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Magnetic structure and hysteresis characteristics of $Ni_{49}Fe_{18}Ga_{27}Co_6$ shape memory alloy crystals

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The magnetic properties of $Ni_{49}Fe_{18}Ga_{27}Co_6$ shape memory alloy crystals have been studied. The influence of features of the crystal structure on the parameters of magnetic hysteresis is shown. For $Ni_{49}Fe_{18}Ga_{27}Co_6$ alloy, the magnetic state of which is multi-domain, an approach to estimating the hysteresis characteristics is proposed based on a model of magnetostatically interacting single-domain particles with effective spontaneous magnetization.

Keywords: shape memory alloy, twinning, magnetic domains, magnetic hysteresis, magnetization, coercivity, magnetostatic interaction.

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1. Introduction

Geisler ferromagnetic alloys are of interest because they have a shape memory effect, including the magnetic control capability [1]. Some crystal compositions of quadruple alloys Ni–Fe–Ga–Co, for example, $Ni_{55-x}Ga_{27}Fe_{18}Co_x$ [2], $Ni_{52}Fe_{17}Ga_{27}C_4$ [3], $Ni_{49}Fe_{18}Ga_{27}Co_6$ [4] are characterized by relatively high temperatures of martensitic transformation and Curie point, which can be changed by varying the composition and conditions of heat treatment with a saturation mass magnetization, reaching $40-90\,\mathrm{A\cdot m^2/kg}$ [5–7]. One of the important tasks addressed in the field of shape memory alloys studies is the reduction of the control magnetic field from ~ 1 to ~ 0.1 T [8], which is directly related to the magnetic characteristics of the alloy.

The purpose of this paper was to study the magnetic properties of $Ni_{49}Fe_{18}Ga_{27}Co_6$ alloy crystals with the shape memory effect and to evaluate the relationship of the crystal structure and magnetic state with magnetic hysteresis parameters. The hysteresis characteristics of the alloy were theoretically calculated on the basis of a micromagnetic model of magnetostatically interacting single-domain particles with an effective spontaneous magnetization [9].

2. Materials and methods

The studied single crystal of $Ni_{49}Fe_{18}Ga_{27}Co_6$ alloy in the form of a cylinder with a diameter of 6 mm and a height of 10 mm was grown using the Czochralski method along the direction [100] at the pulling speed of 1 mm/min [4]. The sample was annealed at a temperature of 1150°C for 1 h in an argon atmosphere, followed by quenching in water. The composition, surface morphology, and magnetic properties were studied by using a disk with a diameter of 6 mm and a thickness of 0.9 mm, obtained by spark cutting from the original sample.

Microscopic studies were performed using an S-3400N scanning electron microscope (Hitachi, Japan) with an energy dispersive X-ray (EDX) analyzer. The magnetic hysteresis loop and the direct current demagnetization (DCD) curve in the field of the opposite direction were obtained using LakeShore 7410 vibrating sample magnetometer (Lake Shore Cryotronics Inc., USA) at a temperature of 295 K.

3. Results and discussion

The elemental composition deteremined by the EDX method is presented in Table 1, the atomic composition of the sample corresponds to the specified one ($Ni_{49}Fe_{18}Ga_{27}Co_6$). This sample was calorimetrically studied earlier using a differential scanning calorimeter [4]. It has been shown that the direct martensitic transformation occurs at temperatures below 290 K, i.e. the crystal is in the austenite state at room temperature (295 K).

Figure 1 shows experimental curves of magnetic hysteresis with a central part and the DCD curve. The values

Table 1. The elemental composition of the sample of $Ni_{49}Fe_{18}Ga_{27}Co_6$ alloy obtained by EDX method

Chemical element	Atomic content, %
Iron	18 ± 1
Cobalt	6 ± 1
Nickel	50 ± 1
Gallium	26 ± 1

Table 2. Parameters of the magnetic hysteresis of the sample at a temperature of 295 K

$\mu_0 H_c$, mT	$\mu_0 H_{cr}$, mT	M_s, $A \cdot m^2/kg$	M_{rs}, $A \cdot m^2/kg$	H_{cr}/H_c	M_{rs}/M_s
1.10	5.80	45.00	0.84	5.27	0.02

Table 3. Theoretical values of effective spontaneous magnetization $I_{s\,eff}$ and $I_{rs\,eff}$

Volume fraction, occupied by borders between „particles“	Volume fraction, occupied „particles“	$I_{s\,eff}$, kA/m	$I_{rs\,eff}$, kA/m
0.00	0.600	531	9.9
	0.900	354	6.6
0.01	0.594	531	10.0
	0.891	354	6.7
0.05	0.570	531	10.4
	0.855	354	6.9
0.10	0.540	531	11.0
	0.810	354	7.3

of saturation magnetization M_s, saturation remanence M_{rs}, coercive force H_c and remanent coercivity H_{cr} are listed in Table 2. It should be noted that „austenite-martensite“ the transition takes place at temperatures close to room temperature [4]. The low coercive force observed in the sample also indicates that it is in the austenitic state at a temperature of 295 K, since the coercivity of this crystal is significantly higher in the martensitic state [10].

The magnetic state of Ni–Fe–Ga–Co samples similar to the studied sample was studied by the Kerr microscopy [3,11]. It was shown in [3], that the magnetic structure contains a large number of magnetic stripe domains with a characteristic width of about $10\,\mu$m, as well as transverse twinning stripes intersecting them. It is possible to conclude that the sample is in a multi-domain state based on the results of magnetic force microscopy

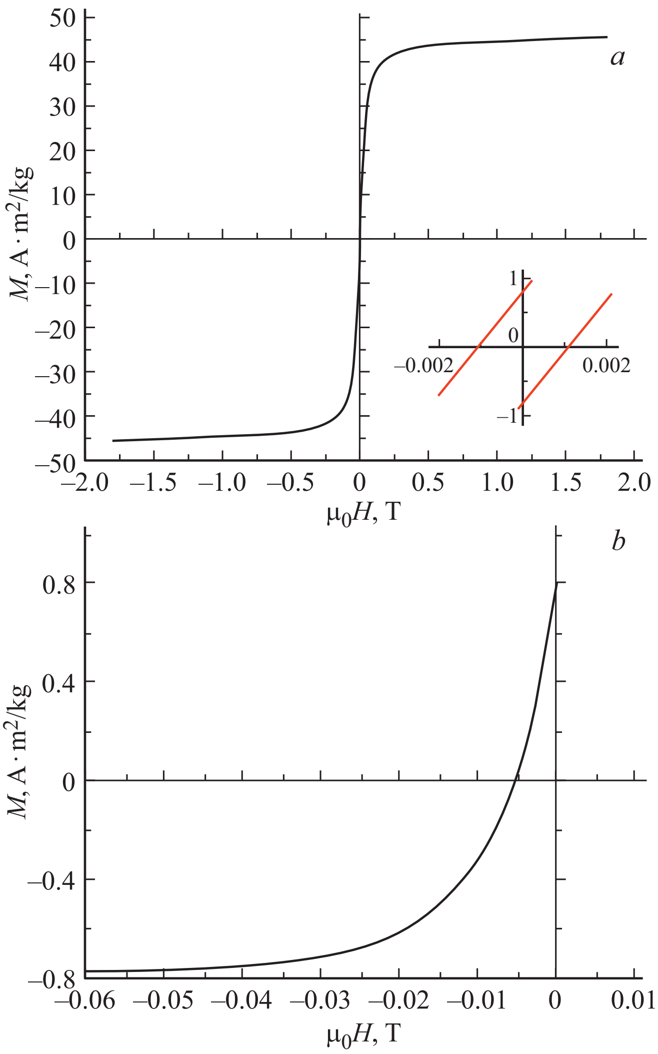

Figure 1. The hysteresis loop with the central part highlighted on the insert (a) and the DCD curve (b) of the sample at a temperature of 295 K.

(Figure 2) and the ratios H_{cr}/H_c and M_{rs}/M_s [12] for our sample. In our case, the magnetic stripe domains separated by thinner domain walls are also intersected by transverse twinning stripes. In our opinion, the areas of intersection of the domain walls and twinning stripes are not homogeneous in crystal and magnetic properties. These regions have a size of the order of several micrometers, and in the absence of an external field they can be considered as separate „single-domain particles“ with effective spontaneous magnetization $I_{rs\,eff}$. At the same time, the contribution to the saturation remanence of the sample M_{rs}, introduced by thin domain walls inside „particles“, can be ignored and effective spontaneous magnetizations can be theoretically calculated (see Table 3) using a model of magnetostatically interacting single-domain particles with effective spontaneous magnetization [9].

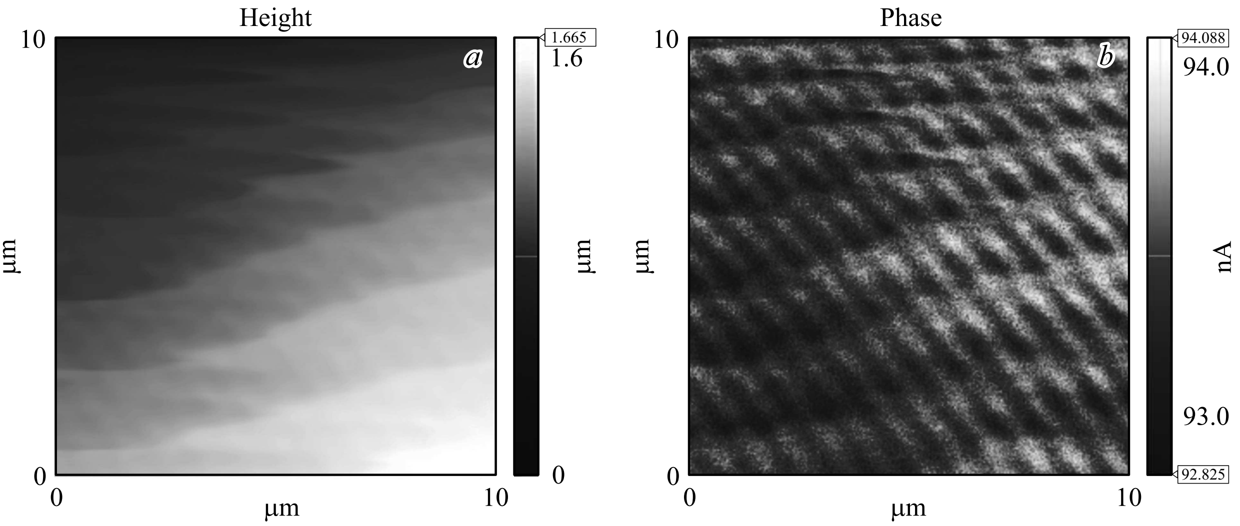

Figure 2. Results of magnetic force microscopy (INTEGRA-AURA (NT-MDT, Russia)): surface relief (*a*) and phase contrast (*b*).

The values M_s and M_{rs} (Table 2) are related to theoretically calculated values by the simple ratio [9]:

$$M_{rs}/M_s = \frac{C_{rs} I_{rs\,eff}}{C_s I_{s\,eff}},$$

where $I_{s\,eff}$ is the effective spontaneous saturation magnetization, $I_{rs\,eff}$ is the effective spontaneous magnetization by saturation remanence, C_s is the volume concentration of ferromagnetic materials in the sample, C_{rs} is the volume concentration of „single-domain particles" contributing to the remanent magnetization.

4. Conclusion

A theoretical estimate of the spontaneous magnetization of $I_{s\,eff}$ (about 300–500 kA/m) shows that the crystal of $Ni_{49}Fe_{18}Ga_{27}Co_6$ alloy in the austenitic state at room temperature has a spontaneous magnetization less than that of pure nickel (510 kA/m). The value $I_{rs\,eff}$ in terms of remanent magnetization (of the order of 7–11 kA/m) is attributable to the restoration of the multidomain structure, the presence of vortex formations and domain walls in a zero external field. The revealed low value of the coercive force H_c (1.1 mT) in crystals of $Ni_{49}Fe_{18}Ga_{27}Co_6$ alloy suggests the fundamental possibility of reducing the magnetic field, which controls the deformation of shape memory in these crystals.

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