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THE INFLUENCE OF DYNAMIC SURFACE FIELDS ON THE COERCIVE FIELD AND ENERGY LOSS OF AMORPHOUS $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ RIBBON

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The M-H loops obtained under different magnetization conditions have been used in order to analyze the coercive field H_c and the energy loss per cycle E for the amorphous $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ ribbon. Applying the model for the influence of the surface fields H_p on the magnetization processes in amorphous ferromagnetic ribbons, we investigated the effects of the dynamic field H_p on H_c and E. It is shown that the influence of dynamic H_p on the M-H loop does not depend on the origin of H_c and E (static or dynamic). This result is important both for the future investigations of the magnetization processes in these materials and for the potential applications.

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1. *Introduction*

The possibility to decrease the energy loss which occurs during the magnetization of soft magnetic materials is important both for the application of these materials and for the better understanding of their magnetization processes. Previous experiments have shown that the direct core currents (passed through the sample from an external current source) affect the M-H loops (the position of its center, the coercive field H_c and the maximum permeability μ_{max}) of amorphous ferromagnetic ribbons [1], and, therefore, affect their energy loss, too. Recently, we developed a simple model which explains these phenomena in terms of the influence of the surface fields H_p (generated by the core current) on the movement of domain walls (DW) within the ribbon [2,3]. This hypothesis was confirmed by generating H_p in different ways [4] and by producing a composite material (sandwich) in which the layer of hard magnetic material generated H_p [5]. These methods allowed the decrease of the apparent energy loss per cycle E by about 50% [5]. However, it was found that such static fields H_p cannot decrease E and H_c below some level, because of the influence of H_p on the surface domain structure and correspondingly increased pinning of the DWs in the vicinity of the surfaces of the sample [6]. However, the dynamic fields H_p (generated by the alternating core current $J = J_0 \sin \omega t$) can decrease the apparent H_c down to zero (providing that they are suitably synchronized with the magnetizing field H [7,8]), which can also be explained in terms of the above mentioned model [8,9]. The measurements have shown that $H_c = 0$ can be achieved over a wide frequency range of the magnetizing field H [10].

It is well known that the energy loss E and H_c in soft ferromagnets increase due to eddy currents [11,12], with increasing frequency of H (dynamic loss). To our knowledge, there was no previous study of the influence of surface fields H_p on the dynamic loss in amorphous ferromagnetic ribbons. In what follows, we discuss the influence of the dynamic field H_p (generated by the alternating core current J) on the loss E and coercive field H_c for the amorphous $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ ribbon at several frequencies of the magnetizing field.

2. *Experimental procedures*

The possibility of the decrease of loss E and H_c has been investigated on a nonmagnetostrictive $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ ribbon (hereafter CoFeSiB) of dimensions $l \times w \times t = 200$ mm × 2 mm × 0.02 mm. All measurements of the M-H loops were performed with an induction technique [13] at room temperature. The variation of H_c and E with the frequency f has been studied in the frequency range $f \leq 120$ Hz. The magnetizing field H had the triangular form with the amplitude 25 A/m which results in the ratio between maximum and saturation magnetization $M_m/M_s \approx 0.97$. The dynamic surface fields H_p were generated by passing the sinusoidal current J along the ribbon during the magnetization measurements. The periodicity of J was always the same as that of the magnetizing field H ($2\pi/\omega = 1/f$), but its phase was adjusted in respect to that of H in order to produce the decrease of H_c with increasing H_p [8,9]. The strengths of the magnetizing field H and the surface fields H_p used in our measurements were comparable to the Earth's magnetic field. However, suitable orientation of the sample made the influence of the Earth's magnetic field on the measured M-H loops negligible. In particular, the sample was oriented in such way that the position C of the center of M-H loop became zero ($C = 0$) in the absence of H_p. In that case, the Earth's field is approximately perpendicular to the directions of magnetization vectors of the domains belonging to the main domain structure.

The variation of the remanent magnetization M_r and H_c with M_m/M_s have been measured in the triangular magnetizing field H with different amplitudes up to 350 A/m, for four different frequencies ($f = 2.2, 10.3, 22$ and 53 Hz). The same frequencies were used for the measurements of variation of H_c vs. H_{p0}.

3. Results and discussion

Figure 1 shows that on increasing frequency f, the M-H loops for the investigated CoFeSiB sample broaden (H_c increases) and, therefore, their areas

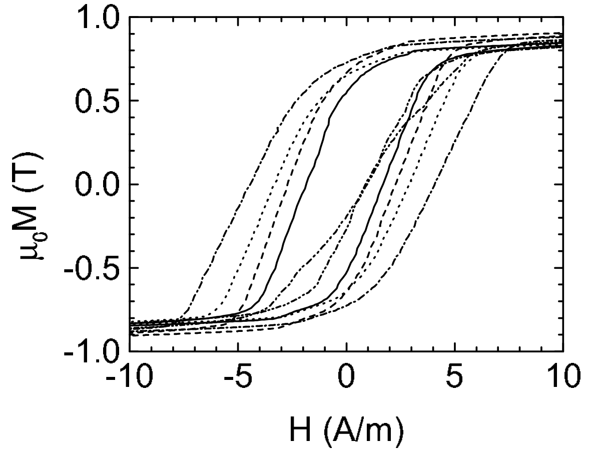

Fig. 1. M-H loops for the $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ *sample measured at frequencies $f = 2.2$ (full line), 10.3 (dashed line), 22 (dotted line) and 53* Hz *(dash-dot line) in the absence of the surface field H_p, and for $H_{p0} = 22$* A/m *measured at frequency $f = 2.2$* Hz *(dash-doubledot line). The measurements were performed with a triangular drive field of an amplitude $H_0 = 25$* A/m.

(energy The variations of H_c and E with f (Figs. 2 and 3) indicate that the main contribution to the enhancement of H_c and E with f is due to the excess eddy currents [12]. In particular, the magnetization processes in the nonmagnetostrictive amorphous ribbons (such as the investigated CoFeSiB sample) are mainly due to the motion of the π-domain walls of the main (inner) domain structure [13,14]. The magnetizations I of these domains form rather small angles δ with the ribbon axis [15]. The analysis of the data shown in Fig. 4 in terms of the model for the influence of the alternating core current on the M-H loops shows that the average angle $< \delta >$ is about 4° for our sample. In particular, in thin long ribbon, the core current J generates the magnetic field H_p which is maximum at the ribbon surfaces $H_{p0} = J_0/(2w)$ (the profile of H_p is shown in the inset in Fig. 4). According to the model for the influence of the surface fields H_p on the magnetization processes in thin ferromagnetic ribbons, the alternating core

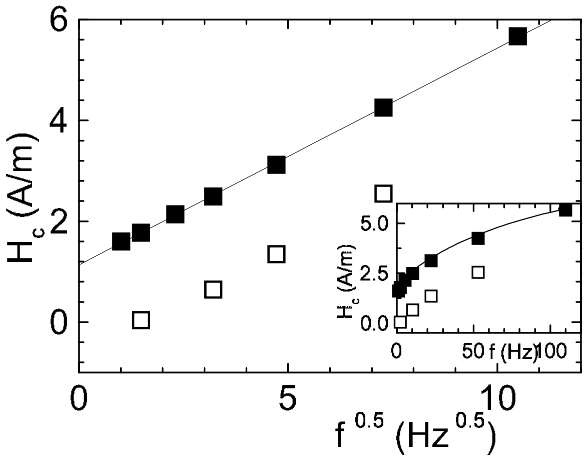

Fig. 2. Variation of the coercive field H_c *with* $f^{0.5}$ *for the* $\mathrm{Co_{70.3}Fe_{4.7}Si_{15}B_{10}}$ *sample in the absence of the surface field* H_p *(□) and for the case when the dynamic surface field (generated by the alternating core current) with the amplitude* $H_{p0} = 22$ A/m *acts on the sample (□). The inset: the same variations of* H_c *with* f*. The magnetizing field of an amplitude* $H_0 = 25$ A/m *was used.*

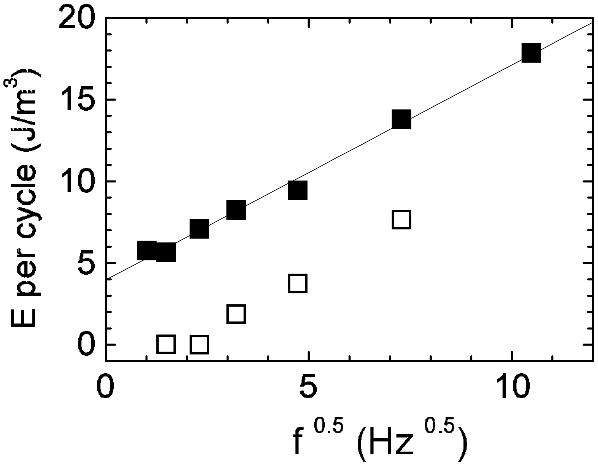

Fig. 3. Variation of the energy loss E *per cycle with* $f^{0.5}$ *for the* $\mathrm{Co_{70.3}Fe_{4.7}Si_{15}B_{10}}$ *sample in the absence of the surface field* H_p *(□) and for the case when dynamic surface field (generated by the alternating core current) of an amplitude* $H_{p0} = 22$ A/m *acts on the sample (□). Other conditions of the measurement were the same as for the results shown in Fig. 2.*

current J (suitably synchronized with H [8]) produces the decrease of the coercive field

H_c [9]:

$$H_c = H_{c0} - H_{p0} \tan < \delta >, \tag{1}$$

where H_{c0} is the coercive field in the absence of J, and $< \delta >$ is the average angle between the magnetizations I of the domains belonging to the main domain structure [14] and the ribbon axis. During their motion, the DWs of the main (inner) domain structure encounter different pinning centres (surface irregularities, chemical inhomogeneities, structural defects, etc. [16]) which cause the coercivity and energy loss in these materials. In the nonmagnetostrictive samples, the strongest pinning centres are located close to the ribbon surfaces [16,17].

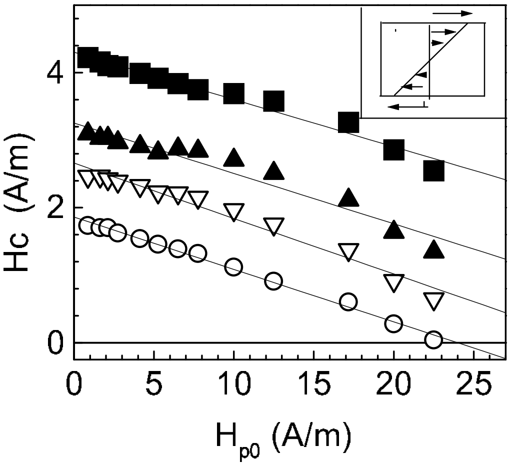

Fig. 4. Variations of the coercive field H_c *in the* $\mathrm{Co_{70.3}Fe_{4.7}Si_{15}B_{10}}$ *sample with the surface field amplitude* H_{p0}*, generated by the alternating core current* J *at the frequencies* $f = 2.2$ *(○), 10.3 (▽), 22 (△) and 53 Hz (□). The magnetizing field of an amplitude* $H_0 = 25$ A/m *was used. The inset: the diagram of the* H_p *profile.*

The variations of $\log H_c$ with $\log(M_m/M_s)$ shown in Fig. 5a confirm that throughout the explored frequency range, three types of pinning centres mainly participate in the magnetization processes. (As observed earlier [18], the $\log H_c$ vs. $\log(M_m/M_s)$ plots consist of three approximately linear parts for all explored frequencies.) Briefly, the slope of $\log H_c$ vs. $\log(M_m/M_s)$ curve is proportional to the strength of the pinning centres which participate in the magnetization processes within the given range of M_m/M_s [13]. Moreover, if within the same range of M_m/M_s, $\log M_r$ increases with $\log(M_m/M_s)$, then the magnetization of the sample proceeds via the irreversible motion of DWs (M_r saturates with M_m/M_s if the reversible DW bulging occurs) [13,18]. Figure 5b shows that the magnetization in our CoFeSiB sample occurs via the irreversible shifts of DWs over the encountered pinning centres (the Barkhausen's jumps) [13,18].

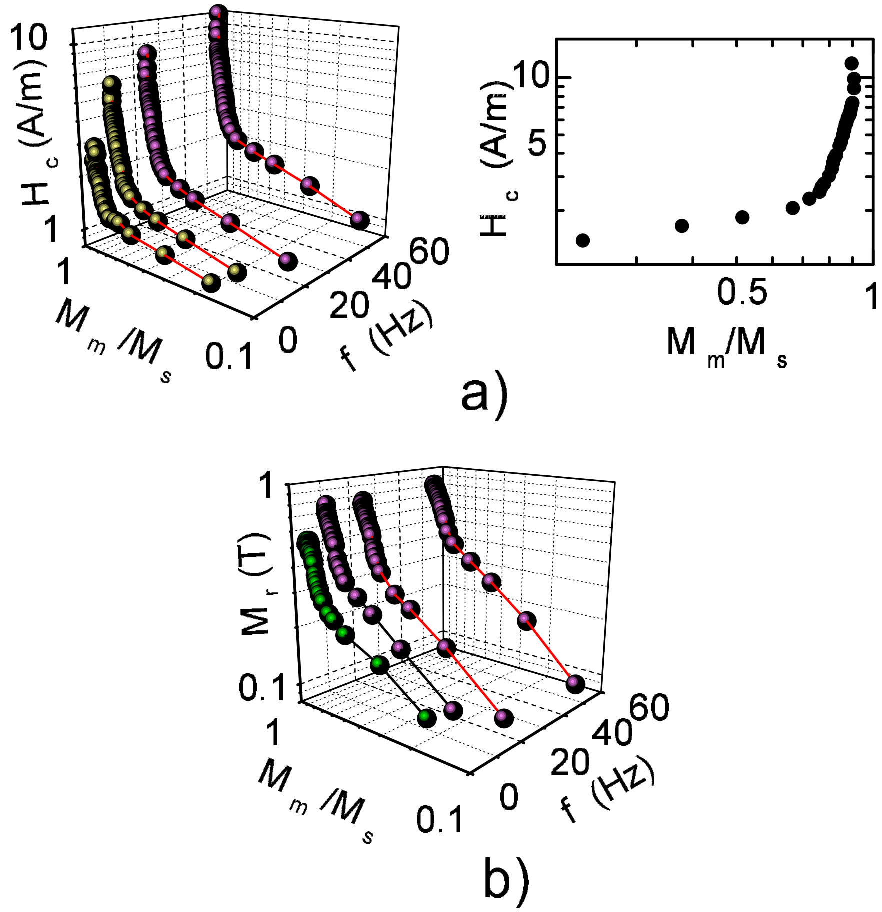

Fig. 5. a) (left). Variation of the coercive field H_c with the normalized magnetization M_m/M_s for the $\mathrm{Co_{70.3}Fe_{4.7}Si_{15}B_{10}}$ *sample and with frequency f of the driving field. The frequency of the driving field was 2.2, 10.3, 22, and 53* Hz*, respectively. a) (right) variation of the coercive field H_c with the normalized magnetization M_m/M_s ($f = 53$ Hz) for the same sample. b) Variation of the remanent magnetization M_r with the normalized magnetization M_m/M_s for the* $\mathrm{Co_{70.3}Fe_{4.7}Si_{15}B_{10}}$ *sample and with the frequency f of the driving field. Other conditions of the measurement were the same as those for the results shown in Fig. 5.a.*

The energy losses associated with the motion of DWs can be divided in different ways. The energy loss, which would be obtained by adding the losses associated with individual DW jumps, represents the histeresis loss which should not depend on the frequency of the magnetizing field [12]. However, if one takes into account the complexity of the real domain structure within the sample, it is clear that the motion of DWs is not mutually independent and, therefore, the total loss is not a simple sum of the elementary losses associated with the individual jumps [12,19]. The appearance of the eddy currents within the sample causes the occurrence of the frequency-dependent energy losses called dynamical losses. The dynamical losses associated with the classical eddy currents (occurring in the regions of homogeneous magnetization) are proportional to the frequency, $E \sim f$ [12]. The losses associated with the superposition of the eddy currents in the vicinity of DWs ("excess" eddy currents) are higher than the classical ones, but they increase slower with f ($E_{ex} \sim f^x$ where $x < 1$) [12]. Since we obtained $H_c \sim f^{0.5}$ and $E \sim f^{0.5}$ (Figs. 2 and 3), it follows that throughout the explored frequency range the losses associated with excess eddy currents dominate the dynamical losses in our CoFeSiB sample. This conclusion is consistent with other results for the amorphous ferromagnetic ribbons [12,20,21].

The data shown in Fig. 4 demonstrate that H_c and E decrease on increasing the amplitude of the dynamic H_p, irrespective of their actual origin (static or dynamic losses). Namely, in the absence of H_p, the variations of H_c and E with f for our sample (Figs. 2 and 3) are well described by the following expressions:

$$H_c = (1.1 + 0.4 \cdot f^{0.5})\mathrm{A/m}, \tag{2}$$

and

$$E = (4 + 1.2 \cdot f^{0.5})\ \mathrm{J/m^3}. \tag{3}$$

From the expressions (2) and (3), we can estimate the static coercive field H_{c0s} (i.e. H_{c0} for $f \to 0) = 1.1$ A/m, and the static energy loss ($f \to 0$) per cycle $E_s = 4$ J/m^3. These results and the data in Figs. 2 and 3 show that H_p decreases both the static and the dynamic contributions to H_c and E. In particular, the decrease of the coercive field (ΔH_c) and loss (ΔE) for $H_{p0} = 22$ A/m (Figs. 2 and 3) is $\Delta H_c \approx 2$ A/m and $\Delta E \approx 6$ J/m^3. Since $\Delta H_c > H_{c0s}$ and $\Delta E > E_s$, it is clear that H_p decreases both the static and dynamic contributions to H_c and loss.

We note that the decreases in H_c and E with H_p are not due to some change of the intrinsic properties of the sample (such as the change in the strength of the pinning centres within the sample). Instead of that, the field H_p simply helps the magnetizing field H to move the domain walls across the pinning centres. In particular, for H_p which is suitably synchronized with H [8], one needs lower field H to shift some DW which is reflected in the M-H loop as lower H_c and E. Because of this, the slope of H_c vs. H_{p0} variation (Fig. 4) does not depend on frequency of the driving field H. This slope depends on the angle $< \delta >$ only as predicted by the model and Eq. (1). Also, at higher values of H_p, H_c and E may take on negative values. We note that the core current transfers considerable electromagnetic energy into the sample. Accordingly, the result $E < 0$ may indicate that part of this energy is transferred into the energy of the magnetic field.

4. Conclusion

Detailed studies of the dynamic M-H loops have shown that the magnetization processes in amorphous CoFeSiB ribbon mainly involve the shifts of DWs belonging to the main (inner) domain structure. The main contribution to the dynamical energy loss E is due to the "excess" eddy currents which arise in the vicinity of DWs ($H_c \sim f^{0.5}$ and

$E \sim f^{0.5}$, Figs. 2 and 3). The M-H measurements in the presence of the alternating core current show that the dynamic surface field H_p decreases both H_c and E, irrespective of their actual origin (static or dynamic). This shows that the desired changes in the M-H loops of the amorphous ferromagnetic ribbons can be achieved over a broad frequency range which may be useful for their applications. Furthermore, our data show that the variation of H_c with f and H_{p0} for CoFeSiB sample can be described by the following expression:

$$H_c = H_{c0s} + Af^{0.5} - H_{p0} \tan < \delta >, \tag{4}$$

where H_{c0s} is the coercive field of the static M-H loop, and A is the coefficient which depends on the internal properties of the sample (such as the structure, pinning centres, domain structure, etc.), and on the range of the maximum magnetization M_m [12]. (A similar expression can be constructed for $E(f, H_{p0})$.) The relation (4) can be graphically represented as 3D-surface (Fig. 6). Such a representation is useful since it allows the prediction of the behaviour of the sample for a given set of parameters (f, H_{p0}) and may also allow the prediction of the results of the investigations on some similar materials. Clearly, the prediction of the behaviour of the system under different (working) conditions is important for its applications.

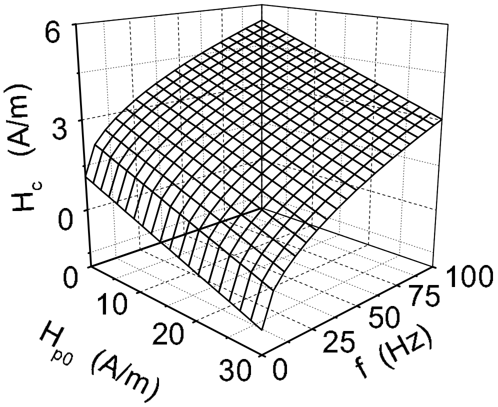

Fig. 6. Variation of the coercive field H_c for the $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ *sample with the surface field amplitude H_{p0} generated by the alternating core current J and with the frequency f of the driving field (Eq. (4) in text).*

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UTJECAJ DINAMIČKIH POVRŠINSKIH POLJA NA KOERCITIVNO POLJE I GUBITKE ENERGIJE U AMORFNOJ VRPCI $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$

Gubitke energije E po jednom ciklusu te koercitivno polje H_c proučavali smo analizom M-H krivulja dobivenih u različitim uvjetima magnetiziranja amorfne vrpce $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$. Primjenom modela za utjecaj površinskih polja H_p na procese magnetiziranja amorfnih feromagnetskih vrpci proučavali smo utjecaj dinamičkih H_p na E i H_c. Pokazuje se da taj utjecaj ne ovisi o porijeklu H_c i E (statički ili dinamički) što je važna činjenica kako za daljnje istraživanje tako i za primjenu ovakvih materijala.