1. INTRODUCTION

Iron-based soft magnetic nanocrystalline alloys (Fe–Si–Nb–B–Cu (Finemets)) produced in the form of ribbons by quenching from the melt onto a rotating drum, acquire excellent soft magnetic properties (magnetic permeability $\mu \approx 10^5$, coercive force $H_c \approx 1$ A/m, and saturation magnetization $M_s = 1.24$ T) after nanocrystallization annealing at temperatures in the range from 510 to 570°C [1].

A continuing interest in these alloys is associated with their wide use in products of electronics and other high-technology industries. A practically important feature of Finemets is the possibility of purposefully controlling their magnetic permeability through the formation of states with induced magnetic anisotropy in alloy samples as a result of heat treatment in a magnetic field (thermomagnetic treatment) or in a field of mechanical stress (thermomechanical treatment).

The microstructure of the nanocrystalline Fe–Si–Nb–B–Cu alloy can be represented as a great number of isotropically oriented $\alpha’$-(FeSi) nanocrystallites with the average grain diameter of approximately 10 nm with the body-centered cubic (BCC) lattice and clusters of non-magnetic face-centered cubic (FCC) Cu(Fe) grains with the average size of approximately 5 nm, which are arranged in the remaining amorphous matrix of the Fe(Nb)–B phase [2]. Therefore, it should be noted that, in crystalline iron–silicon alloys, annealing and cooling in a constant magnetic field or under tensile stress result in the formation of induced magnetic anisotropy constant, which is linearly related to the relative extension and compression of the interplanar spacings for different crystallographic planes and magnetic anisotropy constant has been revealed. The deviation from linearity is observed after annealing at a temperature of 600°C, which is explained by a possible increase in sizes of nanocrystals, changes in their structure, and partial crystallization of the amorphous matrix.

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increase in the temperature, these changes rapidly increase. At a temperature of 450°C, the exposure for a few minutes is sufficient for the complete removal of the effect produced by the thermomagnetic or thermomechanical treatment.

Detailed investigations of the structure of Fe1−xSi x (x = 0.05−0.08) single crystals before and after thermomagnetic or thermomechanical treatment have demonstrated that no changes in the crystal lattice of the single crystals are observed [5, 6]. At the same time, it has been found that, in the local ordering of the atoms in the solid solution, there are anisotropic features, i.e., pairs of silicon atoms formed by the next-nearest neighbors in the BCC lattice and oriented along the (100) directions (short-range order of the B2 type), which coincide with the easy magnetization axes [7]. After the heat treatment, pairs of Si–Si atoms are predominantly oriented along one of the easy magnetization axes, which is specified by an external effect (a magnetic field or a field of mechanical stress). The magnetization reversal along this axis is facilitated, and it becomes the induced magnetic anisotropy axis [6]. It is clear that the reorientation of atoms in the iron–silicon solid solution can occur only through the diffusive motion of the atoms with the participation of vacancies [8]. Nonetheless, the mechanisms of the formation of an anisotropic distribution of the Si–Si atomic pairs under the action of external factors and its influence on the magnetic properties of these materials are still not clearly understood.

The tensile load applied during the nanocrystallization annealing and subsequent cooling of the Fe73.5Si13.5Nb3B9Cu1 alloy gives rise to a mechanical stress and forms a state with transverse magnetic anisotropy in ribbons of the alloy [9]. The magnetization of individual nanocrystals is predominantly oriented across the ribbon, i.e., in directions close to the plane perpendicular to the axis of application of the tensile load during the thermomechanical treatment [9, 10]. Upon the magnetization reversal along the ribbon, the magnetic hysteresis loop of the alloy takes on an inclined linear shape with a constant value of the magnetic permeability over a wide range of variations in the magnetizing field (Fig. 1). The efficiency of the thermomechanical treatment is estimated from the induced magnetic anisotropy constant K_u. The quantity K_u, which depends on the tensile load applied during the thermomechanical treatment and can reach 7000 J/m^3, becomes comparable to the local energy of magnetocrystalline anisotropy of the crystalline Fe–Si phase [11].

Earlier [12], we investigated the influence of thermomechanical treatment conditions, such as the temperature and annealing duration, on the induced magnetic anisotropy constant K_u. In addition, we compared the results obtained in the one-step and two-step modes of thermomechanical treatment. In the former case (one-step procedure), the ribbon samples quenched from the melt onto a rotating drum are simultaneously subjected to crystallization annealing and tensile stress. In the latter case (two-step procedure), first, the sample undergoes nanocrystallization and, then, the crystallized sample is subjected to tensile stress (thermomechanical treatment). It was shown that the dependence of the magnetic anisotropy constant K_u on the stress σ (created by the mechanical stress load) is linear. The straight line K_u(σ) obtained in the one-step process passes approximately two times higher than that plotted in the two-step process. The observed effect rapidly reaches saturation (for 5–10 min); in this case, the effect is the more pronounced, the higher is the heat treatment temperature. The magnetic anisotropy constant K_u changes within 10% at temperatures in the range from 515 to 560°C. In the case where the thermomechanical treatment is performed on preliminarily crystallized samples, the lower is the heat treatment temperature, the longer is the time required for the saturation of the effect; i.e., this time is approximately 1 h at a temperature of 560°C and exceeds 2 h at temperatures ranging from 500 to 530°C. After the two-step procedure, the effect (i.e., the value of K_u) is approximately two times smaller and one order of magnitude stronger temperature-dependent than that after the one-step procedure.

Moreover, we investigated the stability of the state with transverse magnetic anisotropy upon annealings without external influence [12]. After the one-step thermomechanical treatment, the magnetic anisotropy constant did not change at temperatures below