STUDY OF THE POSITION OF THE DOMAIN WALL PINNING CENTRES WITHIN THE Co\textsubscript{70.3}Fe\textsubscript{4.7}Si\textsubscript{15}B\textsubscript{10} AMORPHOUS RIBBONS

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Dedicated to Professor Mladen Pai\u010d on the occasion of his 90\textsuperscript{th} birthday

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Variations of the positions and strengths of the domain wall pinning centres within an amorphous Co\textsubscript{70.3}Fe\textsubscript{4.7}Si\textsubscript{15}B\textsubscript{10} ribbon were studied by means of a model for the influence of the surface fields $H_p$ on the process of magnetization of amorphous ribbons. The strongest pinning centres are situated close to the free surface of the ribbon and the strength of the pinning centres decreases towards its centre.

1. Introduction

Main contribution to the magnetization of amorphous ferromagnetic ribbons along their length is associated with the motion of the $\pi$-domain walls (DW) of the main domain structure (MDS) [1,2]. At low frequency of the magnetizing field $H$ the coercive field $H_c$, and the hysteresis loss $E$ (the area of the $M - H$ loop) arise due to the pinning of the DW's at the pinning centres which they encounter during their motion [3]. Because of this, the knowledge of the types of the pinning centres and their distributions within the ribbons are important, both for a
better understanding of the magnetization processes, and in order to develop new materials with better soft magnetic properties.

It is known that a direct current (DC, $J_\text{D}$) and alternating current (AC, $J_\text{A}$) affect the process of magnetization of amorphous ferromagnetic ribbons [4,5]. In particular, $J_\text{D}$ shifts and changes the shape of the maxima of the $dM/dt$ versus $H$ curve [6]. This affects some parameters of the $M-H$ loop, such as $H_\text{c}$, the remanent magnetization $M_r$, the maximum permeability $\mu_{\text{max}}$, and in some cases the maximum magnetization $M_m$. Usually, $J_\text{D}$ also shifts the center $C$ of the $M-H$ loop [7]. A simple model that explains these effects in terms of the field $H_p$ generated by $J_\text{D}$ has been proposed [8]. A number of the experiments [8,9] proved the validity of the model.

$AC (J)$ can produce $H_\text{c} = 0$ in some amorphous ribbons [10]. This phenomenon can also be explained in terms of the model developed for $J_\text{D}$ [10]. It has been shown that large difference between the strengths of the pinning centres situated close to the opposite surfaces of the ribbon ($\Delta S$) facilitates the achievement of $H_\text{c} = 0$.

Here we show how the model for the influence of $H_p$ on the magnetization of amorphous ribbons enables the approximate determination of the positions of the DW pinning centres within the samples, and also the determination of the samples surface near which the pinning of the DW’s is stronger. The knowledge which side of the ribbon accommodates the stronger pinning centres is important in a case when one wishes to increase or decrease artificially $\Delta S$. (The increase of $\Delta S$ can then be used to achieve $H_\text{c} = 0$ by means of $J$).

2. Model

As previously described [6-10], we consider a hypothetical ribbon consisting of two domains separated by $\pi$-DW. The domain magnetizations $I$ forms an angle $\delta$ with the ribbon axis. We label one surface of the ribbon as the “upper” and the opposite as the “lower” one. Accordingly, we denote the strengths of the pinning centres close to upper and lower surfaces of the sample by $S_u$ and $S_l$, respectively, and, for the calculational purposes, we assume $S_u < S_l$. We also define the average pinning strength $< S > = (S_l + S_u)/2$ and the pinning inhomogeneity $\Delta S = S_l - S_u$.

The magnetizing field $H$, increasing from $-H_0$ to $H_0$ ($H_0$ is the field amplitude), is taken as “positive” ($H > 0$), whereas that decreasing from $H_0$ to $-H_0$ as “negative”. The magnitude of $H$ required to release DW in the absence of the core current from the upper and lower surface of the sample we denote by $H_{\text{su}}$ and $H_{\text{sl}}$, respectively. The corresponding quantities, when the core current flows, are $H_{\text{su}}$ and $H_{\text{sl}}$ (for $H > 0$) and $H_{\text{su}}$ and $H_{\text{sl}}^-$ (for $H < 0$). The projection of the field $H_p$ generated by the core current on $I$ we denote by $P$. Clearly, depending on the direction of $J_\text{D}$, $P \neq 0$ results.

As shown earlier [9-11], when $J_\text{D}$ flows along the ribbon, one finds

\[ H_\text{c} = H_{\text{sl}}, \]
for $P \leq \Delta S/2$, and
\[ H_c = \langle S \rangle / \cos \delta - H_p \tan \delta, \]
and
\[ C = \mp \Delta S/2 \cos \delta, \] (2)
for $P > \Delta S/2$. The signs in Eqs. (2) and (4) correspond to the two directions of $J_D$ [9]. For thin long ribbon, $H_p = yJ_D/\omega t$, where $w$ and $t$ are width and thickness of the ribbon and $y$ is the vertical distance from the centre of the ribbon ($-t/2 \leq y \leq t/2$) [5]. Therefore, for $P \leq \Delta S/2$, the centre $C$ of the $M-H$ loop shifts linearly with $J_D$. The slope of the $C(J_D)$ variation is
\[ \Delta C/\Delta J_D = y \tan \delta / \omega t. \] (5)
This slope can provide the interesting information about the positions ($y$) from which DW’s are released and about the angle $\delta$. The diagrams showing the variations of $H_c$, $C$ and the depinning field $H_S$ of DW with $H_p(J_D)$ are shown in Fig. 1 of Ref. 9.

The surface field, $H_p$, can also be produced by external sources [11,12]. If such field acts at the upper surface of the sample only (inset to Fig. 1), the magnetizing fields required to release DW from the upper and lower surface of the ribbon, respectively, are
\[ H_{su} = H_{su0} \mp H_p \tan \delta, \] (6)
\[ H_{sl} = H_{s0}, \]
\[ H_{su}^- = -H_{su0} \mp H_p \tan \delta, \] (7)
\[ H_{sl}^- = -H_{s0}. \] (8)
The upper signs in Eqs. (6) and (8) correspond to the direction $H_p$ shown in the inset to Fig. 1, and the lower ones to the opposite direction of $H_p$. For $H_p$ acting on the “lower” surface only follows:
\[ H_{su} = H_{su0}, \] (9)
\[ H_{sl} = H_{s0} \mp H_p \tan \delta, \] (10)
\[ H_{su}^- = -H_{su0}, \] (11)
\[ H_{sl}^- = -H_{s0} \mp H_p \tan \delta. \] (12)
According to the relations (6) to (13), $H_c$ does not change with $H_p$ for $P \leq \Delta S/2$ both for $H_p$ acting at the “lower” and the “upper” surface of the sample. When $H_p$ acts at the “upper” surface only, $C$ obeys Eq. (4) and for $H_p$ acting on the “lower” surface, $C = 0$, all for $P \leq \Delta S/2$.

For $P > \Delta S/2$, $H_c$ decreases linearly with $H_p$ both for $H_p$ acting at the “upper” and “lower” surface only:

$$H_c = \frac{<S>}{\cos \delta} - H_p \tan \delta/2.$$  \hfill (14)

Within the same regime for $H_p$ acting at the “upper” surface only, one finds for $C$

$$C = \mp(\Delta S/2 \cos \delta + H_p \tan \delta/2).$$  \hfill (15)

The corresponding relation for $H_P$ along the "lower" surface is

$$C = \mp(-\Delta S/2 \cos \delta + H_p \tan \delta/2).$$  \hfill (16)

Fig. 1. Variations of the coercive field $H_c$, position of the centre of the $M-H$ loop $C$ and depinning fields $H_s$ and $H_{s-}$ (required in order to release DW’s for the "positive" and "negative" $H$, respectively) with the surface field $H_p$ for the case when $H_p$ acts on the "upper" surface of the ribbon only. The inset: schematic representation of fields acting on the sample when $H_p$ is applied to the "upper" surface only ($I$ is the domain magnetization).

Fig. 2. Variations of the same quantities from Fig. 1 in a case when $H_p$ acts at the lower surface only. The inset: schematic representation of the fields acting on a sample (right).

Graphical representation of the above relations is given in Figs. 1 and 2. Obviously, the measurements with an external $H_p$ applied first to one and then to the other surface of the ribbon allows (by the use of the above relations) to determine which surface of the ribbon is closer to the stronger DW pinning centres.
3. Experimental

The investigation of the DW pinning centres has been performed on an amorphous nonmagnetostrictive Co\textsubscript{70.3}Fe\textsubscript{4.7}Si\textsubscript{15}B\textsubscript{10} (hereafter CoFeSiB) alloy. All measurements were performed on the same sample in a form of ribbon with the dimensions $l \times w \times t = 200$ mm $\times 2$ mm $\times 0.02$ mm. The magnetization measurements were performed using the induction technique [13] at room temperature. The triangular drive field $H$, with the frequency 5.5 Hz, has been used. In order to access the distribution of the strengths of the pinning centres dominating the process of magnetization in different ranges of $M_m$, the $M - H$ loops have been measured for different amplitudes $H_0$ of the drive field $H$. In order to determine the positions within the ribbon of the pinning centres governing the variations of the parameters of the $M - H$ loops for a given $M_m$, $J_D$ has been passed along the sample during the magnetization measurements. In order to determine the surface of the ribbon exhibiting the stronger pinning of DW’s, we used the combination of the homogeneous field $H_z$ achieved with the Helmholtz pair of coils and the field $H_i$ generated with the direct core current $J_D$, as illustrated in Fig. 3. Obviously, for the properly selected $J_D$, one achieves $|H_i| = |H_z|$, in which case the resultant field $H_p$ is zero at one surface (lower in Fig. 3) of the ribbon. On the opposite surface, $H_p = H_i + H_z$. The profile of the magnetic field within the sample, which may be expected in this case is shown in the inset to Fig. 3.

Fig. 3. Drawing illustrating the method for production of field acting on one surface of the sample (“upper”) by using the combination of constant field $H_z$ (generated by the Helmholtz coils) and field $H_i$ generated by constant current $J_D$ flowing along the sample. The inset: field profile within the sample.

4. Results

The variations of $H_c$ and $M_r$ with $M_m/M_s$ ($M_s$ is the saturation magnetization) for CoFeSiB sample in the absence of $H_p$ are shown in Fig. 4. As reported in Ref.
both \( H_c \) and \( M_r \) show somewhat different variations in different ranges of \( M_m/M_s \). In particular, \( H_c \) shows power low variations \( H_c \sim (M_m/M_s)^\alpha \) with the exponent \( \alpha \approx 0.15 \) for \( M_m/M_s \leq 0.5 \), \( \alpha \approx 1.1 \) for \( 0.5 < M_m/M_s < 0.75 \) and \( \alpha \approx 6.4 \) for \( M_m/M_s > 0.75 \), which agrees well with the earlier results for different samples of the same alloy [14]. The regions of \( M_m/M_s \), corresponding to the values of \( \alpha \approx 0.15, 1.1 \) and 6.4, are labeled with I, II and III, respectively, in Figs. 4 and 5. \( M_r \) also shows different variations in the same three regions of \( M_m/M_s \) (Fig. 4). In particular, the increase of \( M_r \) with \( M_m/M_s \) is slower in the region I, then in II and \( M_r \) tends to saturate in the region III.

The slopes of variation of \( C \) versus \( J_D \) (measured within the range of \( J_D \) values over which \( C \) varies linearly with \( J_D \)), \( \Delta C/\Delta J_D \), initially increase with \( M_m \) but tend to saturate for \( M_m/M_s > 0.75 \) (Fig. 5). Comparing the variation of \( \Delta C/\Delta J_D \) with \( M_m/M_s \) with that of \( H_c \) with \( M_m/M_s \) (Fig. 4), we note that in the region I \( \Delta C/\Delta J_D \) increases rapidly with \( M_m \) and reaches the value of about 15 m\(^{-1}\) at the end of this region. The increase of \( \Delta C/\Delta J_D \) is slower in the region II (\( \Delta C/\Delta J_D \leq 21.5 \) m\(^{-1}\)) and \( \Delta C/\Delta J_D \) seems to saturate in the region III at the value 22 m\(^{-1}\). As illustrated in Fig. 6a, the variations of \( C \) with \( J_D \) remain linear. Moreover, both the variation of \( H_c \) with \( J_D \) (approximately constant) and \( C \) with \( J_D \) (linear) show that the measurements were performed in the conditions \( P < \Delta S/2 \).

Fig. 4. Variations of the remanence \( M_r \) and coercive field \( H_c \) of Co\(_{70.3}\)Fe\(_{4.3}\)Si\(_{15}\)B\(_{10}\) amorphous sample with maximum magnetization \( M_m \) normalized to the saturation magnetization \( M_s \). Numbers I, II and III denote regions with different variations of \( H_c \) and \( M_r \) with \( M_m/M_s \). The triangular drive field with frequency 5.5 Hz was employed.

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Fig. 5. The slope ($\Delta C / \Delta J_D$) of the variation of the position of $M - H$ loop centre $C$ with the constant current $J_D$ flowing through the $\text{Co}_{0.3}\text{Fe}_{4.7}\text{Si}_{15}\text{B}_{10}$ sample versus the normalized maximum magnetization $M_m / M_s$ in different regions of $M_m / M_s$ (denoted with I, II and III, respectively). The inset: illustration of the positions of the pinning centres effective in the regions I, II and III $M_m / M_s$. The frequency of the triangular drive field was 5.5 Hz.

Fig. 6. Variation of the coercive field $H_c$ (circles) and the position of the centre of the $M - H$ loop $C$ (triangles) for $\text{Co}_{0.3}\text{Fe}_{4.7}\text{Si}_{15}\text{B}_{10}$ sample with: a) the field $H_p$ generated by the direct core current $J_D$ (open symbols), and $H_p$ acting on “upper” surface only (solid symbols); b) the field $H_p$ acting on “lower” surface only. The amplitude of the triangular magnetizing field was $H_0 = 25$ A/m and the frequency $f = 5.5$ Hz.
The results of the measurements performed with the field $H_p$ at one surface of the ribbon only are shown in Fig. 6 with the solid symbols. Fig. 6a shows that for $H_p$ applied at the upper surface only, $C$ decreases linearly with $H_p$ with the slope $\Delta C/\Delta H_p \approx 0.082$, which is close to that observed in a case of the core current $J_D$ only. The total change of $C$ within the employed interval of $H_p$ is about 3.5 A/m, again essentially the same as in the case of $J_D$ (giving approximately the same $H_p$) only. As shown in Fig. 6b, when $H_p$ is applied at the lower surface of the ribbon only, $C$ shows, within a considerable scatter of the data, only a weak variation with $H_p$. The total change of $C$ within the same interval of $H_p$, as in Fig. 6a, is only about 0.75 A/m, which is about five times smaller than in a case of $H_p$ applied at the upper surface only. The coercive field $H_c$ is in both cases ($H_p$ applied to the upper or lower surface only) approximately constant, which means, according to the model, that the condition $P < \Delta S/2$ is fulfilled.

5. Discussion

Several types of DW pinning centres (such as the structural defects in the magnetostrictive alloys, the intrinsic fluctuations in the exchange energy and local anisotropy, the surface defects (irregularities, the chemical inhomogeneities etc.) contribute to coercivity of amorphous ferromagnets [3]. The different variations of $M_r$ and $H_c$ with $M_m$ in the different regions $M_m/M_s$, observed both in the magnetostrictive and nonmagnetostrictive amorphous ferromagnets, indicate that different types of DW pinning centres dominate the process of magnetization in different regions of $M_m/M_s$. In particular, at lower $M_m$, the depinning of DW’s from the weaker pinning centres is likely to dominate, whereas at elevated $M_m$, the stronger pinning centres seem to affect the magnetization of the sample [14]. Indeed a larger slope of the log $H_c$ vs log($M_m/M_s$) plot in Fig. 4 at elevated $M_m$ indicates that the stronger pinning centres are effective at higher $M_m$ [14]. The present (Fig. 4), as well as the earlier results [14], indicate that in the nonmagnetostrictive CoFeSiB alloys at least three types of pinning centres with different strengths can be associated with different dependences of $M_r$ and $H_c$ with $M_m$ in three regions of $M_m/M_s$. As seen from Fig. 5, $\Delta C/\Delta J_D$ (which according to Eq. (6) depends both on the vertical distance of the pinning site from the centre of the ribbon and the angle $\delta$) also shows different variations with $M_m$ in the same three regions of $M_m/M_s$. Since the real samples posses a rather complex domain structure (i.e., different groups of domains form somewhat different angles $\delta$ with the ribbon axis [15]), we replace $\delta$ with an average value $< \delta >$. For the rest of this discussion, we will assume that $< \delta >$ does not change with $M_m$, hence $\Delta C/\Delta J_D$ depends on the distance $y$ of effective pinning centres from the centre of the ribbon only. Clearly, the region III in Figs. 4 and 5 is associated with the strongest DW pinning centres. Since $\Delta C/\Delta J_D$ saturates in this region (Fig. 5), this probably indicates that these pinning centres are situated at the largest $y$, i.e., close to the surface of the ribbon ($y = t/2$). This conclusion is consistent with the earlier experiments in which the etching of the surfaces of the samples caused a rapid decrease of $H_c$ [16]. Since $\Delta C/\Delta J_D$ is proportional to $y$ for constant $\delta$ (Eq. (6)), we can determine the
approximate positions of the different pinning centres as illustrated in the inset to Fig. 5. By using Eq. (6), we estimate that the weakest DW pinning centres (region I in Fig. 4) are situated in the interior of the ribbon within about 9μm from its centre, whereas the stronger ones (corresponding to region II in Fig. 4) are at larger distances y. Obviously, the borderlines between the different regions are not sharp, because in the real sample there should exist some distributions in the pinning strengths and, hence, some kind of gradual change in the average pinning strength on going from the centre towards the surface of the sample. The strongest pinning centres are, however, situated close to the sample surface and can, therefore, be associated with the surface irregularities and inhomogeneities [3].

In the model for the influence of $H_p$ on the magnetization of amorphous ribbons we assumed the different pinning strengths at the opposite surfaces of the ribbon ($\Delta S \neq 0$). Indeed, during the production of the amorphous ribbons (melt-spinning), one side of the ribbon is in the contact with the roller (“contact” surface) whereas the other is free (“free” one). Because of this, the surface irregularities (and presumably the inhomogeneities) are different on the two surfaces, which leads to different pinning of DW’s [3]. The different variations of C with $H_p$ (Fig. 6) for $H_p$ on the “contact” and “free” surface of the ribbon, respectively, support the different pinning of DW’s at the two surfaces. (In our experiments the “contact” surface was the “upper” one and the “free” surface was “lower” one). In particular, a linear change of C with $H_p$ for $H_p$ acting on the “contact” (“upper”) surface shows, according to Eq. (4) that the pinning centres at this surface are weaker then those at the “free” surface. Conversely, a weak irregular change of C with $H_p$ acting on the “free” (“lower”) surface is consistent with the stronger pinning of DW’s at this surface.

6. Conclusion

The detailed measurements of the magnetization of the amorphous ferromagnetic CoFeSiB ribbon have shown that the strongest DW pinning centres are situated in the immediate vicinity of the surface of the ribbon and that the strength of the pinning centres decreases towards the centre of the ribbon. The calculation shows that the model for the influence of the "surface" field $H_p$ on the process of magnetization of amorphous ribbons can be used for the approximate determination of the positions of the different DW pinning centres within the ribbon.

In addition, the model has been extended to the case in which $H_p$ acts on only one surface of the sample. Depending whether $H_p$ acts on the surface containing stronger or weaker DW pinning centres, a different variation of C with $H_p$ is predicted. This finding enabled us to show that in the employed as-prepared non magnetostrictive CoFeSiB alloy, the stronger pinning centres are situated at the "free" surface of the ribbon. The method employed in this paper is non-destructive and can be employed for any kind of amorphous or conventional ferromagnets in a form of a ribbon. This is important because the effects of the various surface treatments aimed for the improvement of the magnetic properties of these materials can be easily monitored.
References

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PROUČAVANJE POLOŽAJA CENTARA ZAPINJANJA DOMENSKIH ZIDOVA U AMORFNOJ Co<sub>70.3</sub>Fe<sub>4.7</sub>Si<sub>15</sub>B<sub>10</sub> VRPCI

Korištenjem modela za utjecaj površinskih polja $H_p$ na proces magnetiziranja amorfnih feromagnetskih vrpci proučavan je položaj i jakost centara zapinjanja unutar amorfinog Co<sub>70.3</sub>Fe<sub>4.7</sub>Si<sub>15</sub>B<sub>10</sub> vrpca. Rezultati mjerenja, dobiveni djelovanjem polja $H_p$ samo na jednoj površini, pokazuju da se jači centri zapinjanja nalaze na površini koja u procesu proizvodnje nije bila u kontaktu s valjkom. Ta činjenica je važna za daljnje tretiranje uzorka radi poboljšanja mekih magnetskih svojstava amorfnih feromagnetskih vrpci.