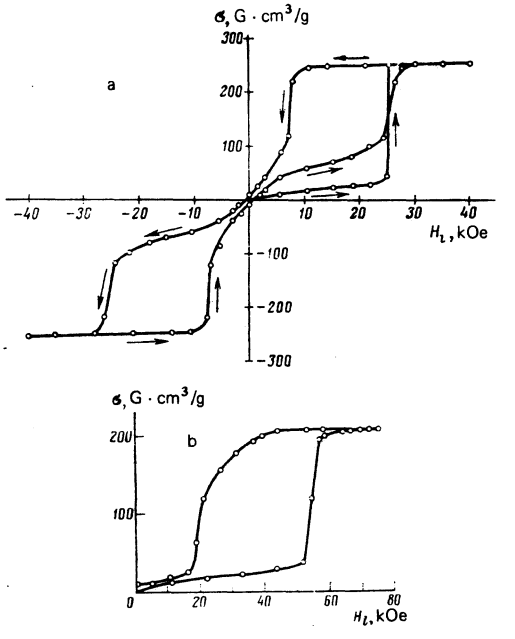

FIG. 1. Magnetization curves and hysteresis loops for terbium-yttrium alloys at 4.2 °K: a-Tb+37 at.% Y; b-Tb+50 at.% Y.

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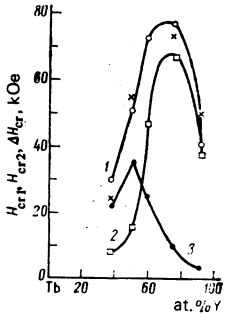

FIG. 2. Concentration dependences of the critical magnetic field strengths H_{cr1} (curve 1) and H_{cr2} (curve 2) and their difference ΔH_{cr} (curve 3) for terbium-yttrium alloys at 4.2 °K. The open circles and squares represent pulsed-field measurements of H_{cr1} and H_{cr2}, respectively, and the crosses, static-field measurements of H_{cr1}.

According to current ideas,[7,8] the appearance and character of helicoidal and sinusoidal magnetic structures in REM are determined to a considerable extent by the topology of the Fermi surface, the energy spectrum of the conduction electrons, and features of the $s-f$ exchange interaction. Changes in the exchange parameters, the magnetic anisotropy, and the magnetostriction incident to changes in termperature and concentrations of the rare-earth components in the alloys doubtless also affect the stability of these structures.[5,9]

It is of interest to trace the variations in the critical magnetic field strengths and the width of the hysteresis loop as functions of the yttrium concentration in the terbium-yttrium alloys. Magnetization measurements were made in static fields up to 75 kOe and in pulsed magnetic fields up to 200 kOe (Fig. 2), the magnetic fields being applied in the basal plane along the $\langle 10\bar{1}0\rangle$ crystallographic direction (the b axis). The magnetic field strength was determined within 0.5% in the static regime and within 10% in the pulsed regime. H_{cr1} was taken as the field strength at the maximum of $d\sigma/dH$ in the vicinity of the sharp rise of the magnetization σ incident to destruction of the helicoidal magnetic structure. H_{cr2} was determined similarly from the $d\sigma/dH$ maximum in the vicinity of the sharp decrease in the magnetization on the downward branch of the magnetic hysteresis loop. H_{cr1} and H_{cr2} were determined within 2.5% in the static regime and within 12% in the pulsed regime. In all cases the width ΔH_{cr} of the magnetic hysteresis loop was defined as the difference between H_{cr1} and H_{cr2}, i.e., $\Delta H_{cr}=H_{cr1}-H_{cr2}$. It is evident from Figs. 1 and 2 that the critical field strength is considerably higher and the hysteresis loop considerably wider for the Tb+ 50 at.% Y alloy than for the Tb+ 37 at.% Y one. The concentration dependence of H_{cr} at 4.2 °K exhibits a maximum at 70 at.% Y (see Fig. 2). The critical magnetic field strengths decrease sharply as the temperature rises and approaches the Néel point. As the specimen is heated within the interval 4.2–60 °K the width of the hysterisis loop decreases approximately as the fifth power of the relative magnetization σ_s/σ_0, i.e,

$$\Delta H_{cr}(T)=\Delta H_{cr}(0)\,(\sigma_s/\sigma_0)^5,$$

where $\Delta H_{cr}(0)$ is the value of H_{cr} at 0 °K. The Tb+ 37 at.% Y alloy, whose antiferromagnetic-paramagnetic transition temperature is $\Theta_2=176$ °K, exhibits virtually no magnetic hysteresis near H_{cr} when $T>130$ °K.

If the hysteresis near H_{cr} were due entirely to the magnetic anisotropy in the basal plane, there would be a considerable difference between the values of H_{cr} for fields H parallel to the a and b axes, respectively. However, these differences do not exceed 10% of the critical field strength H_{cr}. In principle, the magnetoelastic energy might also affect the hysteresis. In this case ΔH_{cr} should be proportional to the magnetoelastic energy:

$$\Delta H_{cr}\sim\frac{1}{I_s}\left[\frac{C_{11}-C_{12}}{2}(\lambda^{\gamma,2})^2+\frac{C_{33}\lambda_c^2}{2}\right],$$

where $\lambda^{\gamma,2}$ and λ_c are constants specifying the magnetostriction in the basal plane and along the c axis, respectively; the C_{ij} are the elastic constants; and I_s is the magnetization. On substituting into this formula the experimental values $\lambda^{\gamma,2}\sim 10^{-3}$, $\lambda_c\sim 10^{-3}$, $C_{11}\sim 0.75\times 10^{12}$ dyne/cm^2, $C_{12}\sim 0.26\times 10^{12}$ dyne/cm^2, $C_{33}\sim 0.6\times 10^{12}$ dyne/cm^2, and $I_s\approx 1700$ G obtained for Tb+ 37 at.% Y alloys at 4.2 °K, we find that $\Delta H_{cr}\sim 300$ Oe. This is two orders of magnitude lower than the observed values of ΔH_{cr}.

In terbium-yttrium alloys,[9] the magnetic anisotropy and magnetostriction in the basal plane fall off monotonically with decreasing terbium concentration, since they are mainly single-ion effects, being due to the interaction of the orbital angular momentum of the terbium with the field of the crystal lattice.

The experimental data show (Fig. 2) that H_{cr} grows considerably with decreasing terbium concentration down to a concentration of 70 at.% Y but then falls with further decrease of the terbium concentration. As a function of concentration, ΔH_{cr} has a maximum at 50 at.% Y. Such behavior of H_{cr} and ΔH_{cr} cannot be explained by taking account of the magnetic anisotropy and magnetostriction alone. The critical magnetic field strength and the width of the hysteresis loop depend on the energy barrier between the ferromagnetic and helicoidal structures. The height of this barrier depends to a considerable extent on changes in the exchange interaction between the magnetic layers and in the electronic structure at the transition between the helicoidal antiferromagnetic and ferromagnetic phases.

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Phonon retardation of a domain wall in a rare-earth orthoferrite

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The topic is interaction of a moving domain wall in a rare-earth orthoferrite with elastic vibrations of the lattice and with spin waves that are localized near the domain wall. It is shown that this interaction leads to a sharp increase of the retarding force acting on the domain wall at a velocity close to one of the velocities of sound. The retarding force due to one- and two-particle processes is calculated; consideration is also given to the effect of this phenomenon on the variation of the domain-wall velocity with external magnetic field.

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INTRODUCTION

In the motion of domain walls (DW) in perfect, magnetically ordered crystals, there is particular interest in the study of the dynamic retardation of DW that is caused by interaction of a DW with magnons and with lattice vibrations (phonons) and that exists even in an ideal crystal.

In calculation of the dynamic retardation of DW, usually only interaction of the DW with magnons is taken into account.[1] Actually, this is due to the fact that the coupling between the magnetic and elastic subsystems is small and manifests itself significantly only when definite resonance conditions are satisfied.[2] As we shall show below, in the present case this condition is coincidence of the domain-wall velocity with the phase velocity of an elastic wave; there is then the possibility of sound radiation, which leads to a significant contribution to the dynamic retarding force. This phenomenon has been observed in experiments[3,4] carried out on rare-earth orthoferrites (REO).

We note that such effects can in principle be observed only in magnetic materials in which the limiting velocity V_c of DW motion is larger than the velocity of sound. As an example, one may cite antiferromagnets or ferrites with equivalent magnetic sublattices (for example, REO),[1)] in which the limiting DW velocity is determined by exchange interaction alone[5] ($V_c \sim I_a/\hbar \sim 10^4$ m/sec; I is the exchange integral, a the lattice constant; the experimental value of V_c in REO, obtained by Konishi *et al.*[3] and by Chetkin *et al.*,[4] is of the order of $2 \cdot 10^4$ m/sec).

The present paper treats radiation of sound during motion of a DW in REO. Characteristic of this problem is the fact that the DW is plane (a one-dimensional system). It is shown that this significantly changes the nature of the radiation as compared with the standard situation of Cerenkov radiation (a particle-like or linear system[6]); specifically: the condition for radiation of a phonon is satisfied only in a narrow range of DW velocity near the sound velocity s, and not for $V > s$ as in the standard situation. This fact leads to the necessity for considering processes of radiation of several particles (phonons or phonons and spin waves).

We shall consider processes of radiation of one and of two phonons, and also the process of radiation of a phonon and a spin wave (Sections 2 and 3). We shall calculate the contribution of these processes to the DW retarding force. It turns out that of all the two-particle processes, the one that makes the greatest contribution is the process of radiation of a volume phonon and of a spin wave localized near the DW. The closing section 4 of the paper discusses the effect of these processes on

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