THE INFLUENCE OF THE NANOSTRUCTURE ON THE MAGNETOCALORIC EFFECT OF MELT-SPUN NdCo₅ ALLOYS


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Abstract
A study of the magnetocaloric effect (MCE) effect (using the direct method) and microstructure (using atomic force microscopy) has been carried out on the single crystals and melt-spun alloys of NdCo₅ intermetallic compounds. The statistical model was proposed to explain and estimate of the value MCE, caused by the rotation of the magnetization vector of the melt-spun alloys.

Keywords: magnetocaloric effect, melt-spun alloys, atomic force microscopy

1. INTRODUCTION

Recently, the study of the magnetocaloric effect (MCE) of the well known RCo₅ (R - rare-earth element) compounds have been significant interest in its possible exploitation in magnetic refrigeration and cryocooling systems. The ferrimagnetic rare-earth Co - rich intermetallics exhibit the strong exchange interaction between the two magnetic sublattices (R and Co), and a strong magnetocrystalline anisotropy provided by the rare earth 4f electrons. Due to these characteristics, some of these compounds have been used as high-coercivity permanent magnets (e.g., SmCo₅ compounds) that have high temperature stability. In addition, RCo₅ compounds have a wide variety of magnetic phase transitions, which makes them an object of significant attention of researchers. The giant values of the rotating MCE of the NdCo₅ compounds in the spin-reorientation region have been found for the first time by S.Nikitin et al [1]. The NdCo₅ compound possess the high values of the magnetic anisotropy energy and magnetic moment. The NdCo₅ compound demonstrates two spin-reorientation regions at T_{SR1}=245 K and T_{SR2}=285 K. Investigations of the influence of the size factor on the MCE of NdCo₅ in the spin-reorientation region are of great interest.

2. EXPERIMENTAL DETAILS

The original NdCo₅ alloy was produced by the induction melting method in an argon atmosphere. The synthesis method allowed us to get coarse-grain ingots. The samples were received from the alloys and were authenticated by the methods of x-ray structural and x-ray phase analyses, as well as by optical metallographic methods.

At the first stage of the sample authentication, the x-ray diffraction structural analysis of the alloys was performed. The diffractograms were taken with the DRON-3M using Kα-Cu radiation. The analysis of the diffractograms of the NdCo₅ alloys confirms that the object of study is characterized by the hexagonal CaCu₅ - type structure (P6/mmm). The x-ray phase analysis showed that the alloy does not contain second phases; i.e., it is a single-phase alloy. The melt-spin alloys were received using the method of rapid quenching, on a fast-rotating copper disk with a linear rotation speed of 15 m/s. As a result of fast cooling, the scale-like nanostructure presented in Fig. 1 was received. The nanostructure of the melt-spin NdCo₅ alloy was investigated using the methods of atomic force microscopy (AFM).The MCE was measured by a direct method. A temperature change of a sample under adiabatic magnetization was determined by the copper-
constantan thermocouple. The measurements were taken in the temperature range of 280-700 K in a constant magnetic field of up to $H=18.5$ kQe.

3. RESULTS AND DISCUSSION

The images of the surface of the melt-spun NdCo$_5$ alloy, received using the AFM methods, are presented in the Figs. 1. As we can see from these images, the grains with the linear size of 100 nm were formed as a result of fast cooling of the liquid alloy.

![Fig. 1](image_url)

**Fig. 1** The AFM image of the microstructure of the melt-spun NdCo$_5$ alloys.

Fig. 2 shows the temperature dependence of the magnetocaloric effect MCE measured in the NdCo$_5$ single crystal along both the hexagonal c-axis and the a-axis which lies in the basal plane. One can see that the MCE values strongly differ from each other. The giant MCE values caused by the rotation of the magnetization vector were observed in the spin-reorientation transition (SRT) range. It was caused by the high values of the magnetic anisotropy energy [2] and spin-reorientation transition [3], in the area of which we observed a considerable change of the anisotropy constant values with temperature. A giant rotating magnetocaloric effect of 1.6 K, caused by rotation of the magnetization vector was discovered in the NdCo$_5$ single crystal for the first time by S.Nikitin et al [1]. The measurements of the MCE on the melt-spun alloys of the NdCo$_5$ compound were carried out (see Fig. 2) in order to determine the influence of the dimensional factor on the MCE value and on the temperature of magnetic phase transition. As it is seen from Fig. 2, the MCE of the melt-spun alloys is significantly lower than the MCE measured on the NdCo$_5$ single crystal along the a-axis, but at the same time it is significantly higher than the MCE measured along the c-axis. An attempt was undertaken to explain the nature of these phenomenon using the obtained results. Based on these results, we can to assume that the total MCE is determined by the average MCE value of all separate nano-dimensional grains with different orientations of the c-axes. In order to describe and to estimate the MCE value of the melt-spun NdCo$_5$ alloys, a statistical model was proposed. It describes the temperature dependence of the MCE magnetic material, which consists of a large number of grains with different orientation of the magnetic moment. If all directions of the hexagonal c-axis of the nano-dimensional grains in space are equally possible, then the density of the possibility in all directions is the same and equal to:

$$p(\Theta, \varphi) = \frac{1}{4\pi^2} \sin(\Theta)$$

(1)

where $\Theta$ - the angle between the vector of the magnetic field $H$ and hexagonal c-axis, $\varphi$ - the angle between the projection of the vector of the magnetic field $H$ on the basal plane and the a-axis. Therefore, the average MCE value of a magnetic material of this kind may be found as the mathematical expectation value of the function of the MCE value distribution from the direction easy axis of nanoparticles in space in relation
to a magnetic field, i.e. $\Delta T(\phi)$. The function $\Delta T(\phi)$ can be determined by the approximation of the MCE angle dependences from [1]. The results of the calculations are shown in Fig. 2 by the solid line.

![Diagram showing MCE of NdCo$_5$ single crystal and melt-spun alloy](image)

**Fig. 2** The MCE of the NdCo$_5$ single crystal measured along the c- and a-axes, the MCE of the melt-spun NdCo$_5$ alloy, and the calculated average MCE value.

The graph shows that the curve calculated as the average MCE value (solid black line) well coincides to the experimental data received on the melt-spun NdCo$_5$ alloys (Fig. 2). This confirms that the MCE of the melt-spun alloys is determined by the average value of separate nano-dimensional grains, and the melt-spun alloys are isotropic magnetic materials. Besides, based on the conducted analysis, we can conclude that the grain size of ~ 100 nm is not sufficient to significantly influence the MCE value in the spin-reorientation region.

4. CONCLUSIONS

The investigations of the MCE and the nanostructure of the melt-spun NdCo$_5$ alloys were carried out. It was shown that the melt-spun NdCo$_5$ alloys are isotropic magnetic materials, and the MCE of the given alloys is determined by the average MCE value of different grains.

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LITERATURE