THERMAL STABILITY OF FIELD-AND STRESS-INDUCED ANISOTROPY IN NANOCRYSTALLINE Fe-BASED AND AMORPHOUS Co-BASED ALLOYS

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Thermal stability of induced magnetic anisotropy (IMA) was studied in a course of subsequent annealings without any external effects for already field- or stress-annealed specimens of the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ and amorphous $Fe_3Co_{67}Cr_3Si_{15}B_{12}$ alloys. For these alloys the dependence of IMA thermal stability on the magnitude of the IMA constant (K_u) and temperature of stress-annealing was investigated. For the nanocrystalline alloy thermal stability of field- and stress-induced anisotropy with identical K_u was compared. It was shown that nanocrystalline specimens with identical K_u values after field- or stress-annealing have identical thermal stability of IMA. This can point to a similarity of the mechanisms of IMA formation after field- or stress-annealings. Thermal stability of stress-induced anisotropy in the nanocrystalline alloy with K_u value less than $1000 \, J/m^3$ and the amorphous alloy with K_u less than $100 \, J/m^3$ depends on the value of K_u. For both stress-annealed nanocrystalline and amorphous alloys magnetic anisotropy induced at higher temperatures is more stable because more long-range and energy-taking processes take place at these temperatures.

Keywords: Induced magnetic anisotropy; Thermal stability; Thermomagnetic and thermomechanical treatments; Nanocrystalline and amorphous alloys

INTRODUCTION

It is known that amorphous and nanocrystalline materials show the highest soft magnetic properties. The required level of soft magnetic

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properties is reached by different kinds of anisotropies induced in these materials by various treatments. These are thermomagnetic treatments in d.c., a.c. and high frequency magnetic fields, quenching from the Curie temperature into water (Glazer *et al.*, 1992; 1994), thermomechanical treatment which is the only effective one in ferromagnetics with low Curie temperature (Kurlyandskaya *et al.*, 1996). The practical use of soft magnetic materials with induced magnetic anisotropy is determined by their thermal stability. In present work the thermal stability of field- and stress-induced anisotropy in the amorphous $Fe_3Co_{67}Cr_3Si_{15}B_{12}$ and the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloys is studied, the thermal stability of these anisotropies is compared. This is important both for the estimation of the thermal stability of the magnetic properties and for understanding of the nature of the induced magnetic anisotropy (IMA).

EXPERIMENTAL

The alloy ribbons were produced by melt quenching on rotational disc in air. In order to achieve soft magnetic properties Fe-based amorphous ribbons were to be nanocrystallized by annealing at 530°C for 1 h (NCA). Thermomagnetic treatment (TMT) in transverse d.c. magnetic field $H = 2.5 \cdot 10^5$ A/m always was carried out during NCA. Thermomechanical treatment (TMechT) was carried out either simultaneously with NCA (regime 1) or after NCA (regime 2) at different temperatures: 300°C, 400°C and 530°C for 4, 2 and 2 h, respectively (Lukshina *et al.*, 1996). For all Co-based amorphous specimens preliminary 1 h annealing at 350°C for stress releasing was performed. Field-annealing for this material is not effective because the Curie temperature is too low (160°C) (Kurlyandskaya *et al.*, 1996). Stress-annealing was carried out at 250°C and 350°C for 4 and 1 h, respectively. These exposures were necessary for obtaining ultimate magnitudes of IMA constants. The magnitudes of IMA constants were determined from the hysteresis loops according to the formula $K_u = -\frac{1}{2}(M_sH_s)$, where M_s is the saturation magnetization, H_s is the magnetic field in which saturation magnetization is achieved.

Thermal stability of induced magnetic anisotropy was studied in a course of subsequent annealings without any external effects for already field- or stress-annealed specimens of the alloys mentioned above.

RESULTS AND DISCUSSION

For the nanocrystalline alloy thermal stability of the magnetic anisotropy was studied using the samples after TMT with $K_u = 100$ and $350\,J/m^3$ and after TMechT (regime 1) with K_u from 400 to $4000\,J/m^3$. The specimens with different K_u were annealed without any external effects for 1 h at progressively increasing temperatures in steps of 50 K, starting from 200°C, K_u was measured at room temperature after each annealing.

It was found that the specimens with K_u about $1000\,J/m^3$ and more had the most thermally stable magnetic anisotropy. It was stable during 1 h annealing at 450°C. For K_u less than $1000\,J/m^3$ the thermal stability depends on the magnitude of K_u; the less the magnitude, the less the temperature up to which K_u was stable. Maximal K_u magnitudes obtained after TMT usually were equal to $100-150\,J/m^3$. These values were essentially less than the ones after TMechT. So, thermal stability of K_u which we can obtain after TMT is less than that after TMechT (see Fig. 1).

For some specimens Fig. 1 displays the relative variation of the constant of IMA, $K_u(t)/K_u$ depending on the (1 h) annealing temperature; K_u is the magnitude of the anisotropy constant immediately after TMT or TMechT and $K(t)$ is the magnitude after annealing without any external effects following TMT or TMechT. It can be seen from Fig. 1 that the less
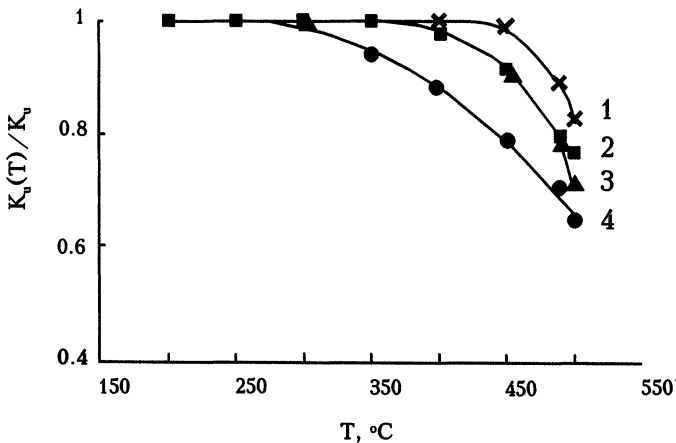

FIGURE 1   Relative K_u variation after stress and magnetic field-free annealing for 1 h at different temperatures for the nanocrystalline alloy. Curves 1 and 2: for K_u obtained after TMechT and equal to 4000 and $400\,J/m^3$, respectively; curves 3 and 4: for K_u obtained after TMT and equal to 350 and $100\,J/m^3$, respectively.

the magnitude of K_u the less the 1 h annealing temperature up to which K_u does not yet decrease (compare curves 1, 2, 3 and 4). It should be noticed that if the magnitudes of K_u obtained after TMT and TMechT are close to each other their thermal stabilities are equal, as well (compare curves 2 and 3). It can point to a similarity of mechanisms of magnetic anisotropy induced after TMT and TMechT, as well.

Analogous investigations of the thermal stability of IMA for Co-based amorphous alloy show that magnetic anisotropy induced by TMechT is stable after 1 h annealing without any stress at 240°C for specimens with K_u values being equal or more than 100 J/m^3. For this amorphous alloy we considered the dependence of thermal stability on the magnitudes of K_u obtained after stress-annealing. The samples with K_u from 25 to 500 J/m^3 were prepared by TMechT at 350°C for 1 h with σ from 80 to 1400 MPa, respectively. Figure 2 shows the change of K_u against annealing time at 260°C without any load. It is seen that specimens with K_u from 500 (curve 1) to 100 J/m^3 (curve 2) have the same thermal stability; the experimental points are situated on the same curve. The specimen with $K_u = 25$ J/m^3 has less thermal stability; the respective curve 3 runs below curve 1. Thermal stability of stress-induced anisotropy in amorphous alloys with K_u values less than 100 J/m^3 depends on the K_u value: the less K_u, the less the thermal stability.

For the above-mentioned alloys the influence of TMechT temperature on the thermal stability of IMA was investigated. For the
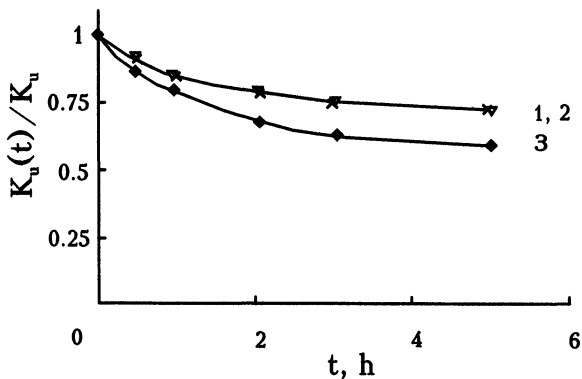

FIGURE 2   The relative change of IMA constant against the annealing time at 260°C without any load for the amorphous alloy. Starting K_u (in J/m^3) = 500 (curve 1), 100 (curve 2), 25 (curve 3) induced by TMechT with various σ at 350°C for 1 h.

nanocrystalline alloy after TMechT by regime 2, we took three samples with the same K_u ($= 150 \, J/m^3$) obtained at different temperatures of TMechT (530°C, 400°C and 300°C) and different loads (25, 160 and 320 MPa, respectively). The samples were treated by TMechT at 530°C, 400°C and 300°C for 2, 2 and 4 h, respectively. These exposures were necessary for obtaining ultimate magnitudes of IMA constants. For the Co-based amorphous alloy two samples were prepared with the same K_u values, which were equal to 200 J/m^3, induced at various temperatures of TMechT: 350°C (1 h, $\sigma = 500 \, MPa$) and 250°C (4 h, $\sigma = 1500 \, MPa$).

These samples were annealed without any load: at 260°C for Co-based amorphous alloy and at 300°C for the nanocrystalline alloy. In certain intervals of time, the samples were cooled to room temperature, and the magnetic anisotropy constant, $K_u(t)$, was measured. Figures 3 and 4 show the relative changes of the IMA constant, $K_u(t)/K_u$, against the annealing time (K_u is the IMA constant value immediately after TMechT). $K_u(t)/K_u = 1$ for $t = 0$, which conforms to a state immediately after TMechT.

Figures 3 and 4 show that the IMA constant induced at higher TMechT temperature decreases slowly with the exposure time. The K_u of the nanocrystalline alloy sample that was subjected to TMechT at 530°C remains virtually unchanged after 4–5 h annealing at 300°C
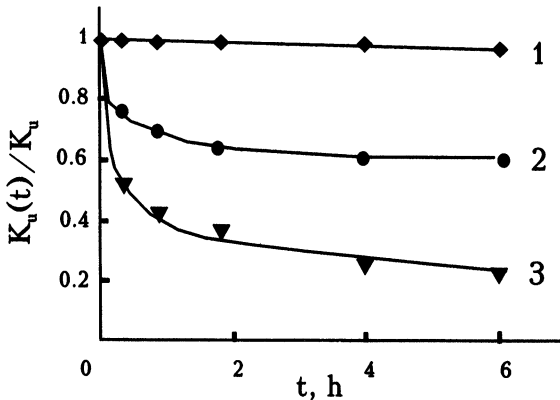

FIGURE 3   Variation of K_u depending on the stress-free annealing time at 300°C for the samples of the nanocrystalline alloy treated by regime 2 under the following conditions: NCA at 530°C for 1 h + TMT at (1) 530°C for 2 h and $\sigma = 25 \, MPa$; (2) 400°C for 2 h and $\sigma = 160 \, MPa$; and (3) 300°C for 4 h and $\sigma = 320 \, MPa$. (After all these TMechTs the magnitude of K_u was the same, equal to 150 J/m^3.)
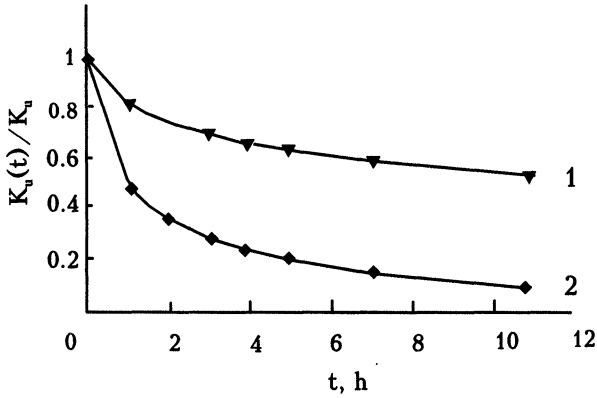
FIGURE 4   The relative change of starting $K_u = 200\,J/m^3$ induced by TMechT at 350°C with $\sigma = 500\,MPa$ for 1 h (curve 1) and at 250°C with $\sigma = 1500\,MPa$ for 4 h (curve 2) following annealing at 260°C without any load for the amorphous alloy.

(curve 1, Fig. 3); after the TMechT at 400°C K_u decreases by 40% (curve 2, Fig. 3); and annealing at 300°C without load after TMechT at 300°C decreases K_u by 75% (curve 3, Fig. 3). For the Co-based amorphous alloy after 10 h of annealing without any load, K_u decreases by 50% if a sample was stress-annealed at 350°C and by 90% if the sample was stress-annealed at 250°C (Fig. 4). The higher thermal stability of IMA induced by TMechT at 350°C for Co-based amorphous alloy and at 530°C for the nanocrystalline alloy shows that an increase of the TMechT temperature not only accelerates the diffusion processes but gives rise to more long-range and energy-taking processes, as well. Indeed for Co-based amorphous alloys the activation energies, estimated for a change of 50% of K_u from the kinetic curves of the IMA relaxation, have the following values: 2.2 eV for IMA induced at 350°C and 1.9 eV for IMA induced at 250°C.

CONCLUSIONS

From the above the following conclusions can be made:

1. The induced magnetic anisotropy (IMA) is stable after 1 h annealing at: (a) 450°C for the nanocrystalline alloy after TMechT by regime 1 with K_u value being equal to or more than $1000\,J/m^3$; (b) 300°C for the nanocrystalline alloy after TMT with K_u value about $100\,J/m^3$;

(c) 240°C for amorphous alloy with K_u value being equal to or more than 100 J/m³.

2. Thermal stability of stress-induced anisotropy in the nanocrystalline alloy with K_u value less than 1000 J/m³ and in the amorphous alloy with K_u value less than 100 J/m³ depends on the value of K_u: the less K_u, the less the thermal stability.

3. It is shown that for both stress-annealed nanocrystalline by regime 2 and amorphous alloys magnetic anisotropy induced at higher temperatures is more stable because more long-range and energy-taking processes take place at higher temperature of TMechT.

4. Identical thermal stability for nanocrystalline specimens with identical K_u values after TMT and TMechT points to a similar nature of field- and stress-induced anisotropy.

Acknowledgements

References

Glazer, A.A., Shulika, V.V. and Potapov, A.P. (1992). Domain structure destabilization of amorphous alloy by thermomagnetic treatment in high frequency field. Docladi Academii Nauk (Russian), **324**(6), 1191–1193.

Glazer, A.A., Shulika, V.V. and Potapov, A.P. (1994). Effect of induced magnetic anisotropy upon static and dynamic magnetic properties of amorphous soft magnetic alloys with different magnetostriction. *The Physics of Metals and Metallography*, **78**(4), 383–387.

Kurlyandskaya, G.V., Dmitrieva, N.V., Zayarnaya, T.Ye., Lukshina, V.A. and Potapov, A.P. (1996). The thermomechanical treatment of an amorphous Co-based alloy with a low Curie temperature. *Journal of Magnetism and Magnetic Materials*, **160**, 307–308.

Lukshina, V.A., Dmitrieva, N.V. and Potapov, A.P. (1996). Thermomechanical treatment of nanocrystalline FeCuNbSiB alloy: induced magnetic anisotropy and its thermal stability. *The Physics of Metals and Metallography*, **82**(4), 376–378.