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Mechanisms of the magnetic properties improvement of amorphous soft magnetic Fe- and Co-based alloys as a result of the in-air heat treatment

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Abstract

Physical causes of the formation of magnetic characteristics amorphous soft magnetic alloys under heat treatment in air have been studied. It has been established that the physical causes of the formation of the magnetic characteristics of the cobalt-based alloys are the same as those for iron-based alloys. Change in the magnetic characteristics after annealing results from the relaxation of the quenching induced internal stresses, as well as from the effect of the stresses induced by the hydrogen and oxygen atoms embedded into the ribbon surface in the course of its interaction with water vapor in air and by the formation of the amorphous-crystalline surface layer. The study of the magnetization distribution and the magnetic characteristics of the Co–Fe–Ni–Cr–Si–B amorphous soft magnetic alloy have shown the possibility of using the vapor treatment of the amorphous soft magnetic alloy ribbon surface to determine the sign of its magnetostriction. The magnetostriction sign dependence on the structural state of the ribbon is found on the basis of the obtained results.

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Keywords: Magnetic permeability, magnetization, amorphous soft magnetic alloys, heat treatment, temperature of isothermal holding, magnetization distribution, interaction with vapor.

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1. Introduction

The electromagnetic field of the industrial frequency is unfavorable factor that has influence on the personnel health during operation with the high voltage electrical installation. In this case, static shielding method using ferromagnetic materials with high magnetic permeability becomes useful. Ribbons of the amorphous soft magnetic cobalt-based alloys are used in electronics and also in magnetic shielding (Chen et al. (2002)). Magnetoimpedance (MI) changes due to surface modification of the sensitive element caused by chemically active medium can be used in the development of various sensors including a biosensor working on a principle of electrochemical magnetoimpedance spectroscopy (Kurlyandskaya et al. (2007)). They have high values of the maximum magnetic permeability (μ_{max}) even in the as-quenched state due to low values of saturation magnetostriction. Magnetic properties of these materials can be improved by a heat treatment. Annealing in the air is the most economical option. It should not lead to noticeable oxidation of a ribbon surface because of the relatively low temperature of isothermal holding (350 – 400 ºC). Determination of the mechanisms that contribute to the magnetic properties improvement leads to the properties optimization with the least time consumption.

Analysis of the magnetic properties studies of rapidly quenched soft magnetic alloys shows that great works in this direction were occurred. The use of modern methods allows structural studies to be implemented at a high scientific level. It helps to establish a connection between the structure and the level of magnetic properties. In order to improve magnetic properties of rapidly quenched soft magnetic alloys it is used generally the same methodology as for crystalline materials. It mainly includes thermal, thermomagnetic and laser treatment. Hence, the improvement of magnetic properties as a result of these treatments were explained by only following causes: relaxation of internal stresses at elevated temperatures, inducing anisotropy by magnetic field and mechanical stresses, destabilization of domain walls (Wang et al. (1983), Noskova et al. (2005), Kekalo et al. (1984), Kekalo et al. (2005), Egami (1978), Komatsu et al. (1985), Luborsky et al. (1978), Dragoshanskii et al. (1993)).

Iron-based amorphous soft magnetic alloys compared to cobalt-based alloys have relatively high saturation magnetostriction. For iron-based alloys the magnetization distribution and magnetic properties are more sensitive to the level of the internal stresses. Therefore, the mechanisms of heat treatment in air were first investigated for these alloys. The results of the investigation into the effect of heat treatment in air on the magnetic properties of ribbons of amorphous soft magnetic iron-based alloys suggest the physical model that makes it possible to understand changes in the set of magnetic properties caused by heat treatment (Skulkina et al. (2001), Skulkina et al. (2005)). Along with the stress relaxation during the heat treatment, the interaction of ribbon surface with atmospheric water vapor and the formation of surface amorphous–crystalline layer are of importance. The atoms of hydrogen and oxygen embedded in the ribbon surface upon its interaction with water vapor induce plane tensile stresses in the amorphous matrix. Such stresses additionally reduce the volume of domains with orthogonal magnetization and weaken the stabilization of the domain walls with planar magnetization. The oxidation and hydrogenation occur in an anisotropic fashion. Since this is energetically favorable (Kekalo et al. (1989)), an enhanced concentration of atoms incorporated into the surface arises in the direction perpendicular to the resulting magnetization that assists the formation of a pseudo-uniaxial tension in this direction.

A change in the experimental conditions is one of the most important factors corroborating the reliability of the suggested model. For this purpose electrolytic oxidation and hydrogenation, water and vapor treatments of the ribbon surface of amorphous soft magnetic iron-based alloys were carried (Skulkina et al. (2011), Skulkina et al. (2010), Skulkina et al. (2014)).

2. Experimental

The investigation was performed on the ribbon samples of amorphous soft magnetic $Fe_{77}Ni_1Si_9B_{13}$ and $Fe_{81}B_{13}S_4C_2$ alloys with a positive magnetostriction and a close level of their magnetic properties. The samples were used both in the as-quenched state and after annealing in air. The samples (with dimensions of 110 × 10 × 0.025 mm) were fabricated from ribbons of the commercial alloys. The specific magnetic losses were measured by the wattmeter method with an error of ~4% in the regime of sinusoidal induction that was maintained with the help of a feedback amplifier. The magnetization curves and hysteresis loops in the static regime of magnetization reversal were measured by the induction pulse method. The magnetization distribution: relative volumes of domains with