Growth of magnetic moments in heavy rare-earth metals and their alloys due to samarium impurities

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Small additions of Sm from 0.2 to 2 at.% to heavy, rare-earth metals Ho, Dy, and Tb and also to their binary alloys increase the average magnetic moments μ_I and μ_{eff}, of the alloy atom. This effect is attributable to an increase in polarization of the conduction electrons in such systems.

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In this paper we report the results of an experimental investigation of the magnetic properties of Ho, Dy, and Tb and their alloys with samarium, which was performed in the temperature range 4.2–400 K in fields up to 50 kOe. Alloys of heavy, rare-earth metals (HREM) with samarium have not been adequately studied. However, anomalies of the electrical and galvanomagnetic properties were observed when Sm was introduced into the Ho and Dy matrices.

Samples and the Measuring Method

Investigations were performed by using polycrystalline Ho, Dy, and Tb samples

and the alloys $Ho_{1-x}Sm_x$, $Dy_{1-x}Sm_x$, $Tb_{1-x}Sm_x$, and $(Ho_{0.5}Dy_{0.5})_{1-x}Sm_x$ prepared at Giredmet from 99.98% pure materials. The samarium concentration in the alloys was determined by the neutron-activation method with an accuracy up to 0.1%. We studied alloys with concentrations of samarium from 0.15 to 12 at.% ($0.0015 \leqslant x \leqslant 0.12$). The ballistic method was used to measure magnetization in the cylindrical samples with $e/d = 10$ in the temperature range of 4.2-400 K in 50-kOe fields. An electronic stabilization system allowed us to maintain the temperature with accuracy of 0.03 —0.5°, depending on the temperature region in which the measurements were conducted. The paramagnetic susceptibility χ_p was calculated from the magnetization isotherm in the temperature region $T \gg \Theta_p$, where Θ_p is the paramagnetic Curie temperature. It was established that the paramagnetic susceptability χ_p in all the investigated alloy systems obeys the Curie-Weiss law. This made it possible to construct direct regressions of the form $1/\chi_{pi} = f(T)$ from the numerical values of χ_{pi} and to estimate the correlation coefficients by using the least-squares method. The temperatures Θ_p of the alloys were determined by extrapolating the straight lines $1/\chi_{pi} = f(T)$ to the temperature axis. The accuracy of determining Θ_p was ± 0.5 K. The obtained values of the magnetization I, χ_p, and Θ_p were used for calculating the magnetic moments of magnetization μ_I^* and the effective moments μ_{eff}. The moments were calculated per alloy atom according to the equations

$$\mu_I^* = I^* A/Nd\mu_B , \tag{1}$$

$$\mu_{\text{eff}}^2 = 3\chi_p(T - \Theta_p)\, kA/Nd\mu_B , \tag{2}$$

where I^* is the magnetization of the alloy in a field $H = 50$ kOe, A is the atomic weight of the alloy, d is the density of the alloy, N is the Avogadro's number, and k is the Boltzmann constant. The confidence interval of the magnetic moments is ± 0.08 of the Bohr magneton. The Neél temperature T_N and the ferromagnetic Curie temperature T_C of alloys were determined by standard methods from the location of the singularities in the magnetization isofields.

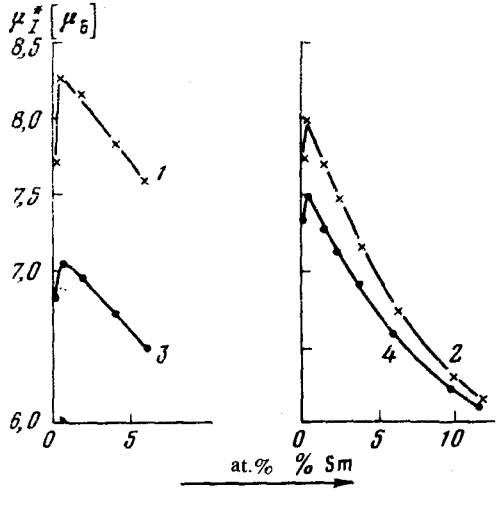

FIG. 1. Dependence of the magnetic moment μ_I^* on samarium concentration in alloy systems: 1, $(Ho_{0.5}Dy_{0.5})_{1-x}Sm_x$, $T = 4.2$ K; 3, $(Ho_{0.5}Dy_{0.5})_{1-x}Sm_x$, $T = 80$ K; 2, $Tb_{1-x}Sm_x$, $T = 4.2$ K; 4, $Tb_{1-x}Sm_x$, $T = 80$ K.

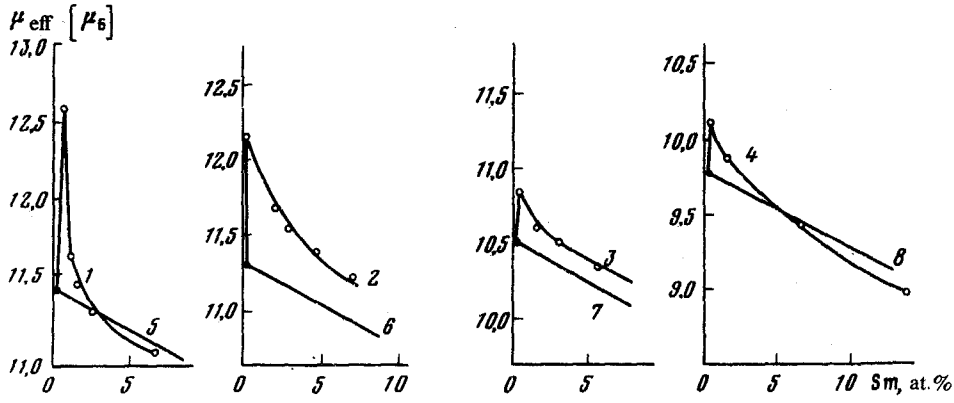

FIG. 2. Dependence of the effective magnetic moment μ_{eff} on samarium concentration in alloy systems: 1, $Ho_{1-x}Sm_x$, experiment; 5, $Ho_{1-x}Sm_x$, theory; 2, $(Ho_{0.5}Dy_{0.5})_{1-x}Sm_x$, experiment; 6, $(Ho_{0.5}Dy_{0.5})_{1-xSm_x}$, theory; 3, $Dy_{1-x}Sm_x$, experiment; 7, $Dy_{1-x}Sm_x$, theory; 4, $Tb_{1-x}Sm_x$, experiment; 8, $Tb_{1-x}Sm_x$, theory.

Experimental Results

The magnetic properties differ sharply in the alloys with a small content ($0.0015 \leqslant x < 0.03$ alloys I) and a large content ($x > 0.05$ alloys II) of samarium. Both I and χ_p in alloys I at all temperatures are smaller than those in the original HREM matrices and in alloys II they are smaller than those in the original HREM matrices. The Θ_p of alloys I remains almost constant with increasing samarium concentration, and of alloys II it decreases by approximately 1.5° per 1 at.% Sm. The T_N decreases linearly in all the alloys with increasing samarium concentration.

Figure 1 shows the $\mu_I^*(x)$ functions calculated at $T_1 = 4.2$ K and $T_2 = 80$ K for the alloys $(Ho_{0.5}Dy_{0.5})_{1-x}Sm_x$ and $Tb_{1-x}Sm_x$ (curves 1–3 and 2–4, respectively). Figure 1 shows that at T_1 and T_2 in alloys I μ_I^* increases in comparison with μ_I^* of the matrices. In alloys II μ_I^* decreases, and at $x > 0.05$ it becomes smaller than μ_I^* of the matrices. A similar increase of μ_I^* is observed in alloys I of all the investigated systems.

Figure 2 shows the $\mu_{eff}(x)$ functions for alloys of all the investigated systems (curves 1–4). Clearly, μ_{eff} increases in alloys I of all the systems and decreases in alloys II as compared with μ_{eff} of the matrices. It was established that the increase of μ_{eff} in alloys I depends on the material of the original HREM matrix. This effect is maximized for holmium and minimized for terbium. Thus, $\Delta\mu_{eff}/\mu_{eff}$ matrices, where $\Delta\mu_{eff} = \mu_{eff}\cdot\max - \mu_{eff}$ matrices are equal: for holmium-10.5%, for the alloy $(Ho_{0.5}Dy_{0.5})_{1-x}Sm_x$-7.5%, for dysprosium-4.3%, for terbium-3.1%.

As is known,[3] as a result of fusing the REM, μ_{eff} of the alloys coincide well with the values calculated according to the equation:

$$\mu_{eff} = \sqrt{\mu_{1\,eff}^2\,(1-x) + \mu_{2\,eff}^2}\,, \qquad (3)$$

where μ_{1eff} and μ_{2eff} are the effective moments of the components.

Figure 2 (curves 5–8) shows the functions $\mu_{eff}(x)$ calculated by using Eq. (3) for

all the alloy systems. These curves show that addition of weakly magnetic samarium to HREM, in accordance with Eq. (3), μ_{eff} of the alloy should decrease linearly with increasing concentration of samarium in the alloys.

Thus, the observed effect of increasing μ_{eff} in alloys I of the system HREM-Sm cannot be attributed to direct contribution of the magnetic moment of an isolated samarium atom. For alloys II, as seen in Fig. 2, there is an agreement between μ_{eff} calculated from our experimental data and that calculated from Eq. (3).

The increase of μ_l^* and μ_{eff} in alloys I of the investigated systems and the anomalous variation of the reluctance and of the Hall emf in alloys I of the $Ho_{1-x}Sm_x$ and $Dy_{1-x}Sm_x$ systems[1,2] are attributable to the fact that small additions of samarium to the HREM matrices increase the magnetic polarization of the nonlocalized electrons around the ions, which is associated with indirect interaction of the Ruderman-Kittel-Kosui-Yoshida (RKKY) type. This leads to an increase of the effective magnetic moments of ions in the crystal lattice of the alloys as compared with the moments of the isolated ions.

We should note that the polarization effects in samarium contribute to the magnetic moment, which is comparable to the contribution from the $4f$ electrons.[4]

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