Origin of zero-loss M-H loops in amorphous ribbons carrying an ac current

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M-H loops with a vanishing coercive field H_c and loss E have been obtained for an amorphous $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ ribbon carrying an ac current of appropriate amplitude, frequency, and phase. The actual shape of the ac-current pulse is immaterial as long as the phase and amplitude remain the same. The phenomenon is explained within the framework of the recent model for the magnetization of a ferromagnetic ribbon carrying a dc current. The general condition for the occurrence of $H_c=0$ is derived and some applications of the phenomenon are discussed.

It has been known for some time that an electric current passing along a magnetic ribbon influences its M-H loop.[1,2] Some interesting phenomena such as narrowing, shifting, and slanting of M-H loops have been observed. ac core currents appear to be particularly effective in controlling the M-H loop.[2] Moreover, under rather complex experimental conditions the M-H loop with zero coercive field H_c and loss E has been obtained for Metglas 2826 ribbon. The effect has been ascribed to the shift of two halves of the M-H loop but no explanation of the origin of this shift was given.

More recently, systematic investigation of the effects of dc currents on M-H loops of amorphous ribbons has been performed.[3-5] Since a rather low current used in these experiments ruled out the domain-wall (DW) dragg[6] the above-mentioned phenomena were ascribed to the magnetic field H_p generated by the flow of current.[3,4] Later experiments confirmed this hypothesis and showed that these phenomena do not depend on the actual origin of H_p.[5] This knowledge has been used to produce the prototype composite material with soft magnetic properties exceeding those of the original material.[7] However, contrary to the model predictions[3,4,8,9] M-H loops with zero H_c and E have not been obtained.[9,10] This was ascribed to increased pinning of DW's at elevated H_p (Ref. 9) but no direct evidence has been provided.

In what follows we show that M-H loops with $H_c=0$ can also be obtained for amorphous $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ ribbon (thereafter $Co_xFe_{1-x}SiB$) carrying an ac current. Furthermore, we show that this phenomenon can be explained within the framework of the model for magnetization of amorphous ribbon carrying dc current.[4,8,9] Accordingly, the general condition for the occurrence of M-H loops with $H_c=0$ has been derived and the evidence provided that the pinning strength of DW's increases at elevated H_p. Finally, we propose the use of ac core current in order to deduce the variation of the pinning strength of DW's (responsible for H_c) with H_p and show that $H_c=0$ can be obtained regardless of the actual wave form and frequency of the core current as long as the condition for the occurrence of $H_c=0$ can be fulfilled.

The measurements of M-H loops have been performed with an induction technique[11] at room temperature. In order to facilitate the intercomparison of the present with previous results for dc core current[9] the driving field amplitude $H_0=25$ A/m was consistently used. The drive and sample current (having the same frequency) were synchronized in order to achieve the desired phase difference between the drive field H and the core current J.

Figures 1(a) and 1(b) show the dM/dt vs H curve and the corresponding M-H loop of the $Co_xFe_{1-x}SiB$ sample for $J=0$ and triangular drive field with $f=5.5$ Hz. Figure 1(c) shows dM/dt vs H curves obtained with the same drive field but with dc currents $J=99.6$ mA (dashed line) and $J=-99.6$ mA (full line) flowing along the sample. Note that the lower maximum of dM/dt vs H curve for $J=99.6$ mA is precisely below the upper maximum of dM/dt vs H for $J=-99.6$ mA. As a result, the "negative" branch of M-H loops (corresponds to H decreasing from H_0 towards $-H_0$, thereafter "negative" H) for $J=99.6$ mA overlaps with the "positive" branch (corresponds to "positive" H, i.e., H increasing from $-H_0$ to H_0) for $J=-99.6$ mA [Fig. 1(d)]). Figures 1(e) and 1(f) show dM/dt vs H curve and the corresponding M-H loop for a rectangular ac core current with an amplitude of 99.6 mA. As shown in the inset of Fig. 1(e) $J=99.6$ mA for negative H and $J=-99.6$ mA for positive H has been adjusted. Under these conditions the maxima of dM/dt vs H curve are precisely one below the other [Fig. 1(e)] and M-H loops with overlapping branches,[12] i.e., $H_c=0$, results [Fig. 1(f)].

Figures 1(c)–1(f) make the occurrence of $H_c=0$ self-explanatory. Depending on its direction the dc core current shifts the M-H loop either to $H>0$ (thereafter $J>0$) or $H<0$ (thereafter $J<0$). When these shifts (C) are equal to H_c the positive branch of M-H loops for $J<0$ overlaps with the negative branch of M-H loops for $J>0$ [Figs. 1(c) and (d)]. Accordingly, by changing the direction of J every half cycle as shown in the inset of

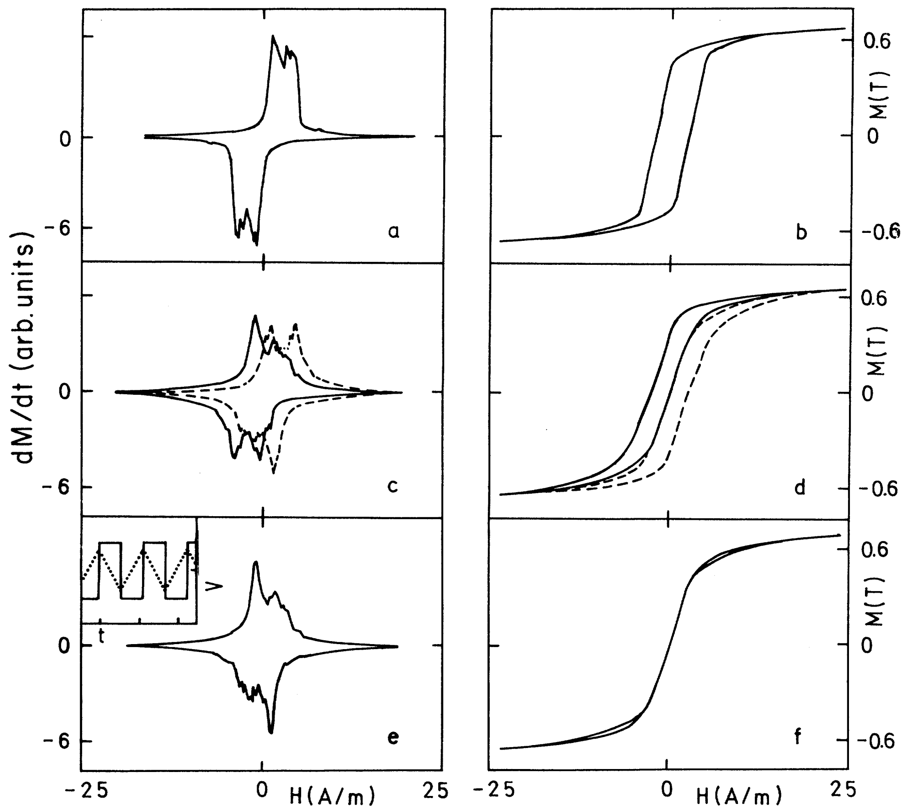

FIG. 1. dM/dt vs H curves and the corresponding M-H loops for the $Co_{70.3}Fe_{4.7}Si_{15}B_{10}$ sample measured at 5.5 Hz with triangular drive field ($H_0=25$ A/m) for different core currents J: (a) and (b) $J=0$; (c) and (d) $J=99.6$ mA (dashed) and -99.6 mA (full line); (e) and (f) rectangular J with the same amplitudes as in (c) and (d). The inset: drive field (dotted) core-current relationship corresponding to (e) and (f).

Fig. 1(e) M-H loops with $H_c=0$ results.

Apparently, the phenomenon can be described in terms of the model for the magnetization of an amorphous ribbon carrying dc current. For the sake of clarity we shall briefly review the main assumptions and results of this model[4,8,9] and then apply the model to the present case.

The model attributes the changes in the width, shape, and position of M-H loops to nonvanishing projection[3,4] of the perpendicular field H_p (generated either by the core current or an external source[5,7]) onto the domain magnetizations (I). Accordingly, when the current flows along the sample the projections of both the drive field H (P_H) and H_p (P) exert the pressure on the domain walls. Therefore, in general, the knowledge of the actual domain structure and the distribution of DW pinning centers is required in order to calculate the M-H loop.

In amorphous ribbons the main process of magnetization seems to be the movement of DW's separating wide domains with antiparallel I.[13,14] Because of this the behavior of two domains separated with 180° DW describes the essential features of the process of magnetization.[4] The actual domain structure can approximately be taken into account through an average angle δ (Refs. 8, 9, and 15) between I (wide domains only) and the length of ribbon (hence $P_H=H\cos\delta$). Different pinning centers dominate the process of magnetization in different ranges of maximum magnetization M_m.[11,16] In particular, in our nonmagnetostrictive $Co_xFe_{1-x}SiB$ ribbon for $M_m \geq 0.5M_s$ (M_s is the saturation magnetization) the strongest pinning centers situated at the surfaces of the ribbon dominate the magnetization.[17,18] Since for $Co_xFe_{1-x}SiB$ $M_m > 0.5M_s$ for $H_0=25$ A/m, $P=(J/2w)\sin\delta$ where w is the width of the ribbon.

The magnetization of the ribbon changes when the algebraic sum of P_H and P reaches the value S required in order to release DW from the particular surface of the sample. In general S is different for opposite surfaces[19,20] and we denote with S_1 and S_2 at the upper and lower surface of the ribbon, respectively. Since DW is always first released from the surface with lower S, assuming $S_1 < S_2$, $H_{c0}=P_{H1}=S_1$ for $J=0$. P_H's required to release DW from the particular surface of the sample when $J\neq 0$ are listed below:

$$P_{H1}=S_1+P \;, \tag{1}$$

$$P_{H2}=S_2-P \;, \tag{2}$$

$$P_{-H1}=-S_1+P \;, \tag{3}$$

$$P_{-H2}=-S_2-P \;, \tag{4}$$

$$P_{H1}^{-}=S_1-P \;, \tag{5}$$

$$P_{H2}^{-}=S_2+P \;, \tag{6}$$

$$P_{-H1}^{-}=-S_1-P \;, \tag{7}$$

$$P_{-H2}^{-}=-S_2+P \;. \tag{8}$$

In particular, P_{-H1} is the projection of H on I required to release DW from the upper surface for negative H ($H_0\rightarrow -H_0$) and $J>0$ whereas P_{-H1}^{-} denotes the corresponding projection for $J<0$. The other labels follow the same pattern. For a given direction of J the width H_c and shift C of M-H loops are determined by the lowest absolute values of P_H in each half (positive and negative H, respectively) of the magnetization cycle.[9,15]

When the direction of J changes during the magnetization cycle [as shown in the inset of Fig. 1(e)] P_H's required to release DW at a given surface for positive H are given with Eqs. (5) and (6), whereas those for negative H should obey Eqs. (3) and (4). Again, the lowest values of P_H in each half cycle (P_{H1}^- and P_{-H1}, respectively) determine H_c and C:

$$H_c=(P_{H1}^- - P_{-H1})/2=S_1-P \ , \tag{9}$$

$$C=(P_{H1}^- - P_{-H1})/2=0 \ . \tag{10}$$

Apparently, for a sufficiently large amplitude of $J(J_0)$, $P\equiv(J_0/2w)\sin\delta=S_1$ and $H_c=0$ results [Figs. 1(e) and 3]. For S_1 independent of H_p Eq. (9) yields a linear decrease of H_c with J [$P=(J/2w)\sin\delta$] and providing that δ is known one can predict the value of J for which $H_c=0$. δ can be determined from H_c vs H_p measurements at low dc core currents[8,9] and for $Co_xFe_{1-x}SiB$ ribbon $\delta\simeq 6°$ has been deduced.[9,15]

The observed and predicted [Eq. (9) assuming $S_1=H_{c0}$] variations of H_c with P are shown in Fig. 2. At elevated $P(H_p)$ the measured values of H_c deviate somewhat from the predicted ones. This seems to confirm that the strength of the pinning centers responsible for H_c increases with H_p (at elevated H_p) which limits the reduction of H_c due to dc core current.[9,15] Indeed for dc core current $H_c=(S_1+S_2)/2-P$ at elevated H_p [$P\geq(S_2-S_1)/2$] hence, any increase of S_1 and S_2 tends to suppress the decrease of H_c (Refs. 9 and 15). By combining the results for dc and ac core current one can deduce both S_1 and S_2 at given H_p. The resulting variation of S_1 with P for $Co_xFe_{1-x}SiB$ ribbon is shown in Fig. 2. We note that $S_1=2.15$ A/m at $H_p=0$ and 2.56 A/m at $H_p=24.9$ A/m ($J=99.6$ mA). Obviously, the use of ac core current as compared to dc current is advantageous because only the increase of S_1 affects H_c.

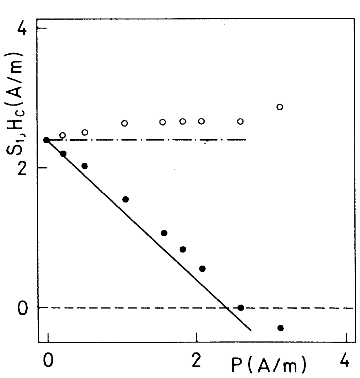

FIG. 2. Variation of H_c (full circles) and S_1 (empty circles) with the projection of field H_p (generated by rectangular core current) for the $Co_xFe_{1-x}SiB$ sample. Full line shows the variation of H_c according to Eq. (9) and assuming constant S_1 (dash dotted).

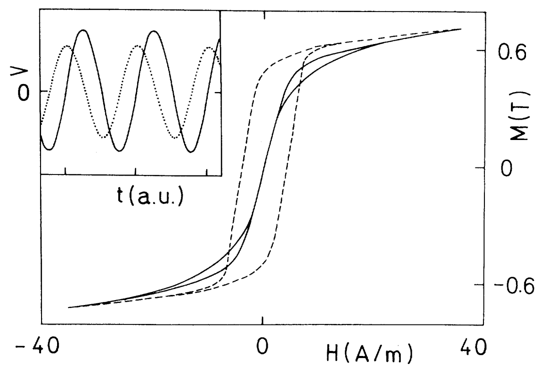

FIG. 3. M-H loop for the $Co_xFe_{1-x}SiB$ sample measured at 12.7 Hz and $H_0=35$ A/m. The inset: the drive field (dotted) core-current ($J_0=135$ mA) relationship.

Although derived for a special case of rectangular core current, the above results are also applicable to other types of core-current pulses. Moreover, when J lags by $\pi/2$ in phase behind H the amplitude of core-current pulse required to obtain $H_c=0$ is the same as that of the rectangular current regardless of its actual shape. This is simply explained in terms of Eqs. (10) and (9) and becomes obvious if one compares the insets in Figs. 1(e) and 3. The use of core-current pulses other than rectangular ones appears to be beneficial because the reduction in M_m associated with dc core current[9,10,15] and rectangular pulses is practically eliminated. This occurs because $H_p=0$ when $H=H_0$ (inset to Fig. 3), hence H_p hardly affects the magnetization at maximum fields. Accordingly, short core-current pulses synchronized with $H=0$ may be the best and the most economic solution.

As shown in Fig. 3 the occurrence of $H_c=0$ is not limited to single (low) frequency only. However at higher frequencies and/or at larger H_0, larger J_0 is required in order to account for larger H_{c0}.

Full control of M-H loops of amorphous $Co_xFe_{1-x}SiB$ ribbon has been achieved by the use of appropriate ac core current. A simple model explains well the observed behavior and yields rather general conditions for the occurrence of zero-loss and coercive field M-H loops. These conditions are not specific to the $Co_xFe_{1-x}SiB$ alloy and, to our knowledge, can be met in several other systems. The success of the very simple model stems from the rather simple pattern of domains[13,14] that constitute the magnetization of amorphous ribbons (and are hence responsible for their excellent soft magnetic properties). The results presented allow the study of the influence of an additional field on the strength of pinning responsible for H_c and, therefore, may help the development of magnetic materials with properties exceeding those of the original materials.[7] Nonhysteretic materials can be used as the cores in flux gates for sensitive magnetometers.

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