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Magnetization of polycrystalline ytterbium in the region of low-temperature structural transition

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The temperature and magnetic field dependences of the magnetic moment $M(T, H)$ of polycrystalline ytterbium were studied in the region of phase transformation from a low-temperature close-packed hexagonal structure to a high-temperature face-centered cubic structure. The $M(T)$ dependences have paramagnetic form for both phases and are described by the Curie–Weiss law in the entire temperature range, except for $T \leq 10$ K. In the temperature range of the structural transformation $150 < T < 400$ K, a hysteresis is observed in the $M(T)$ dependence, the form of hysteresis depends on the magnitude of the applied magnetic field. The hysteretic dependence $M(T)$ can be considered as a consequence of overcooling of the high-temperature phase of ytterbium with decreasing temperature and, accordingly, overheating of the low-temperature phase with increasing temperature. During slow cooling, a small fraction of the high-temperature phase is retained down to low temperatures $T \sim 10$ K. The dependences of the magnetic moment on the magnetic field $M(H)$, for different branches of magnetic hysteresis, are linear up to $H = 140$ kOe. In low fields, a small addition of a ferromagnetic type is observed, probably associated with the presence of a magnetic impurity or with Yb^{3+} ions localized near structural defects.

Keywords: magnetization, paramagnetism, low temperatures, structural transformation, ytterbium.

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1. Introduction

The rare earth metal ytterbium stands out from a number of other rare earth metals due to its chemical and physical properties. One of these properties is the presence of a structural transition in the temperature region $T < 400$ K. The high-temperature phase has a face-centered cubic (fcc) structure, and the low-temperature phase has a hexagonal close-packed (hcp) structure. The transition between two structural phases occurs in the temperature range $\Delta T = 150-400$ K [1], the width of the transition depends on the purity and structural perfection of the material. In this temperature range, hysteresis of the physical characteristics of metallic ytterbium is observed upon heating and cooling, which was demonstrated by measuring resistivity $\rho(T)$ [2], thermopower [3], and magnetic susceptibility [4]. The low-temperature hcp phase of ytterbium has a high magnetoresistance (up to 440% in a magnetic field $H = 140$ kOe at $T = 5$ K), and the high-temperature fcc phase is much smaller, and therefore the hysteresis on the $\rho(T)$ dependences measured in a magnetic field becomes even more pronounced [5].

The structural phases of metallic ytterbium also have different magnetic properties. Early measurements of the magnetization of the low-temperature phase were carried out in [6], which showed paramagnetic behavior satisfying the Curie–Weiss law. At the same time, in pure ytterbium (RRR = 100), a transition from the paramagnetic state to the diamagnetic state was observed with decreasing temperature, associated with the transition from the fcc phase to the hcp phase [4]. Further studies did not show the presence of diamagnetism in ytterbium at low temperatures, which may be due to the presence of magnetic impurities, the preservation of the high-temperature paramagnetic phase to low temperatures, or a large proportion of magnetic Yb^{3+} ions associated with structural defects [7,8].

In this work, we measured the dependences of the magnetic moment on temperature and magnetic field $M(T, H)$ on polycrystalline ytterbium samples, including the temperature region of structural transformation, where hysteresis of Yb physical properties is observed.

2. Method

We studied samples similar to those used in [5], obtained by distillation of the starting metal in a high vacuum, having RRR $\sim$ 20, which indicates good purification of ytterbium from gas impurities. Magnetization measurements were carried out using a vibration magnetometer of a PPMS installation (Quantum Design) in the temperature range $2-400$ K and magnetic fields up to 140 kOe.

3. Results and discussion

Figure 1 shows the temperature dependences of the magnetic moment $M(T)$ of ytterbium in magnetic fields $H = 1$ kOe (Figure 1, *a*) and 140 kOe (Figure 1, *b*). As the

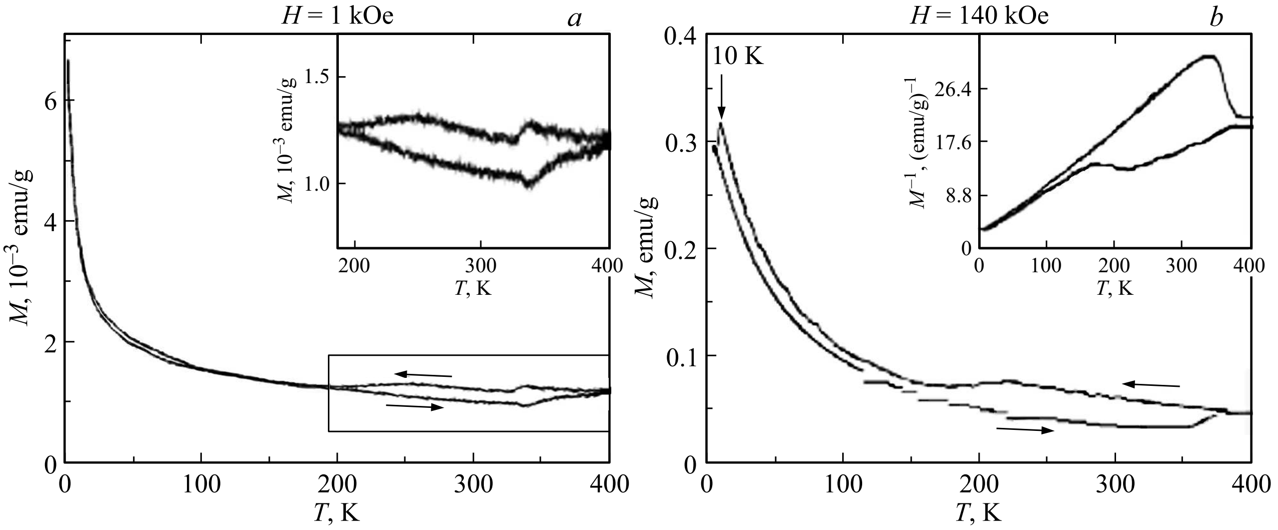

Figure 1. Temperature dependence of the magnetic moment $M(T)$ of ytterbium in a magnetic field: (a) $H = 1\,\mathrm{kOe}$, the inset shows the dependence of $M(T)$ in the region of the structural transition and (b) $H = 140\,\mathrm{kOe}$, the inset shows the dependence $1/M(T)$.

temperature decreases, the magnetic moment increases and hysteresis is observed, the width of which depends on the strength of the magnetic field. The hysteresis dependence $M(T)$ can be considered as a consequence of supercooling of the high-temperature phase with decreasing temperature with one ($H = 140\,\mathrm{kOe}$) or two ($H = 1\,\mathrm{kOe}$, inset in Figure 1, a) sharp transitions to the low-temperature phase and, accordingly, as a consequence of overheating of the low-temperature phase with increasing temperature with a sharp transition to the high-temperature phase. Thus, the temperature dependence of the magnetic moment of both phases can be analyzed in a wide temperature range, including regions of overheating and overcooling. The inset to Figure 1, b shows the temperature dependence of the inverse magnetic moment, demonstrating the fulfillment of the Curie–Weiss law for both phases. Deviations from this law are observed only at low temperatures, which may be due to the presence of a small amount of magnetic impurities [9].

The $M(T)$ dependence measured in a magnetic field $H = 140\,\mathrm{kOe}$ (Figure 1, b) exhibits an additional feature: a sharp change in magnetization upon cooling of ytterbium in the region $T \sim 10\,\mathrm{K}$ (indicated by an arrow in Figure 1, b). This feature is apparently associated with the preservation of part of the high-temperature phase down to low temperatures and was previously observed in ytterbium after plastic deformation [4] and in thin crystalline Yb films [10].

The magnetic field dependences of the Yb magnetic moment $M(H)$ at the temperature range $T = 2{-}400\,\mathrm{K}$ are presented in Figure 2. Dependences $M(H)$ of a paramagnetic type are observed both for the high-temperature fcc phase and for the low-temperature hcp phase. In addition, in low fields, a small feature of a ferromagnetic type is observed, which can be associated both with the presence of a small amount of magnetic impurity and with Yb^{3+} ions localized on structural defects. The influence of magnetic Yb^{3+} ions on the overall magnetization in Yb containing compounds was considered earlier in [11]. In the temperature range where hysteresis is observed in the $M(T)$ dependence, the $M(H)$ dependences measured at the same temperature have a different slope, depending on the phase (low temperature, during heating, or high temperature, during cooling). Thus, at $T_1 = 200\,\mathrm{K}$ and $T_2 = 300\,\mathrm{K}$, the difference in the magnetic moments of the low-temperature and high-temperature phases in a magnetic field $H = 140\,\mathrm{kOe}$ is $\Delta M_1 = 0.02\,\mathrm{emu/g}$ and $\Delta M_2 = 0.026\,\mathrm{emu/g}$, respectively (Figure 2), which is

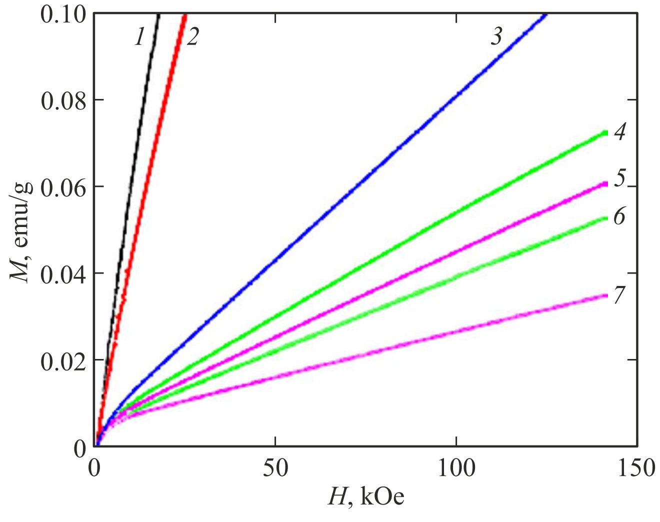

Figure 2. Dependence of the magnetic moment of ytterbium on the magnetic field $M(H)$ for temperatures $T = 2\,\mathrm{K}$ (curve *1*), $5\,\mathrm{K}$ (*2*), $100\,\mathrm{K}$ (*3*), $200\,\mathrm{K}$ (*4* — cooling, *6* — heating) and $300\,\mathrm{K}$ (*5* — cooling, *7* — heating).

consistent with the data in Figure 1 $\Delta M_1 = 0.022$ emu/g and $\Delta M_2 = 0.026$ emu/g.

4. Conclusion

The measurements of the temperature and magnetic field dependences of the magnetic moment of polycrystalline ytterbium showed that both high-temperature and low-temperature structural phases demonstrate paramagnetic character and are described by the Curie−Weiss law in the entire temperature range, except for $T \leq 10$ K. In the region of structural transformation $150 < T < 400$ K, the $M(T)$ dependence exhibits hysteresis, the form of which depends on the magnitude of the applied magnetic field. During slow cooling, the $M(T)$ dependence measured in a magnetic field $H = 140$ kOe showed a feature in the form of a sharp change in magnetization in the region $T \approx 10$ K, associated with the retention of a part of the high-temperature phase down to low temperatures. The dependences of the magnetic moment on the magnetic field $M(H)$, measured at the same temperature for different branches of magnetic hysteresis, are linear up to $H = 140$ kOe. In low fields, a small feature of the ferromagnetic type is observed, probably associated with the presence of a small amount of magnetic impurity or with Yb^{3+} ions localized on structural defects.

Conflict of interest

The authors declare that they have no conflict of interest.

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