THE MODEL FOR THE MAGNETIZATION OF CURRENT CARRYING AMORPHOUS FERROMAGNETS

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A recent model for the explanation of the decrease of coercive field $H_c$ and the core loss $E$ in amorphous ribbons carrying a direct current $J_d$ has been extended in order to account for the effects of an alternating core current $J$. The model predicts a linear decrease of $H_c$ with the amplitude $J_0$ of $J$ and the achievement of $H_c = 0$ for $J_0$ which is sufficient in order to release the domain walls responsible for $H_c$ in the absence of the drive field $H$. The actual shape and frequency of the core current pulses appear to be immaterial as long as the condition $J = J_0$ at $H = 0$ is fulfilled. The accurate measurements performed on the stress-free Co$_{70.3}$Fe$_{4.7}$Si$_{15}$B$_{10}$ and twisted Fe$_{80}$B$_{20}$ ribbons confirm the validity of the model. Some applications of the phenomenon are briefly discussed.

1. Introduction

The earlier investigations have shown that a direct current $J_d$ flowing along an amorphous ferromagnetic ribbon affects its process of magnetization [1-2]. In particular $J_d$ shifts, broadens and decreases the maxima on its $dM/dT$ vs. $H$ curve. This results in M-H loop which is narrower (of a lower coercive field $H_c$) and slanted (of a lower maximum permeability) than that obtained in the absence of $J_d$. Usually $J_d$ also shifts the center ($C$) of the M-H loop [3-4]. It has been shown [3-5] that
these effects are caused by the self-field of $J_d$ which at the surfaces of a thin ribbon has the magnitude $H_p = J_d/2w$ ($w$ is the width of the ribbon). Indeed, the surface fields $H_p$ obtained from the external sources [6-7] produced the same effects on the M-H loops of amorphous ribbons as $J_d$. Accordingly, the effects of $J_d$ on the M-H loops of amorphous ribbons have been attributed to the simultaneous influence of the drive field $H$ and $H_p$ on the movement of the domain walls (DW) responsible for $H_c$.

Recent calculation [8] of the variations of $H_c$ and $C$ with $H_p$ for a hypotetic ribbon consisting of two domains with antiparallel magnetizations $I$ forming a small angle $\delta$ with the ribbon axis confirmed the validity of the above approach. In particular, the calculated variations of $H_c$ and $C$ with $H_p$ agreed quite well with those observed at lower magnitudes of $H_p$ in the nonmagnetostRICTive Co$_{70.3}$Fe$_{14.7}$Si$_{15}$B$_{10}$ (hereafter CoFeSiB) amorphous alloy. However, at the elevated $H_p$ the observed variations deviated strongly from the calculated ones. Whereas the calculation predicted a linear decrease of $H_c$ with $H_p$ and constant $C$, the observed $H_c$ tended to saturation and $C$ showed an anomalous increase with $H_p$. This discrepancy was ascribed to the effects of the elevated $H_p$ on the actual domain structure and the pinning of the DW in real sample. Therefore, it seems impossible to achieve the nonhysteretic M-H loop ($H_c = 0$) by means of $J_d$ (or more generally static $H_p$) in the real amorphous ribbons.

Very recently [9] it was realized that a large increase of $C$ at the elevated $H_p$ can be employed in order to achieve $H_c = 0$ by means of an alternating core current $J$. Here we extend the calculations of Ref. 8 in order to account for an arbitrary $\delta$ and an alternating core current. A rather general condition for the occurrence of $H_c = 0$ by means of $J$ is derived. The predictions of these calculations are verified by measuring the variations of $H_c$ with dynamic $H_p(J)$ for the unstressed CoFeSiB and twisted Fe$_{80}$B$_{20}$ amorphous ribbons. The observed variations agree very well with the predicted ones.

2. Model and calculations

The model for the influence of core currents on the magnetization of the amorphous ferromagnetic ribbons takes into account the following observations:

- the main contribution to the magnetization of the as-quenched amorphous ribbon along its length comes from the stripe domains [10] separated with $\pi$-DW’s,
- the magnetization $I$ of a such domain forms in general an angle $\delta$ with the ribbon axis and this angle is not the same for all domains [11],
- at lower magnetizing fields $H$ the magnetization of the ribbon occurs [12] through the movement of $\pi$-DW’s,
- the strongest DW pinning centers are usually located at the surfaces of the ribbon and their strengths are generally different at the opposite surfaces [13].

Under these circumstances a useful simplification is to consider a ribbon consisting of two domains with magnetizations $I$ separated with $\pi$-DW [5]. We label
the angle between $I$ and the ribbon axis with $\delta$ and denote one surface of the ribbon as the “upper” and the opposite as the “lower”. Accordingly, the strengths of pinning of DW at the upper and lower surface of the ribbon are denoted with $S_u$ and $S_l$, respectively. In order to be specific we assume $S_u < S_l$ and define the average pinning $\langle S \rangle = (S_u + S_l)/2$ and the pinning inhomogeneity $\Delta S = S_l - S_u$. Furthermore, we denote the magnetizing field $H$ as “positive” when it increases from $-H_0$ to $H_0$ ($H_0$ is the amplitude of $H$) and “negative” when it decreases from $H_0$ to $-H_0$.

In the absence of the core current the magnetization changes when the projection of $H$ on $I$, $P_{Hi} = H \cos \delta$ ($i = u, l$) reaches the value $S_i$ which is required in order to release the DW from the particular surface of the sample. Since DW is first released from the surface with the lower pinning strength (the upper in our case) the coercive field will be $H_c = S_u / \cos \delta$.

When direct current $J_d$ flows along the ribbon, its self-field $H_p$ exerts the pressure on DW, too. $H_p$ lies in the plane of the ribbon and has the opposite directions ($H_{pu}$ and $H_{pl}$ in the inset to Fig. 2) at the opposite surfaces of the ribbon. We denote the projections of $H_p$ on $I$ by $P = H \sin \delta$. Under these conditions $P_{Hi}$’s required to release DW for the “positive” $H$ are [8]:

$$P_{H_u} = S_u \mp P$$
$$P_{H_l} = S_l \pm P.$$  

For the “negative” $H$ one has:

$$P_{-H_u} = -S_u \mp P$$
$$P_{-H_l} = -S_l \pm P.$$  

In Eqs. (1)–(4) the upper signs of $P$ corresponds to the directions of $H_{pu}$ and $H_{pl}$ shown in the inset to Fig. 2. Conversely, lower signs corresponds to the opposite direction of $J_d$. The variations of $P_{H_i}$’s and $P_{-H_i}$’s with $P$ (assuming constant $S_u$ and $S_l$) were illustrated in Fig. 1 in Ref. 8. Since the magnetization changes as soon as the projection of $H$ on $I$ reaches the lowest value required in order to unpin DW in the given circumstances (the direction of $H$, the directions and magnitudes of $H_{pu}$’s) only parts of the relations for $P_{Hi}$’s and $P_{-Hi}$’s will be relevant for the determination of the width ($H_c$) and the center ($C$) of the M-H loop. Accordingly [8] the variations of $H_c$ and $C$ with $P$ will depend on the magnitude of $P$. In particular for $|P| \leq \Delta S/2$ is $|P_{Hu}| < |P_{Hi}|$ (Eqs. (1) and (2)) and $|P_{-Hu}| < |P_{-Hi}|$ (Eqs. (3) and (4)) for both signs of $P$. Therfore:

$$H_c = (P_{Hu} - P_{-Hu})/2 \cos \delta = S_u / \cos \delta$$  

and

$$C = (P_{Hu} + P_{-Hu})/2 \cos \delta = \mp P / \cos \delta.$$  

Analogously for $P > \Delta S/2$ is $|P_{Hu}| < |P_{Hi}|$ and $|P_{-Hi}| < |P_{-Hu}|$, hence:

$$H_c = (\langle S \rangle - P) / \cos \delta$$  

and

\[ C = -\Delta S/2 \cos \delta. \tag{8} \]

For the opposite direction of \( J \) is \( |P_{H_u}| < |P_{H_u}| \) and \( |P_{-H_u}| < |P_{-H_u}| \). This changes the sign of \( C \) in Eq. (8) but leaves Eq. (7) unchanged. Apparently the expressions (5)–(8) which are valid for an arbitrary angle \( \delta \) coincide with Eqs. (5)–(8) in Ref. 8 when \( \delta \) is a small angle (\( \cos \delta \approx 1 \)). Furthermore since \( \delta \) is constant in a given case the variations of \( H_c \) and \( C \) with \( P \) shown in Fig. 1 in Ref. 9 are qualitatively the same as those predicted by Eqs. (5)–(8).

We now consider the case when an alternating core current \( J \) flows along the ribbon. The simplest situation occurs when \( J \) has a rectangular waveform and the same frequency as \( H \). For such \( J \) with the phase in respect to \( H \) shown in the inset in Fig. 1 \( P_{H_i} \)'s required in order to release DW are obtained by simple combining the relations (1)–(4) for both directions of \( J \) (signs of \( P \)). One obtains

\[ P_{H_u} = S_u - P \tag{9} \]
\[ P_{H_l} = S_l + P \tag{10} \]

Fig. 1. Calculated coercive field \( H_c \) (---), center of the M-H loop \( C \) (⋯⋯) and corresponding projections (Z) of driving field \( H \) for “positive” (−) and “negative” (⋯⋯) \( H \) (see text) vs. projection \( P_0 \) of the field \( H_{p0} \) caused by rectangular current flowing along the “two-domain” ribbon. The inset: phase relationship between the drive field \( H \) (⋯⋯) and rectangular core current (−).
for “positive” $H$, and

$$P_{-Hu} = -S_u + P$$
$$P_{-Hl} = -S_l - P$$  \hspace{1cm} (11)

for “negative” $H$. Since $|P_{Hu}| < |P_{Hl}|$ and $|P_{-Hu}| < |P_{-Hl}|$

$$H_c = (S_u - P)/\cos \delta$$  \hspace{1cm} (13)

and

$$C = 0$$  \hspace{1cm} (14)

irrespective of the magnitude of $P$. The corresponding variations of $P_H$’s, $H_c$ and $C$ with $P$ (caused with the rectangular core current $J$) are shown in Fig. 1. The parameters $H_{c0}$ and $\delta$ (hence $P$) were adjusted according to the experimental results obtained with direct core current $J_d$ at low $H_p$ for CoFeSiB alloy [8]. Evidently, for constant $S_u$, $H_c$ decreases linearly with $P$ and reaches zero value for $P = S_u = H_{c0}\cos \delta$ (Eq. (13)). We note that when using $J_d$ (Eq. (7)) $H_c = 0$ is expected for $P = \langle S \rangle$. Since $\langle S \rangle > H_{c0}\cos \delta$ the use of $J$ instead of $J_d$ is advantageous. Furthermore in a case of $J$, $H_c$ is insensitive to $S_l$, hence an anomalous increase in $C$ (hence $\Delta S$ and $S_l$) at the elevated $H_p$ which prevented the achievement of $H_c = 0$ by the use of $J_d$ in the CoFeSiB alloy [8] should not affect the decrease of $H_c$ with $P(J)$ for the same alloy. Comparing the condition for the achievement of $H_c = 0$ (Eq. (13)), $P = S_u$, with either Eq. (6) or (7) and (8) one finds that $H_c = 0$ is obtained for the amplitude of $J$ equal to $J_d$ for which $|C| = H_{c0}$. Therfore the achievement of $H_c = 0$ by means of $J$ depends whether the shift of the M-H loop $C$ equal to $H_{c0}$ can be achieved by means of $J_d$ or not. We note that the conditions which are detrimental for the reduction of $H_c$ by means of $J_d$ [8] facilate the achievement of $H_c = 0$ by means of $J$.

The physical meaning of Eqs. (13) and (14) is very simple. They simply state that $H_c = 0$ is achieved when $P(J)$ is sufficiently large in order to unpin DW’s responsible for $H_c$ without the help of $H$ ($H = 0$). Because of this the use of rectangular $J$ is not neccessary in order to achieve $H_c = 0$. Indeed any waveform of $J$ which enables one to achieve $P = S_u$ at $H = 0$ can produce $H_c = 0$ [9]. Movere $H_c = 0$ can also be achieved when the frequency of $J$ is an odd multiple of that of $H$ providing that the phases of $J$ and $H$ are properly adjusted [9].

For $P > S_u$, $H_c < 0$ follows (Fig. 1). This means that two branches of the M-H loop (those corresponding to “positive” and “negative” $H$, respectively) have exchanged their positions, i.e. an inverted M-H loop is obtained.

### 3. Experimental verification

The predictions of the model have been verified by measuring the variations of $H_c$ and $C$ with $H_p$ (generated by $J_d$ or $J$) for the stress-free nonmagnetostrictive
CoFeSiB alloy and twisted magnetostrictive Fe$_{80}$B$_{20}$ (thereafter FeB) alloy. The measurements of the M-H loops have been performed with an induction method [14] at room temperature. All the measurements were performed with the frequency 5.5 Hz [8]. The drive field amplitudes $H_0$ were 25 A/m and 100 A/m for the CoFeSiB and FeB sample, respectively. Two oscillators providing the alternating core current $J$ and the drive field $H$ were synchronized [9] in order to achieve the appropriate phase difference between $H$ and $H_p(J)$. The frequency of $J$ was the same as that of $H$. The rectangular and sinusoidal $J$ have been used for CoFeSiB and FeB sample, respectively.

The variations of $H_c$ and $C$ with $H_p(J_d)$ for the stress-free FeB sample revealed that the pinning inhomogeneity $\Delta S$ is too small in order to achieve $C = H_{c0}$. Since a stress affects strongly both $\langle S \rangle$ and $\Delta S$ of the magnetostrictive alloys [2] the sample was twisted through 360° (the length of the sample was 20 cm) and the measurements performed under these conditions. The resulting variations of $H_c$ and $C$ with $H_p(J_d)$ are shown in Fig. 2.

For $H_p \leq 20$ A/m $H_c$ is practically constant and $C$ increases linearly with $H_p$ (hence $P$) as predicted by the Eqs. (5) and (6). From the slope of $C$ vs. $H_p$ we deduced $\delta \approx 32°$ for twisted FeB alloy. For $H_p > 20$ A/m

Fig. 2. Variation of the coercive field $H_c$ (●) and the center $C$ (○) of the M-H loop with field $H_p$ generated by the direct core current $J_d$ flowing along the twisted Fe$_{80}$B$_{20}$ ribbon. The triangular drive field $H$ with the amplitude $H_0 = 100$ A/m and frequency 5.5 Hz was used. The inset: Schematic drawing of the fields applied to the ribbon. $I$ denotes the domain magnetizations, $H_{pu}$ and $H_{pl}$ are the fields induced by core current at the upper and lower surface of the sample, respectively.
Fig. 3. The comparison of the observed (symbols) and calculated (lines) variations of the coercive field $H_c$ with the projection $P_0$ of the field $H_{p0}$ generated by the amplitude $J_0$ of the alternating core current $J$ for Fe$_{80}$B$_{20}$ (■) and Co$_{70.3}$Fe$_{4.7}$Si$_{15}$B$_{10}$ (□) amorphous alloy. The measurements were performed at 5.5 Hz and the amplitudes of triangular drive field $H$ were 100 A/m and 25 A/m for Fe$_{80}$B$_{20}$ and Co$_{70.3}$Fe$_{4.7}$Si$_{15}$B$_{10}$ alloy, respectively.

$H_c$ decreases approximately linearly with $H_p$ (Eq. (7)) but $C$ continues to increase with $H_p$ although at somewhat lower rate. The increase of $C$ for $H_p > 20$ A/m indicates that $\Delta S$ increases with $H_p$ at elevated $H_p$ as was the case for CoFeSiB alloy [8]. This explanation is consistent with the rather slow decrease of $H_c$ with $H_p$ for $H_p > 20$ A/m (Fig. 2). Since at elevated $H_p$, $H_c \cos \delta = (S) - P = S_u + \Delta S/2 - P$, the reduction of $H_c$ due to sizable $P(\delta)$ is almost offset by the increase of $\Delta S$ for $H_p > 20$ A/m. We note that $C = H_{c0}$ is reached for $H_p \approx 23$ A/m which corresponds to $J_d \approx 92$ mA.

The results obtained with sinusoidal core current $J$ flowing along the FeB sample are shown in Fig. 3. Here the calculated (Eqs. (13) and (14)) variations of $H_c$ and $C$ with $H_{p0}$ ($H_{p0} = J_0/2\pi$, were $J_0$ is the amplitude of $J$) are shown. We note a very good agreement between the experimental results and the model predictions. In particular $H_c$ reaches zero at about 23 A/m and becomes negative for $H_{p0} > 23$ A/m.

The variation of $H_c$ and $C$ with $H_p(J_d)$ for the stress-free CoFeSiB sample have been reported earlier [8] and will not be reported here. For this sample the observed variations of $H_c$ and $C$ with $H_p$ deviated strongly from the model predictions at the
elevated values of $H_p$ [8]. However $C$ reached $H_{c0}$ at about 22 A/m (corresponding
to $J_d \approx 97$ mA).

The variations of $H_c$ with $H_{p0}(J_0)$ for CoFeSiB sample is shown in Fig. 3.
We note that the agreement between the calculated and observed variation for
$H_{p0} \leq 22$ A/m is almost as good as that the twisted FeB sample. In particular
$H_c$ becomes zero at $H_{p0} = 22$ A/m. However for $H_{p0} > 22$ A/m $H_c$ decreases less
rapidly then expected. The comparison of the results obtained for $J_d$ [8] with those
presented here has shown that this occurs due to an increase of $S_u$ with $H_p$ which
sets in for $H_p \geq 25$ A/m. [8,15] As for FeB sample $C \approx 0$ throught the explored
$H_{p0}$ range has been obtained.

4. Conclusion

The calculations along the lines of a simple model for the influence of direct
core current $J_d$ on the M-H loops of amorphous ferromagnetic ribbons have been
extended in order to account for effects of the alternating core currents $J$. Although
the actual calculations were performed for a rectangular $J$ having the same fre-
quency as the magnetizing field $H$, the results obtained are valid for any waveform
of $J$. Particulary, important result is a rather general condition for the occurence of
$H_c = 0$. This condition shows that $H_c = 0$ can be achieved by means of $J$ whenever
the shift $C$ of M-H loop due to $J_d$ can reach $H_{c0}$. Since $C$ is associated with the
pinning inhomogeneity $\Delta S$ and $\Delta S$ can be simply controlled (eg. with the appli-
cation of the stress on the magnetostrictive alloy), it appears that $H_c = 0$ can be
obtained by means of $J$ in almost any ferromagnetic material. This was verified by
comparing the calculated variations of $H_c$ and $C$ with $H_{p0}(J)$ with those observed
for the stress-free CoFeSiB and twisted FeB sample. In both cases the agreement
between the model predictions and experimental results was very good. The reason
that such a simple model explains so well the magnetization processses in amor-
phous ferromagnetic ribbons probably stems from a rather simple main domain
structure of these materials [12]. The possibility to achieve $H_c = 0$ by means of $J$
may be useful for the application in the cores of sensitive fluxgate magnetometers.

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MODEL MAGNETIZIRANJA AMORFNOG FEROMAGNETA KOJIM TEĆE STRUJA

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Orginalni znanstveni rad

Nedavno predloženi model za sniženje koercitivnog polja \( H_c \) i gubitaka energije u feromagnetskim trakama kojima teče istosmjerna struja \( J_d \) proširen je na izmjenične struje \( J \). U slučaju izmjenične struje model predviđa linearno smanjenje \( H_c \) s amplitudom \( J(J_0) \) te dostizanje \( H_c = 0 \) kod vrijednosti \( J_0 \) koja je dostatna da oslobodi domenske zidove koji su odgovorni za \( H_c \) u odsustvu magnetizirajućeg polja \( H \). Sam oblik i frekvencija \( J \) su nevažni dotle dok je \( J = J_0 \) za \( H = 0 \) ispunjeno. Precizna mjerenja izvršena na nenapregnutoj \( Co_{70.3}Fe_{4.7}Si_{15}B_{10} \) i tordiranoj \( Fe_{80}B_{20} \) amorfnoj slitini potvrđuju valjanost modela. Ukratko su razmatrane neke primjene modela te posebno odsustva koercitivnog polja.