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THE INFLUENCE OF DOMAIN STRUCTURE ON THE VARIATION OF COERCIVE FIELD AND MAXIMUM MAGNETIZATION OF $Fe_{77.5}B_{22.5}$ AMORPHOUS ALLOY

MARKO KOLANOVIĆ and DAMIR PAJIĆ

Department of Physics, Faculty of Science, P.O.Box 162, University of Zagreb, 10001 Zagreb, Croatia

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The magnetic hysteresis of $Fe_{77.5}B_{22.5}$ amorphous ribbon has been studied by the induction method. The results for coercive field (H_c), maximum magnetization (M_m) and remanent magnetization (M_r) are explained by the twofold domain structure of amorphous alloys in form of ribbons. The analysis of the measurements shows that the inner domains are responsible for the magnetization up to about 65% saturation magnetization (M_s) and that the interaction between two domain structures plays an important role in enhanced increase of H_c on $M_m > 0.5\ M_s$. The frequency dependence of parameters of the hysteresis curve is briefly discussed.

1. *Introduction*

The discovery of the soft magnetism in amorphous alloys allowed considerable improvement of some devices that use soft magnetic materials. Since in present-day technology the most widely employed magnetic materials are soft ferromagnets, further improvement of their properties is of particular importance. In order to obtain information that will help the development of soft magnetic materials, a detailed study of the processes associated with the magnetization in such materials is required. Although these processes have been extensively studied and their general features are rather well understood, some details are still not well explained.

In order to analyse and explain the variation of parameters of magnetic hysteresis curve during the process of magnetization of $Fe_{77.5}B_{22.5}$ amorphous magnetostrictive alloy, systematic measurements of the hysteresis curves have been performed at different frequencies and driving field amplitudes.

It is known [1] that amorphous alloys in the form of long straight ribbon exhibit two different domain structures: a narrow one in spaced surface domain structures with irregular maze domain patterns, partly similar to fingerprints (hereafter domains A), and several orders of magnitude wider, long inner domains which are responsible for magnetization up to 0.7 M_s and which are parallel at a small angle to the ribbon axis. This kind of domain structure was directly observed by use of the magnetotactic bacteria method [2] (domains A) and Kerr–effect laser–scanning technique [3]. All measurements of the hysteresis loops (which yielded parameters H_c, M_r, M_m) have been performed on a sample of amorphous alloy $Fe_{77.5}B_{22.5}$. The sample was produced by melt-spinning [4] in an inert atmosphere and was in form of a long straight ribbon. According to the results of Refs. 1 and 2, for dimensions of our sample, width of domain B is of the order of a few tenths of a millimetre and width of domain A of order of a micrometer.

The aim of this work is to explain the variation of parameters of hysteresis curves, in particular of M_m and H_c, assuming the existence of two domain structures and their interaction.

2. Experimental

Measurements of the hysteresis curves were made by an induction method [5]. The experimental set–up consisted of two mutually perpendicular coils, 180 mm long and 18 mm in diameter, connected in series. Triangular current from the signal generator was passed through the coils. The pick-up coil with 3000 turns, 12 mm long and 5.2 mm in diameter, was placed in the middle of the primary coil. An additional secondary coil, connected in opposition to the pick–up coil, was placed in the second primary coil in order to compensate the signal from the pick–up coil when no sample was placed in it.

The induced voltage across a standard resistor is proportional to the time derivative of magnetization of our sample, and the strength of the magnetic field is proportional to the current passing through the primary coils. Experiment yielded the $\mathrm{d}M(H)/\mathrm{d}t$ dependence that was stored in a computer for further analysis. Some of measurements (at large drive field amplitudes) have been performed with a vibrating–sample magnetometer (VSM).

3. Results and discussion

The variation of maximum magnetization with driving field amplitude at the frequency of 6 Hz is shown in Fig. 1.

Driving field H is a parameter whose influence on the system is determined by the amplitude H_0 and frequency f, while M_m is a parameter that represents final domain configuration, as the system's response to the driving field. After rapid increase up to a driving field amplitude of 70 A/m, increase of M_m slows down and tends to saturate to a value of approximately 1 T. Measurements of magnetization at saturation with VSM at driving field amplitude of 0.1 T yielded $M_s = 1.45$ T. Experimental results show the existence of two regimes in the process of magnetization. At small driving fields, magnetization is caused by the change of volume of domains B. Relatively small driving fields are needed to set in motion the walls of the domains B, and maximum magnetization achieved by changing volume domain structure of the bulk is about 65% M_s. This is in agreement with the estimation of Ref. 3 about the contribution of domains B in volume of the sample. It should be noted that regions of influence of domains A and B on sample magnetization are not clearly separated. In the transition region between two regimes, increase of magnetization is slowed down by bulging of domain B region to the surface, annihilation of domain walls in region of domains B and rotations of magnetization of domains B in the direction of the driving field (parallel to the ribbon axis). On the basis of a model for magnetization of amorphous ribbons carrying DC current [6], we find that magnetization of domains B is at an angle $\delta \approx 6^o$ to the ribbon axis.

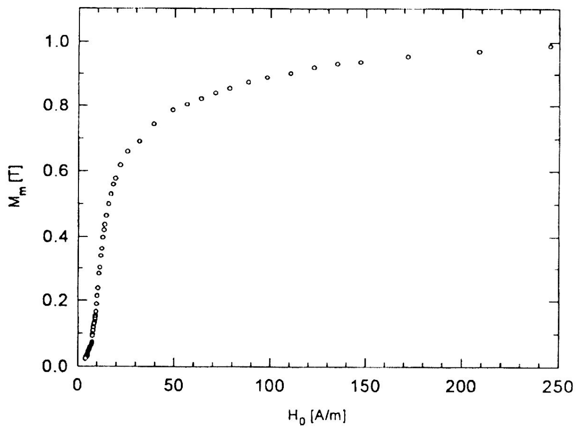

Fig. 1. Variation of maximum magnetization with driving field amplitude at the frequency of 6 Hz.

The dependence of the coercive field H_c on maximum magnetization M_m up to 1 T at six frequencies is shown in Fig. 2. The region of 0.8 T $< M_m <$ 1 T is transitional region in which changes of the domain structure of the bulk (domains B) end, and pronounced changes in surface domain structure (domains A) begin.

One can notice three qualitatively different types of variation of H_c within the explored range of M_m. In the range $M_m < 0.2$ T, the increase is fast. It is caused by the Barkhausen jumps of domain walls at weaker pinning centres. Sudden depinning of domain walls is followed by an increase of the volume of domains favourably oriented with respect to the driving field and in the generation of eddy currents. Fast increase of losses in this region results in fast increase of H_c. This enhanced increase is plausible because hysteresis curves develop from almost reversible lines to broad hysteresis curves of the well–known shape. In the region of 0.2 T $< M_m <$ 0.8

T, the increase of H_c is slower. In this region, as in the preceding one, processes of magnetization are determined by movement of walls of domains B. This region shows the best soft–magnetic properties, what is important for their industrial application. In the region $M_m > 0.8$ T, the increase of H_c is enhanced.

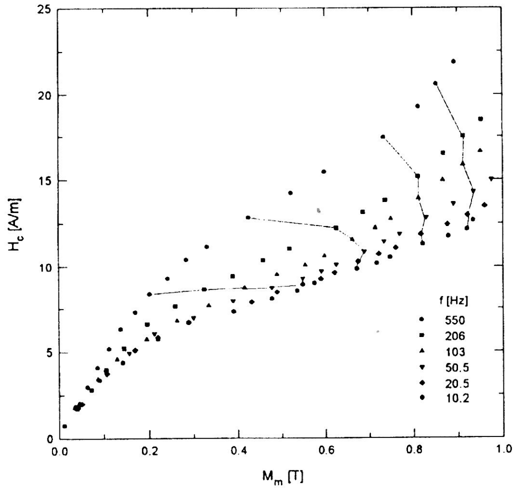

Fig. 2. Dependence of coercive field on the maximum magnetization at different frequencies. Points for which the driving field had the same amplitude, are connected by lines.

Points in Fig. 2, corresponding to the same amplitudes of the driving field, are connected by lines. With the help of these lines, we can simply explain the influence of frequency of driving field on the sample magnetization and determine the boundary (i.e. transition region) between domination of domains A and domains B in the process of magnetization. For small M_m, the lines are nearly parallel to the M_m (horizontal) axis, which means that H_c had the same values for the same amplitudes of the driving field. An increase of the frequency decreased M_m for the same driving field amplitude. That is the consequence of a "viscous" influence of eddy currents on the domain walls dynamics that increases at higher frequencies. At high frequencies, smaller M_m was obtained and more energy was dissipated on generation of eddy currents during the Barkhausen jumps. At lower frequencies, larger M_m was achieved (the domain walls moved farther) and during Barkhausen jumps smaller amounts of energy were dissipated. Of course, total energy losses increased because they are mainly determined by M_m. That can be seen from the relation

$$\mathcal{E} = 45.1 \cdot \mathcal{M}_m^{1.643} \cdot \tilde{f}^{0.05} \tag{1}$$

where $\mathcal{E} = E/(1\mathrm{J})$, $\mathcal{M}_m = M/(1\mathrm{T})$ and $\tilde{f} = f/(1\mathrm{Hz})$, derived for results of measurements at frequencies from 1 to 550 Hz and maximum magnetization up to 1 T. 1.6 is well-known Steinmetz's exponent. The dominant type of eddy–current loss (classical eddy currents) is proportional to frequency ($E \propto f$) , while the loss due to the excess eddy currents in the vicinity of the domain walls is proportional to $f^{0.45}$ [5]. At larger M_m, the lines for the same amplitude H_0 become vertical, what means that frequency does not determine the final domain structure. Increase of H_c with frequency is only a consequence of eddy current losses before the domain walls reach the same locations in the sample. From this fact we can conclude that at 0.8 T $< M_m <$ 1 T, domains B with the direction of magnetization nearly parallel to the driving field occupy almost all volume under the surface domain structure. This is another proof that domains B are responsible for magnetization up to 65% M_s. Figure 3 shows the dependence of H_c on M_m (logarithmic scale) with power law fit in the considered regions.

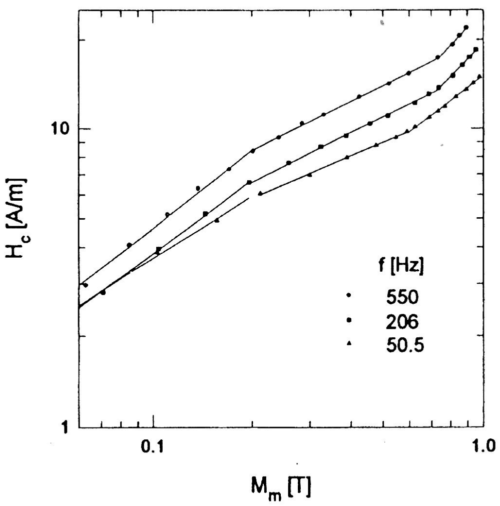

Fig. 3. Variation of the coercive field with maximum magnetization at frequencies 50.5, 206 and 550 Hz. *Note three different regions of variations.*

At frequencies of 550, 206 and 50.5 Hz, we find that $H_c \propto (M_m)^n$, with $n =$ 0.87, 0.82 and 0.75 in the first region, 0.56, 0.56 and 0.47 in the second region and 1.16, 1.16 and 0.88 in the third region, respectively. Almost the same division in three regions and the same exponents were found by Horvat et al. [7] for similar amorphous magnetostrictive alloys. Enhanced increase of H_c in the third region was explained by pinning of domain walls on stronger pinning centres what is followed by the domain wall–bending [6,8]. During the bending of the domain walls, volume fraction in which the excess eddy currents occur increases, increasing also E and H_c. Observed saturation of M_r at $M_m > 0.7\ M_s$ was also explained by the domain–wall bending.

The assumption of twofold domain structure allowed an explaination of these phenomena more precisely. Enhanced increase of H_c in the third region can be explained by the penetration of boundaries of the domains B into the region of domains A. This leads to a more intensive interaction between the two domain structures. In this region begin the changes in surface domain structure that are "locking-up" domain structure of the bulk and manifests itself as an increase of the field needed for returning the structure to the initial state, i.e. as an increase of H_c. As a supporting evidence for this phenomenon, we can consider hysteresis curve measured with VSM at driving field amplitude $H_0 = 0.1$ T shown in Fig. 4.

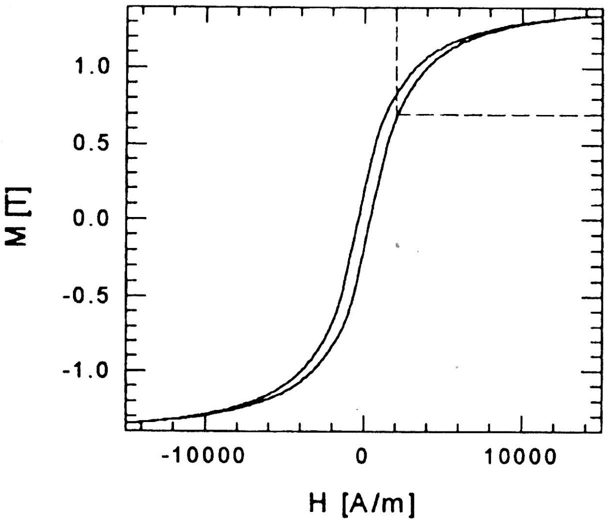

Fig. 4. Hysteresis loop at driving field amplitude of 0.1 T.

The coercive field $H_c = 370$ A/m is about 30 times larger than the typical values of the driving fields that were changing the bulk domain structure. We also find that $M_m = 0.7$ T at the driving field amplitude $H_0 = 2000$ A/m (dashed lines in Fig. 4). This is about 0.5 M_s (that value of M_m was achieved at fields of about 40 A/m, before the changes in surface domain structure appeared), and is an evidence that the changes of domains B are strongly influenced by changes in the surface domain structure.

It is important to mention that the period of driving field was 2 min., so the coercive field is almost unaffected by the frequency dependence, and its major part describes strength of "locking–up" changes in surface domain structure. Slow and oval transition to a "tail" of the hysteresis curve at large driving field amplitude is an evidence for the existence of paraprocesses, which are in our case rotation of domains, and changes and destruction of surface domain structure.

The appearance of hysteresis curves of this shape (with slower rate of change of $M_m(H_0)$) results in slower increase of M_r with respect to the M_m, i.e. saturation of $M_r(M_m)$. The dependence of the remanent magnetization on maximum magnetization is shown in Fig. 5. At $M_m > 0.7$ T, we find a mild tendency to saturation, which indicates slow changes in surface domain structure at these fields.

In the region $M_m < 0.7$ T and for lower frequencies, the dependence of M_r on M_m is approximately linear and frequency independent. The best fit (for lower frequencies) is

$$\mathcal{M}_r = 0.82 \cdot \mathcal{M}_m^{1.03}, \qquad (2)$$

where $\mathcal{M}_r = M_r/(1\mathrm{T})$ and $\mathcal{M}_m = M_m/(1\mathrm{T})$. The inset to Fig. 5 shows the dependence of M_r on M_m at higher frequencies for which the increase of M_r is enhanced in the region $0.1\ \mathrm{T} < M_m < 0.7\ \mathrm{T}$. The remanent magnetization cannot be literally interpreted as the magnetization of the system after the driving field is turned off, but must be considered in terms of the process of dynamical change of magnetization. Otherwise, at different frequencies, different values of M_r would not have been obtained.

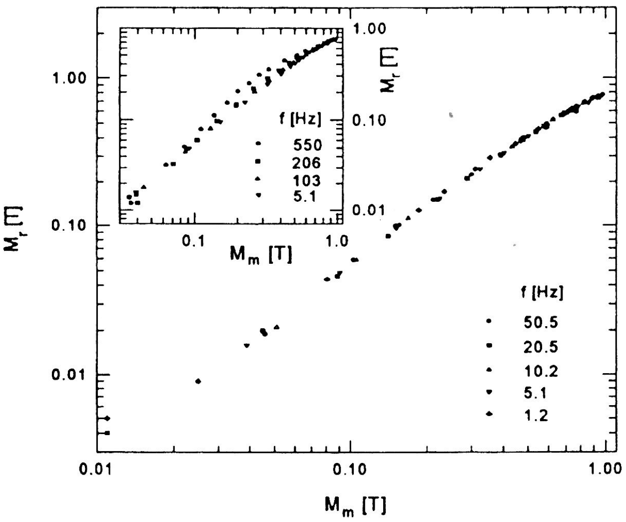

Fig. 5. Variation of remanent magnetization with maximum magnetization for given frequencies. Inset: The same dependence at higher frequencies.

4. Conclusion

On the basis of systematic detailed measurements of parameters of hysteresis curves (H_c, M_m, M_r) for an $Fe_{77.5}B_{22.5}$ amorphous alloy, and the existence of the twofold domain structure of amorphous alloys in form of long straight ribbons, we can conclude:

a) Inner domain structure (domains B), which contributes to the magnetization of the sample up to about 65% M_s, can be completely changed with rather small driving field amplitudes (up to 100 A/m).

b) Analysis of the variation of H_c with M_m and f for the same driving field amplitude has shown a "viscous" effect of eddy currents on the domain wall movement, and hence on the final domain configuration, i.e. on M_m. The existence of the two contributions to magnetization, which are caused by domains A and domains B, was indicated by achieving the same M_m at all frequencies.

c) Changes in the surface domain structure at large driving field amplitudes, which have the character of a paraprocess, are locking-up the inner domain configuration of the bulk. All our results show the influence of interaction between the region of domains A and region of domains B, which allows the assumption that in addition to classical pinning centres that are, e.g. impurities, density fluctuations, quasidislocation, etc., the domain wall pinning of domains B probably can be caused by the interaction with surface domain structure (domains A). In agreement with this assumption are also the results of Ref. 9 in which it is shown that the strongest pinning centres are situated near the surface of the sample, while the pinning centres in the bulk are much weaker.

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UTJECAJ DOMENSKE STRUKTURE NA OVISNOST KOERCITIVNOG POLJA I MAKSIMALNE MAGNETIZACIJE AMORFNE SLITINE $Fe_{77.5}B_{22.5}$

Indukcijskom metodom mjerene su krivulje magnetizacije amorfne vrpce $Fe_{77.5}B_{22.5}$. Ovisnosti koercitivnog polja (H_c), maksimalne magnetizacije (M_m) i remanentne magnetizacije (M_r) mogu se objasniti dvostrukom domenskom strukturom karakterističnom za ovakve uzorke. Analiza mjerenja pokazuje da su unutrašnje domene odgovorne za magnetizaciju do 65% magnetizacije zasićenja (M_s) te da interakcija izmedu dviju domenskih struktura igra važnu ulogu pri ubrzanom rastu H_c pri $M_m > 0.5\ M_s$. Razmatrana je i ovisnost parametara krivulje histereze o frekvenciji.