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LOCAL MAGNETIC ANISOTROPY OF THE Co-BASED AMORPHOUS ALLOY

The magnetization, initial magnetic susceptibility, and magnetostriction of a multicomponent Co-based amorphous alloy have been studied. The exchange constant α and the Curie temperature T_C of the alloy are determined. On the basis of a method based on the theory of stochastic magnetic structure for amorphous ferromagnets and using the magnetization curves, the correlation field H_ℓ, the field H_α, the effective constant of local magnetic anisotropy K_{eff}, and the stochastic characteristics of local anisotropy – the mean square field fluctuations and the correlation radius – have been calculated. The temperature behavior of the examined magnetic characteristics is analyzed. The results of magnetostriction research allow a conclusion to be drawn that the local magnetic anisotropy of the alloy has a single-ion origin.

Keywords: amorphous alloy, magnetization, local magnetic anisotropy, correlation radius, Curie temperature.

1. Introduction

The magnetic parameters of magnetically ordered amorphous alloys, even if the latter are macroscopically isotropic, are random functions of the coordinates. In other words, the values of those parameters randomly change from point to point. In particular, the magnetic anisotropy can vary both in magnitude and direction. It is the fluctuations in the anisotropy axis direction that lead to the formation of a stochastic magnetic structure (SMS). A method based on the SMS theory [1–6] makes it possible to analyze the stochastic characteristics of the local magnetic anisotropy (the mean square fluctuation and the correlation radius of the anisotropy field) by experimentally studying the magnetization curves of amorphous magnets.

Some of Co-based amorphous alloys are known to belong to the class of magnetic materials. They are used, in particular, for the creation of high-quality current and magnetic field sensors [7]. The properties that are used to describe the "softness" of an amorphous alloy as a magnetic material are the magnetic anisotropy and the magnetostriction. For instance, $Co_{72}Fe_3P_{16}B_6Al_3$ and $Co_{81}Fe_{4.5}Si_{4.5}B_{10}$ alloys, owing to the absence of the magnetostriction in them, reveal the following magnetically soft properties: the coercive force $H_c = 2.8$ A/m $= 0.035$ Oe, the saturation induction $B_s = 1.0$ T $= 10.44$ G, and the maximum magnetic permeability $\mu_{max} = 2.8 \times 10^5$.

For $(Co_{0.4}Ni_{0.6})_{78}Si_8B_{14}$ alloy, the magnetostriction constant equals zero at room and nitrogen temperatures. The values of the magnetostriction parameter λ_s for amorphous alloys from the $(Co_{1-x}Fe_x)_{75}Si_{15}B_{10}$ series lie within an interval from -2×10^{-7} to $+1\times10^{-7}$ depending on the cooling rate at their quenching. The corresponding compensation temperature is by 150°C below the room one.

The alloy magnetostriction also depends on the content of both transitive and metalloid elements. In particular, in $Fe_{77}P_{16}B_6Al_3$ alloy, the value of λ_s varies from 2.6×10^{-6} to 16×10^{-6}, when the P : B content ratio changes from 4 to 2.3.

The aim of this work is to study the magnetic properties of Co–Fe–Ni–Cr–P–B multicomponent amorphous alloy, including its parameters and the origin of its local magnetic anisotropy.

2. Researched Specimens

The Co-based amorphous ferromagnetic alloy was an object of concern. The alloy ribbon, from which the specimens were fabricated, was obtained from the Kharkiv Institute of Physics and Technology. In addition to Co, the researched alloy contained the transition metals Fe, Ni, and Cr, and the metalloids P and B. According to the data obtained on an X-ray microanalyzer MAP-1 and a TESSAN VEGA3 electron microscope, the contents of transition elements in the alloy were as follows: 83.6 wt.% for Co, 6.0 wt.% for Fe, 0.5 wt.% for Ni, and 1.7 wt.% for Cr.

For the magnetization measurement, the specimens were fabricated in the form of parallelepipeds composed of 4 squares, each with a side length of 1 mm. The squares were cut from the ribbon of the examined alloy that had 30 μm in thickness and 16 mm in width.

For the magnetostriction research, the rectangular specimens 5×10 mm^2 in dimensions were cut from the ribbon. When measuring the magnetic susceptibility, a ribbon fragment was wound around the end of a ceramic straw that contained thermocouple wires.

3. Measurement Technique

To study the magnetization, a pendulum magnetometer was used [8]. The zero (compensation) method was applied. The specific magnetization in the field H was calculated by the formula

$$\sigma = C\frac{i_k}{mH}, \tag{1}$$

where C is the dynamic constant of a magnetometer, i_k the compensation current, and m the specimen mass. The dynamic constant of a magnetometer C was determined using the formula

$$C = \frac{\sigma_0 m_0}{i_{k0}}H, \tag{2}$$

where σ_0, i_{k0}, and m_0 are the counterparts of the corresponding parameters in Eq. (1), but for a reference nickel specimen.

The magnetic field was created with the help of an electromagnet. The maximum field was equal to 10.6 kOe. The specimen was arranged in a plane parallel to the magnetic field.

The magnetic susceptibility was measured in low fields ($H < 100$ Oe) created by a solenoid. The measurements were carried out on a ballistic installation [8] in a temperature interval of 293–573 K.

Since the change of the magnetization is proportional to a change of the magnetic field, if this field is low (the susceptibility parameter χ does not depend on the field magnitude in this case), the temperature dependence of the magnetization reproduces the temperature dependence of the initial magnetic susceptibility.

The Curie temperature of the researched alloy was determined from the temperature dependence of the initial magnetic susceptibility in low fields by extrapolating the interval with the most drastic recession of the susceptibility to the temperature axis.

The magnetostriction was measured using the method of wire strain gauges [9]. The relative change in the specimen length, which is equal to the relative change in the length of a strain gauge wire, was calculated by the formula

$$\frac{\Delta l}{l} = \frac{1}{c}\frac{\Delta R}{R}, \tag{3}$$

where c is the gauge sensitivity, R the resistance of a working gauge (standard gauges with a resistance of 99.5 ± 0.3 Ω were used), and ΔR the gauge resistance variation. The latter quantity was determined from the deviation of the zero indicator with the help of the relation

$$\Delta R = 10^{-2}\frac{a}{a_{\rm ref}}, \tag{4}$$

where $a_{\rm ref}$ is the deviation obtained, when the resistance of the resistance box series-connected with the operating gauge changed by 0.01 Ω, and a the deviation obtained, when the resistance of a working gauge is changed by ΔR. The sensitivity of the installation to the relative deformation was 8×10^{-7}.

When measuring the temperature dependence of the linear deformation in the low-temperature interval, liquid nitrogen was used. Intermediate temperatures were set by varying the current in the heating oven. The temperature was determined making use of a copper-konstantan thermocouple.

4. Measurement Results, Their Processing and Discussion

4.1. Magnetization

The stochastic characteristics of the local magnetic anisotropy were determined by measuring the magnetization I in a temperature interval of 220–395 K. The magnetization isotherms were measured at several temperatures within this interval. Some of the measured magnetization curves are depicted in Fig. 1. The behavior of magnetization curves is not changed with the temperature. In all cases, the curves saturate at the fields of about 5 kOe.

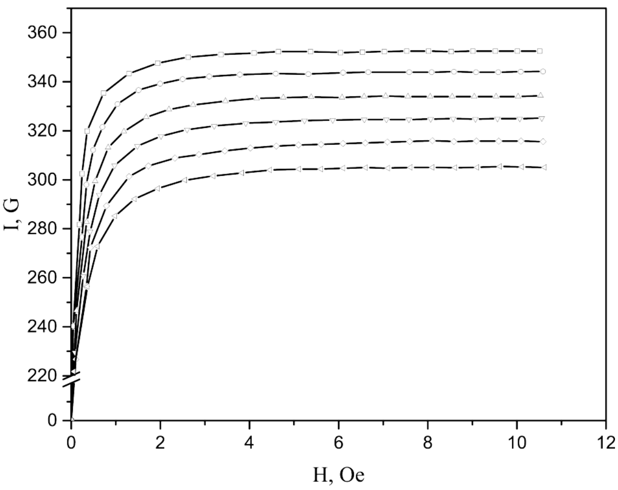

Fig. 1. Field dependences of the specimen magnetization at various temperatures: $T = 295$ (*1*), 315 (*2*), 333 (*3*), 351 (*4*), 368 (*5*), and 386 K (*6*)

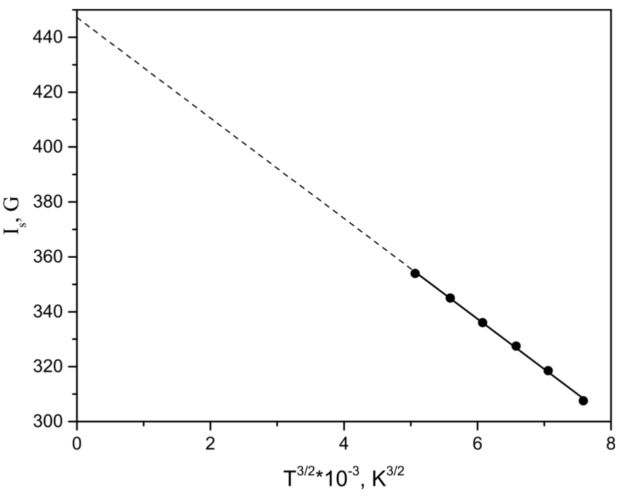

Fig. 2. The same as in Fig. 1, but in the I-versus-H^{-1} coordinates. $T = 295$ (*1*), 315 (*2*), 333 (*3*), 351 (*4*), 368 (*5*), and 386 K (*6*)

In order to determine the saturation magnetization I_s at $T = 0$ K, the magnetization curves were replotted in the coordinates the magnetization I versus the inverse field H^{-1} (Fig. 2), and the values of I_s at various temperatures were found.

Figure 3 demonstrates the dependence $I_s(T^{3/2})$. It is linear, i.e. it is described by the Bloch law

$$I_s(T) = I_s(0)\left(1 - BT^{3/2}\right), \tag{5}$$

where the constant $B = (4.1 \pm 0.1) \times 10^{-5}$ K$^{-3/2}$. The value of $I_s(0)$ obtained by the extrapolation was found to be 447 G. Now, knowing the parameters $I_s(0)$ and B, we can calculate the exchange constant α using the formula [10]

$$\alpha = \left[\frac{2.612\, g\, \mu_\mathrm{B}}{BI_s(0)}\right]^{2/3} \frac{k_\mathrm{B}}{4\pi g \mu_\mathrm{B} I_s(0)}, \tag{6}$$

where $g = 2$, μ_B is the Bohr magneton, and k_B the Boltzmann constant. The resulting value is $\alpha = (4.7 \pm 0.1) \times 10^{-12}$ cm^2.

Information on the parameters of the local magnetic anisotropy was also obtained from the magnetization curves. The magnetization curve of an amorphous ferromagnet is described by the relation

$$I(H) = I_s\sqrt{1 - 2d_m(H)}. \tag{7}$$

Here, d_m is the relative dispersion of fluctuations of the transverse magnetization components. An exact expression for it was obtained in work [3]:

$$d_m = \frac{DH_a^2}{2\sqrt{H}(\sqrt{H_\ell} + \sqrt{H})^3}. \tag{8}$$

In this expression, $\sqrt{D}H_a$ is the root-mean-square fluctuation of the local anisotropy field, which characterizes the amplitude of its spatial fluctuations, and $H_\ell = \alpha I / r_\ell$ is a correlation field that contains information about the correlation radius of the local anisotropy, r_ℓ, which characterizes the fluctuation extension. As one can see from Eq. (8), $d_m \sim H^{-1/2}$ at $H \ll H_\ell$, and $d_m \sim H^{-2}$ at $H \gg H_\ell$. The dependence changes its character in the vicinity of $H \approx H_\ell$.

In order to determine the correlation radius and the mean-square wave fluctuations of the anisotropy, the magnetization curves were replotted on the log-log

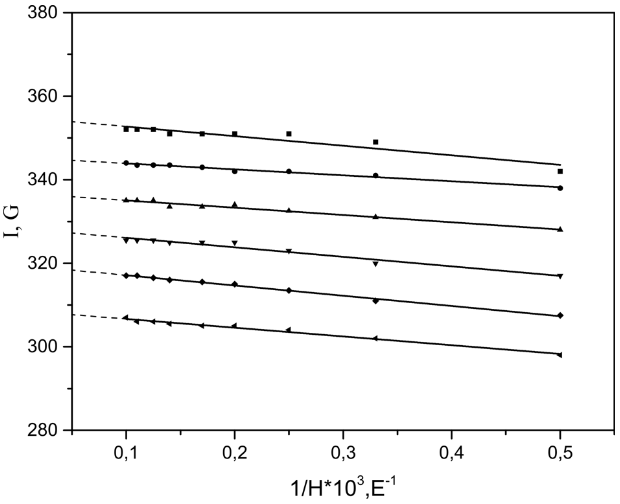

Fig. 3. Temperature dependence of the saturation magnetization

scale: $|\log d_m|$ versus $\log H$. The relative dispersion of the stochastic magnetic structure, d_m, was calculated from expression (7). The dependence $|\log d_m| = f(\log H)$ calculated for $T = 350$ K is depicted in Fig. 4. The plots for other temperatures have the same character. The plot demonstrates three rectilinear sections corresponding to different magnetic field intervals. Section I corresponds to the fields $H \ll H_\ell \ll 4\pi I_s$, section II to the fields $H_\ell \ll H \ll 4\pi I_s$, and section III to the fields $H_\ell \ll 4\pi I_s \ll H$.

The correlation field H_ℓ was determined from the intersection of sections I and II. In each section, the solutions were found by solving together the corresponding equations that describe them. It was found that the magnitude of the correlation field H_ℓ does not depend on the temperature within an interval from 295 to 394 K, being equal to

$H_\ell = (870 \pm 90)$ Oe.

The magnitude of the correlation radius calculated by the formula

$$r_\ell = \sqrt{\frac{\alpha I_s}{H_\ell}} \tag{9}$$

amounts to (138 ± 5) Å at room temperature, i.e. it corresponds to long-range correlations. As the temperature grows, it weakly decreases to a value of 129 Å at $T = 386$ K. Figure 5 demonstrates the temperature

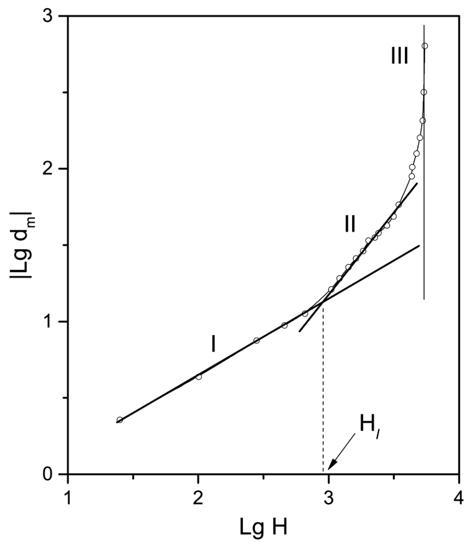

Fig. 4. Field dependence of the relative dispersion of magnetization fluctuations at $T = 350$ K

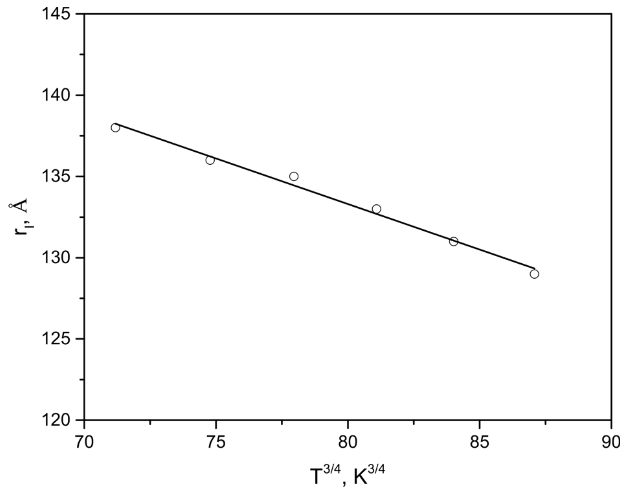

Fig. 5. Temperature dependence of the correlation radius of the local magnetic anisotropy

dependence of r_ℓ. Since this dependence is associated with the temperature-induced variation of I_s, it is linear in the coordinates r_ℓ versus $T^{3/4}$.

The value of the local anisotropy field H_a was also determined from the dependences $|\log d_m| = f(\log H)$. It turned out that the slope of linear section I corresponds to the theoretical value: the tangent of the slope angle is equal to $a_1 = 0.47 \pm 0.03 \approx 1/2$, whereas the slope of section II is smaller than it is predicted by the theory: $a_2 = 1.11 \pm 0.06 < 2$. The fact that the slope of section II is less than 2 can

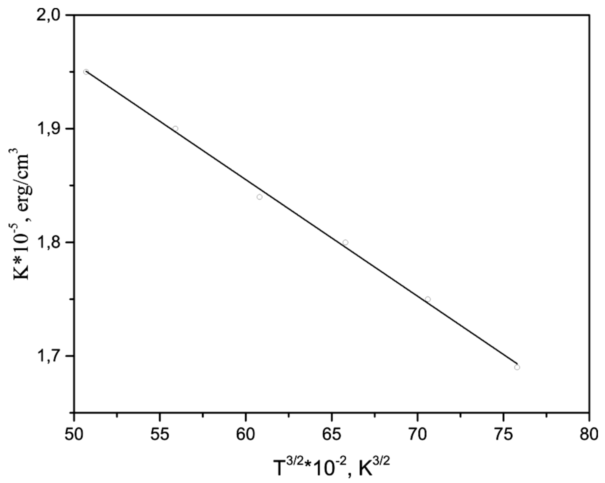

Fig. 6. Temperature dependence of the effective local magnetic anisotropy constant

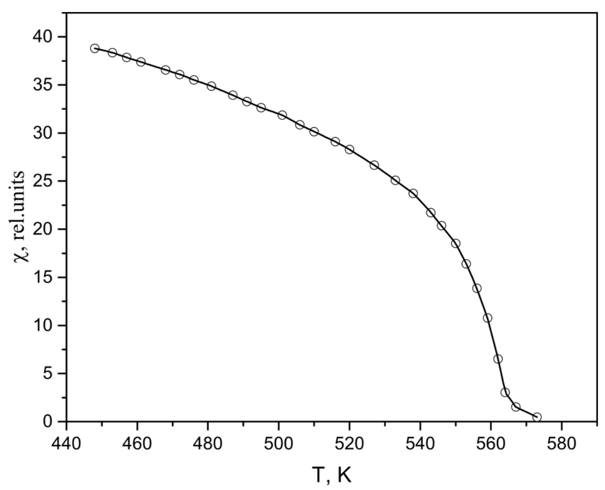

Fig. 7. Temperature dependence of the initial magnetic susceptibility

be a result of the presence of a term $\sim 1/H$ in the expression describing the approach of a magnetization to the saturation mode in this field section [3]. This term may be associated with the presence of nonmagnetic inclusions. There emerges a demagnetizing field in their vicinity, which prevents some of spins from changing their direction. The role of such inclusions in the examined alloy can be played by metalloid atoms.

In order to determine the local anisotropy field, section I was chosen. This section is described by the equation

$$-\log d_m = a_1 \log H + b_1, \tag{10}$$

where $a_1 = \frac{1}{2}$ and $b_1 = \log 2 + \frac{3}{2} \log H_\ell - \log \left(DH_a^2\right)$. Whence

$$\log \left(DH_a^2\right) = \log 2 + \frac{3}{2} \log H_\ell - b_1. \tag{11}$$

The value obtained for the root-mean-square fluctuation of the local anisotropy axis, $\sqrt{D}H_\ell$, equals

$$\sqrt{D}H_a = (290 \pm 60)\ \text{Oe}.$$

In the case of equiprobable fluctuations of the local anisotropy axis direction in space, we have $D = 1/15$, so that the field of the local anisotropy equals

$$H_a = (1100 \pm 200)\ \text{Oe}.$$

The effective constant of the uniaxial local anisotropy, K_{eff}, is calculated from the formula [8]

$$H_a = \frac{2K_{\text{eff}}}{I_s}. \tag{12}$$

By magnitude, the constant K_{eff} has an order of 10^{15} erg cm^{-3}, similarly to what was obtained earlier for Fe- and Fe–Ni-based alloys [11]. As the temperature grows, the constant K_{eff} decreases proportionally to $T^{3/2}$ (see Fig. 6).

4.2. Initial magnetic susceptibility. Curie temperature

The fact that the anisotropy constant changes with the temperature in approximately the same way as the spontaneous magnetization is reflected in the temperature behavior of the initial susceptibility χ_0. This parameter was studied in order to determine the Curie temperature of the alloy. The initial susceptibility associated with the rotation of magnetization vector looks like

$$\chi_0^{\text{rot}} \sim I_s^2/K,$$

and that associated with the displacements of domain boundaries is [9]

$$\chi_0^{\text{dis}} \sim I_s/\sqrt{K}.$$

Let the anisotropy constant decrease faster than the spontaneous magnetization does, as the temperature grows. When approaching the Curie point, where K is already small and I_s still remains significant, a maximum has to be observed in the curve $\chi_0(T)$ with a further sharp decrease at the Curie point (the Hopkinson effect). The dependence $\chi_0(T)$ does not reveal a maximum for the examined alloy (see Fig. 7). A smooth behavior of the dependence may be associated with the spatial fluctuations of the anisotropy and exchange fields.

The Curie temperature T_C was determined by extrapolating the section, where the dependence $\chi_0(T)$ drastically decreases, to the T-axis. It was found to equal

$T_C = (565 \pm 2)$ K.

4.3. Magnetostriction

The effective local magnetic anisotropy in an amorphous ferromagnet may be, by its nature, "crystallographic", i.e. single-ion, by resulting from the influence of a non-uniform electric field created by ions surrounding a magnetically active atom (ion) on this atom, as well as induced by elastic stresses or other inhomogeneities in the substance.

The studies of the magnetostriction were carried out to answer the question: Does the magnetic anisotropy of the magnetoelastic origin contribute to the local magnetic anisotropy of the examined alloy? The magnetostriction magnitude was measured at room and nitrogen temperatures in the fields up to 6.5 kOe and in the directions along and across the applied field. The sensitivity of the installation to the relative lengthening of specimens was 8×10^{-7}. The measurements showed that the specimens revealed no magnetostriction in all cases. Therefore, the measured local anisotropy had mainly a single-ion origin.

Magnetic parameters of Co–Fe–Ni–Cr–P–B alloy

No.	Parameter	Value
1	Spontaneous magnetization I_s at 0 K, G	447 ± 2
2	Bloch constant B, $K^{-3/2}$	$(4.1 \pm 0.1) \cdot 10^{-5}$
3	Exchange constant α, cm^2	$(4.7 \pm 0.1) \cdot 10^{-12}$
4	Correlation field H_ℓ, Oe	870 ± 90
5	Correlation radius r_ℓ at $T = 295$ K, Å	138 ± 5
6	Root-mean-square fluctuation of the local anisotropy field $\sqrt{D}H_a$, Oe	290 ± 60
7	Local magnetic anisotropy field H_a, Oe	1100 ± 200
8	Effective local anisotropy constant K_{eff} at $T = 295$ K, Erg/cm^3	$(1.9 \pm 0.4) \cdot 10^5$
9	Curie temperature T_C, K	565 ± 2
10	Linear magentostriction λ_s	$<8 \cdot 10^{-7}$

The main results of our researches are quoted in Table.

5. Conclusions

1. The magnetization of Co–Fe–Ni–Cr–P–B amorphous alloy has been studied. It is found that the Bloch "law of 3/2" is satisfied for the alloy in a temperature interval from 220 to 395 K. The corresponding exchange constant α was determined. By the order of magnitude, the value obtained for σ agrees with the data for other amorphous alloys.

2. With the help of a method based on the theory of stochastic magnetic structure and using the magnetization curves, the correlation field H_ℓ and the field of the local magnetic anisotropy H_a are determined. Those both parameters are shown to be temperature-independent in an interval from 295 to 395 K.

3. Such stochastic characteristics as the correlation radius and the root-mean-square fluctuation of the local anisotropy field are calculated. The value obtained for the correlation radius, $r_\ell \sim 100$ Å, corresponds to long-range correlations (heterogeneities on the submicronic scale). As the temperature grows, a weak reduction of the correlation radius is observed, which is associated with a change of the spontaneous magnetization.

4. The effective constant of the local magnetic anisotropy K_{eff} is calculated. By the order of magnitude, its value amounts to 10^5 erg cm^{-3}. As the temperature grows, the constant K_{eff} decreases proportionally to $T^{-3/2}$.

5. The linear magnetostriction of the alloy, λ_s, is measured. It is found that $\lambda_s < 8 \times 10^{-7}$ at room and nitrogen temperatures. This fact allows a conclusion to be drawn that the magnetoelastic contribution to the local anisotropy of the examined alloy is insignificant, whereas the single-ion one dominates.

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ЛОКАЛЬНА МАГНІТНА
АНІЗОТРОПІЯ АМОРФНОГО СПЛАВУ НА ОСНОВІ Co

Р е з ю м е

Досліджувалися намагніченість, початкова магнітна сприйнятливість і магнітострикція багатокомпонентного аморфного сплаву на основі Co. Визначені постійна обміну α і температура Кюрі $T_{\rm C}$ сплаву. За допомогою методу, ґрунтованого на теорії стохастичної магнітної структури для аморфних феромагнетиків, по кривих намагнічування розраховані кореляційне поле H_ℓ, поле H_a і ефективна константа $K_{\rm eff}$ локальної магнітної анізотропії, а також стохастичні характеристики локальної анізотропії – середньоквадратична флуктуація поля $\sqrt{D}H_a$ і кореляційний радіус r_ℓ. Вивчено характер температурної поведінки досліджуваних магнітних характеристик. Результати дослідження магнітострикції дозволяють зробити висновок про одноіонне походження локальної магнітної анізотропії сплаву.