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The Nature of Stress-Anneal-Induced Anisotropy in Finemet-Type Magnets

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Possible sources of the stress-anneal-induced anisotropy in FINEMET-type magnets are reviewed and discussed resulting in a conclusion that the most probable origin of this anisotropy is the atomic pair directional ordering. It is also evidence that the anisotropy considered is usually of an easy-plane type.

1. Introduction

It is well known that devitrification under stress of FINEMET-type magnets creates large magnetic anisotropy of its energy volume density of the order of 10^3 J/m^3 (see, e.g. Ref. 1). Several mechanisms have been taken into account in the past as the origin of this phenomenon but till now it is still not prejudged explicitly which of these mechanisms is in fact responsible for this anisotropy. The aim of the present work is to indicate the most probable origin the considered anisotropy.

2. Possible sources of anisotropy

In order to understand the nature of this nature of the stress-anneal-induced anisotropy in FINEMET-type magnets the two-phase character of the nanocrystalline state should be considered. Both components existing in the material can contribute to the anisotropy studied. The most obvious origin, which is intuitively easy to understand, could be crystallographic texture of the nanocrystallites forced by the stress during their growth. X-ray diffraction patterns, obtained for the samples annealed under stress and without stress at the very same geometry of measurement are, however, identical showing that no texture is created [2] (If the texture would appear, then the intensity of lines in the X-ray spectra should be different).

The second possibility is the polarization of atomic bonds in the amorphous intergranular phase due to unelastic strain, the mechanism which is similar to that well known in metallic glasses (see, Ref. 3). However, the observed anisotropy in FINEMET- type alloys is much larger than the anisotropy induced in metallic glasses and additionally only 20-30 % of the volume of this material is occupied by the amorphous phase. Therefore, the above mentioned mechanism can also be excluded as the origin of the considered anisotropy.

The third possibility is the magnetoelastic interaction. Herzer [4] has proposed an explanation, claiming that the stress-anneal-induced anisotropy in FINEMETs is of magnetoelastic nature and is created in the nanocrystalline phase due to tensile back stress exerted by the anelastically deformed residual amorphous matrix (intergranular phase). The above conclusion seems to be highly probable because of a strong g correlation between the stress-induced anisotropy and magnetostriction of the nanocrystallites found by Herzer.

Recently, Hofmann and Kronmüller [1] have suggested the fourth possible origin of the anisotropy studied, namely: diatomic directional of the investigate material (conventional FINEMET), obtaining theoretical value of the energy density of the stress-induced anisotropy of the same order of magnitude as that observed experimentally. Taking into account these results, they claim that besides magnetoelastic interactions, the atomic pair ordering is also a very probable source of the considered anisotropy.

The new experimental data obtained very recently by Lachowicz *et al.* [5], show that the diatomic directional ordering seems to be the most probable origin, indeed. In this work, the temperature dependence of th energy density of the effective anisotropy was measured for samples with various content of the nanocrystalline phase. The parent alloy used for this experiment was metallic glass of the composition $Fe_{73.5}Cu_{12}Nb_3Si_{15.5}B_7$. An analysis of the anisotropy is induced for the samples annealed under stress has shown first of all that the anisotropy is induced within the volume of the nanocrystalline phase since the energy density of this anisotropy is proportional to the content of this phase [5]. The above conclusion is, however, quite obvious since at the annealing temperature used only crystallites exhibit ferromagnetic properties (Curie point of the amorphous matrix is much lower). The second important conclusion drawn from this analysis that the anisotropy created by stress-annealing of the already crystallized sample is an order of magnitude smaller than that induced if the sample devitrifies when annealed under

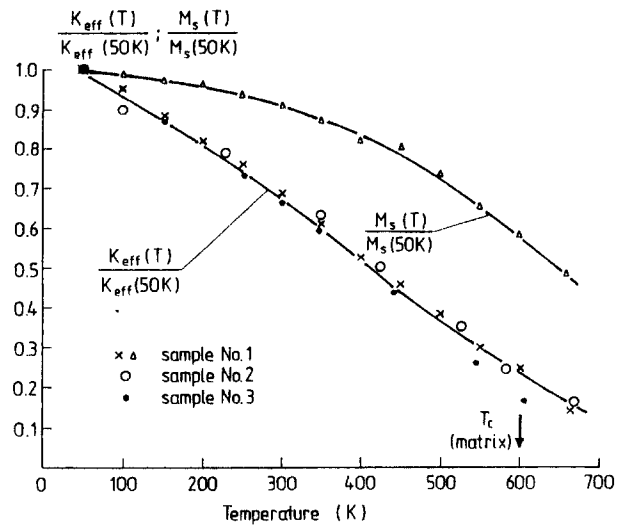

Fig. 1. Temperature dependencies of normalized effective anisotropy for samples No. 1 (annealed: 540°C for 1 h under stress of 213 MPa), No. 2 (540°C, 1 h and next at 350°C, 1 h, 142 MPa), and No. 3 (500°C, 0.5 h, 213 MPa). Temperature dependence of saturation magnetization (sample No. 1) is also shown.

stress. This experimental fact seems to be the most convincing evidence against the magnetoelastic nature of the considered anisotropy since if the magnetoelastic coupling would be the origin, than the anisotropy induced in both samples should be indicate comparable values of the energy density.

The obtained temperature dependencies of normalized effective anisotropy energy (anisotropy constant) for the samples annealed at various stress-heat conditions (see, the caption of Fig. 1) are presented in Fig. 1. They practically overlap each other, decreasing monotonically with an increase of the temperature of measurement. The observed superimposition of these dependencies suggests that the same mechanism operates for all conditions of the applied stress-annealing.

The temperature dependence of the anisotropy originating from the diatomic directional ordering is well known theoretically. The calculations based on the pseudo-dipolar model of magnetic interactions performed neglecting correlation between the spin orientation, show that the anisotropy should be proportional to the saturation magnetization squared [6]. However, this model correctly describes temperature dependence of anisotropy only in high-temperature range, in the vicinity of the critical temperature (Curie point). At low temperature, spin- wave theory (high correlation between spin orientation) shows that the energy of the pair-ordering anisotropy should scale with the cube of the saturation magnetization (see Ref. 6). Therefore, assuming should scale with the cube of the saturation magnetization should be well approximated by a polynomial consisting square and cube terms. Fig. 2. presents such a dependence in the normalized form. The solid line in this figure represents the best fit of the experimental

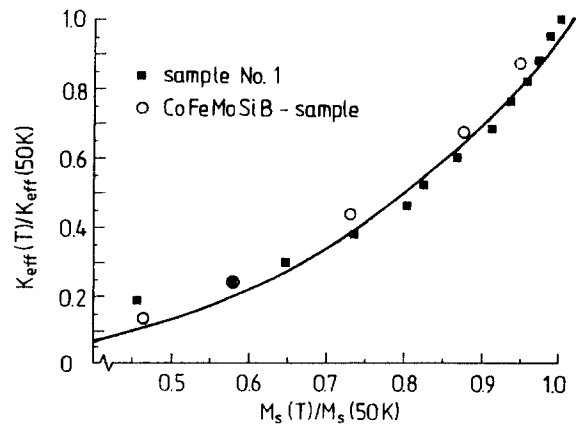

Fig. 2. Normalized energy density of effective anisotropy plotted versus normalized saturation magnetization. Solid line represents the best fit of experimental data to the polynomial consisting square and cube terms.

points to a polynomial of the form $y=ax^3+bx^3$ where $y=K_{eff}(T)/K_{eff}(50K)$ and $x=M_s(T)/M_s(50K)$. The fit gives a=0.15 and b=0.79. Simple analysis shows that the square term prevails for $x<0.2$(T=600K), whereas, for $0.2<x<1$, the cube term is dominant. These results show that the atomic-pair directional ordering seems to be very likely the origin of the stress-anneal-induced anisotropy in FINEMET-magnets.

The stress-anneal-induced anisotropy in metallic glasses originates, as it was mentioned earlier, from polarization of atomic bonds due to anelastic strain. However, its magnetic nature is analogous to that originating from atomic-pair directional ordering. In order to compare characteristics of this anisotropy with those obtained for FINEMET-type samples, $Co_{67}Fe_4Mo_1Si_{17}B_{11}$ metallic glass ribbon (2 mm wide and 24 μm thick) was annealed at 620 K for 1 h under the stress of 204 MPa. It has been proved that for the parent metallic glass of FINEMET-type, the sample after stress annealing at the temperature low enough to prevent crystallization, showed non-linear hard-axis magnetization curve with a minor hysteresis loop appearing in the range of low fields, even for relatively large stress of 355 MPa. The temperature dependence of the anisotropy induced in CoFeMoSiB-sample has been measured and the points obtained from calculations are marked in Fig. 2. As seen, these points follow the anisotropy curve received for FINEMET-type nanocrystalline sample. This seems to indicate that the anisotropy in both samples has analogous nature, that is atomic-pair directional ordering.

3. Uniaxial or easy-plane anisotropy?

The stress-annealing of the considered materials usually creates magnetically hard axis along the direction of stress, i.e. along the ribbon's length. In the direction transversal to this axis but laying in the plane of the sample, magnetization of the specimen proceeds in a much easier way. It is the reason why the considered anisotropy is

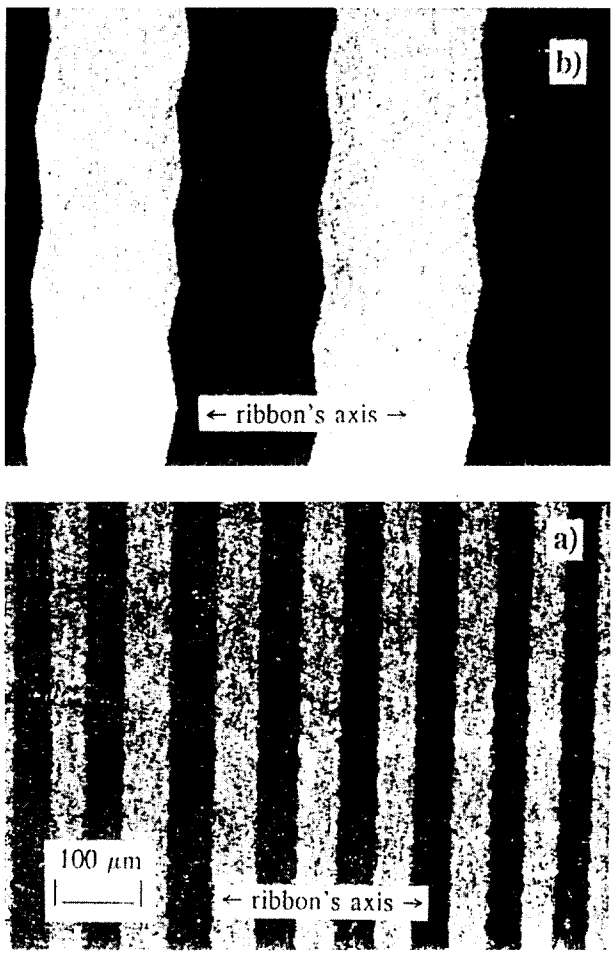

Fig. 3. Kerr-effect domain pattern observed on sample No. 1 surface (a), and enlarge (×5) part of this pattern to make Zig-zags better visible (b).

commonly perceived as the uniaxial anisotropy with its easy axis transversal to the length of the sample. Fig. 3 (a and b) shows an except of the domain pattern obtained by means of Kerr-effect for the stress-annealed sample (No. 1) on its shiny surface. Zig-zag walls are clearly visible in this figure. Since this sharpe of the walls is attributed to the anisotropy of an easy-plane type (see, Ref. 7), appearing of Zig-zags proves that the same type of anisotropy is induced in the studied sample (its cross-section).

It is obvious that the creation of an easy-plane anisotropy should considerably change the spatial distribution of magnetic moments in relation to that in the sample annealed without stress. All three components (N_x, N_y and N_z, while $\Sigma N_{x,y,z}=1$) has been measured using Mössbauer spectroscopy in the so-called "magic-angle" configuration (see, e.g. Ref. 8). The results obtained for the samples in its as-quenched state and annealed without stress and under stress, are presented in Table 1. Since all three components of magnetization were calculated separately using the experimental data obtained independently for three different configuration of measurement, in the last column in Table 1 a sum of these components is given. It is seen that the error in all cases is not larger than 5 %,

Table 1. Spatial components of magnetization obtained for samples in as-quenched state, annealed without stress and under stress

N-component	N_x	N_y	N_z	$N_x+N_y+N_z$
as-quenched	0.296	0.385	0.291	0.972
annealed at 540 °C/1 h	0.424	0.413	0.209	1.001
annealed at 540 °C/1 h/213 MPa	0.046	0.633	0.322	1.046

indicating good reliability of the technique applied. As seen in Table 1. the values of the components of magnetization are in excellent agreement with expectation. For the as-quenched sample, distribution of its magnetization is mainly determined by magnetoelastic interactions. For sample annealed without stress, this distribution is controlled by the geometry of the specimen (demagnetizing factors), whereas, for the sample annealed under stress, the influence of the easy-plane anisotropy is clearly visible (magnetization lies for the most part in the y-z plane). It strongly confirms the occurrence of an easy-plane anisotropy in the considered samples of FINEMET-type material.

4. Conclusions

The results and their analysis presented in the paper allow to conclude that the most probable origin of the stress-induced anisotropy in the considered nanocrystalline magnets is the atomic-pair directional ordering. It also arises from these results that the studied anisotropy is executed much more easier if this anisotropy is induced at the time of devitrification (during the growth of nanocrystallites). It is also shown that the induced anisotropy is not uniaxial but usually of an easy-plane type (hard axis of magnetization along the ribbon length).

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References

[1] B. Hofmann and H. Kronmüller, J. Magn. Mag. Mater., **152**, 91 (1996).

[2] H. K.lachowicz, S. N. Kane, A. Gupta, S. Gierlotka and B. Palosz, Acta Phys Polon., **93**, 799 (1998).

[3] Y. Suzuki, J. Haimovich and T. Egami, Phys. Rev., **B35**, 2162

(1987).
[4] G. Herzer, IEEE Trans. Magn., **30**, 4800 (1994).
[5] H. K. Lachowicz, A. Neuweiler, F. Poplawski and E. Eynowska, J. Magn. Magn. Mater., **173**, 287 (1997).
[6] J. C. Slonczewski, in: Magnetism, G. Rado and H. Suhl (Eds.), vol. II, ch.5, Academic Press, New York, 1963.
[7] K. Závěta, L. Kraus, K. Juraus and V. Kamberský, J. Magn. Magn. Mater., **73**, 334 (1998).
[8] S. N. Kane, K. Ruwali, A. Gupta, L. Kraus and V. Hašla, J. Magn. Magn. Mater., **157/158**, 519 (1996).