Magnetization Process in Hard Axis of Fe-Co Based Amorphous Ribbons with Induced Anisotropy

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Abstract-**Magnetization process of amorphous ribbons in the hard axis of magnetization was investigated by observation of magnetic domains having the easy axis of induced anisotropy in the transverse direction. It was found that a field applied in the longitudinal direction caused wall motion as well as magnetization rotation through re-arrangement of energy balance between magnetostatic and wall energies. Re-annealing of ribbons in a remanent state without a magnetic field caused domain wall pinning that restrained wall motion and improved the magnetic properties at high frequency markedly.**

I. Introduction

In soft magnetic materials used at high frequency, magnetization rotation is utilized by applying a drive field in the hard axis of magnetization. We reported previously that ultra thin amorphous ribbon annealed in a field applied in the transverse direction of the ribbon has a stripe domain structure and showed high frequency magnetic properties superior to those of ferrite [1]. To improve high frequency characteristics, magnetization process in the hard axis was investigated.

II. Experimental

Non-magnetostrictive $Fe_6Co_{74}Si_2B_{18}$ amorphous ribbon quenched in vacuum was used for experiments. The thickness and the width of the ribbon are about 7.2μm and 2~4mm, respectively. The Curie temperature is about 410℃. To induce the anisotropy, the ribbon was annealed at 300℃ for 20min. in a filed of 600 Oe applied in the transverse direction of the ribbon. Permeability and core loss were measured for toroidal samples with an outer diameter of 8.8mm, an inner diameter of 8.2mm and a height of 3.3mm. A Kerr microscope was used to image magnetic domains employing an image processor[2].

III. Results and discussion

Fig.1 shows a dc magnetization curve of a 5cm long (Fe,Co)-Si,B ribbon measured in the hard axis direction, i.e., the longitudinal direction of the ribbon. The ribbon shows a linear magnetization with low hysteresis loss indicating that the magnetization rotation is the major magnetization process. The anisotropy field was about 10Oe which is large enough to align the magnetization in the transverse direction, as shown by stripe domains at remanence in Fig.2. The spacing of stripe domains is 0.1mm ~0.2mm . In the wide domain, closure domains stretching from the ribbon edges can be seen. These seem to help lower the magnetostatic energy stored near the ribbon edges.

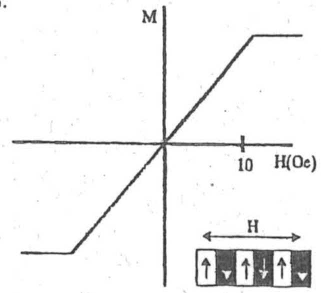

Fig.1 Magnetization curve of Fe-Co based amorphous ribbon measured in the hard axis

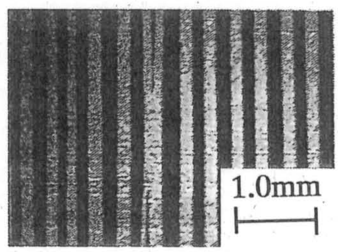

Fig.2 Domain pattern of a field annealed ribbon in the remanent state.

To observe the magnetization process in detail, we extracted the domain change by subtracting the reference domain pattern at remanence from that in a longitudinal applied field using an image processor. By this way, magnetization rotation and wall displacement can be identified from their image, as schematically shown in Fig.3.

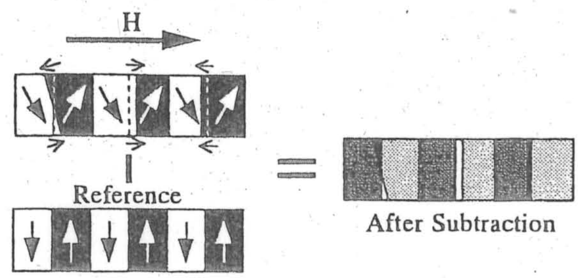

Fig.3 Schematic of domain subtraction by image processor.

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The Kerr effect signal caused by magnetization rotation changes continuously, so domain images would change gradually. Wall displacement shown by dotted lines in Fig.3 generates a discontinuous change in the Kerr effect signal which would create an intense bright or dark image depending on the direction of the wall displacement. Thus, it is expected that evolution of both magnetization processes could be identified from the intensity of the Kerr effect image. The image-processed pictures are shown in Fig.4. The image processor used has a resolution of 8 bits between the bright and dark images[3], so the image just after the subtraction looks gray as shown in Fig.4(a). When a longitudinal field of 2Oe is applied, the bright and dark fine stripe images appear (Fig.4(b)). They are created, respectively, by the growth of bright and dark stripe domains at remanence shown in Fig.2. It is seen that most of the domain walls move in a range of 40~80 μm in a longitudinal field. As an applied field is increased, magnetization rotation become noticeable, and the irregular walls displacement can be seen as indicated by arrows in the picture, where the Kerr effect signal changes sign from bright to dark along the transverse direction (Fig.4(c)). This indicates that the interior and the exterior parts of a single wall tend to move in the opposite direction. When the magnetization is nearly saturated in the longitudinal direction by a field close to the saturation field, the image processing creates the bright and dark domain image similar to that of the remanent state in Fig.2 but with a reversed Kerr effect signal(Fig.4(d)). It can be seen that the number of stripe domains stays the same until the saturation.

As seen above, wall displacement as well as magnetization rotation occurs when a field is applied in the hard axis of the magnetization. In a ribbon form specimen, stripe domain spacing is a function of magnetostatic energy density Em and wall energy density Ew. It seems that the wall displacement is associated with re-arrangement of the energy balance between Em and Ew. Em is not a simple function of domain spacing, and can be written approximately as[4]

$$Em = d \cdot S \cdot M^2, \quad (1)$$

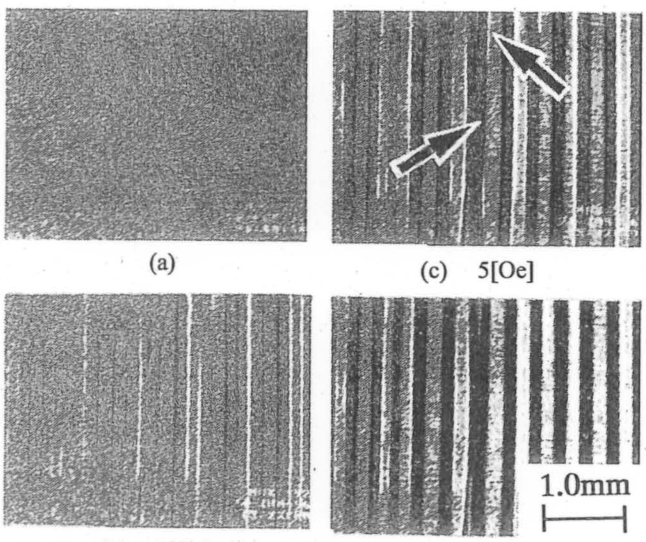


Fig.4 Image-processed domain changes caused by longitudinal applied fields.

$$Ew = W / S, \quad (2)$$

where d is a coefficient related to the demagnetizing factor in the transverse direction, S domain spacing, M charge density at the ribbon edge and W wall energy density. Then, domain spacing can be determined by considering an energy minimum as

$$S = 1/ M \cdot (W/ d)^{1/2}. \quad (3)$$

Both of M and W are functions of the rotation angle θ of the magnetization. The variation of domain spacing can be predicted from $\Delta S/\Delta\theta$. M is a simple function of cos θ, but it is not clear how W depends on θ, especially for such a low anisotropy material having an asymmetric Bloch wall[5]. Micromagnetic treatment would be needed to clarify the situation. So we studied the effect of the demagnetizing factor d. According to eq.(3), it is expected from $\Delta S/\Delta\theta$ having a factor of $(1/ d)^{1/2}$ that the domain spacing would be less affected in ribbons with a large d. Fig.5 shows the domain patterns at a remanent state of ribbons with dimensions of 5cm long x 2mm wide and 2cm long x 4mm wide.

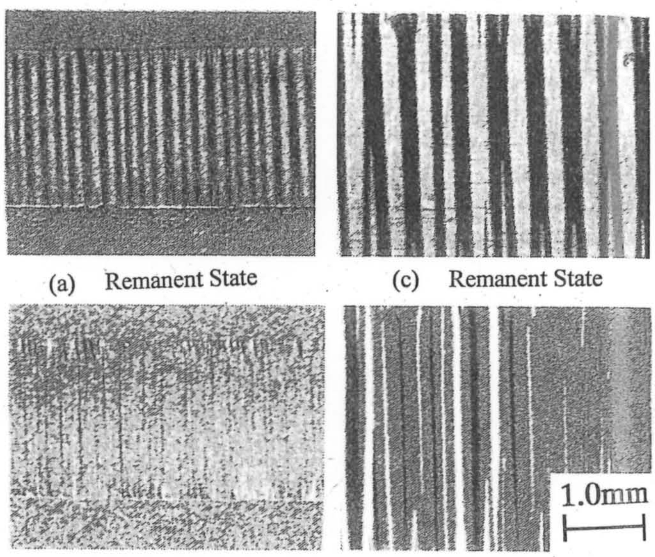
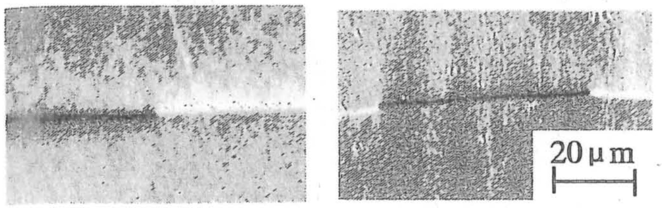


Fig.5 Domain pattern at remanent states and its change caused by a longitudinal field for 2mm wide ribbon (a)(b) and for 4mm wide ribbon (c)(d).

From the domain spacing, it is evaluated that the narrow ribbon has the d factor about 4 times larger than that of the wider ribbon. The narrow ribbon has a smaller domain spacing in a range of 60~100 μm and lots of closure domains extending from ribbon edges to the interior. It is seen that the domain spacing of the narrow ribbon is less affected by an applied field.

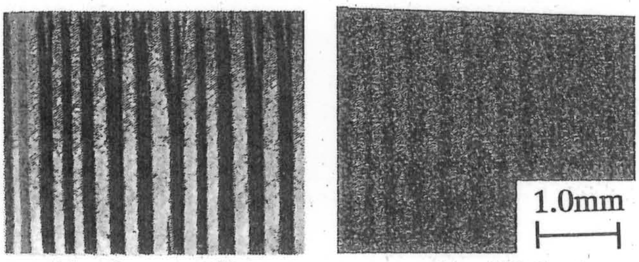
To restrain the wall displacement, the ribbon was re-annealed with no field at 350℃ for 20 min. and the local anisotropy was introduced for the wall pinning [6]. Fig.6 shows the domain wall of the ribbon before and after re-annealing. It is seen that the annealing turns domain wall thicker by lowering the anisotropy energy in the wall. The amplitude of the wall pinning field is related to the anisotropy field: H_k and evaluated as 0.55 H_k by computer simulation[7]. The pinning field of the re-annealed ribbon is evaluated at



(a) (b)

Fig.6 Thick pinned wall and thin free wall.

around 5 Oe from the anisotropy field. Fig.7 shows the domain pattern at a remanent state and its change caused by a longitudinal applied field for the ribbon(4 mm wide) with pinned walls. No wall displacement is observed even in an applied field of 9 Oe , but the image caused by magnetization rotation can be recognized.



(a) Remanent State (b) 9[Oe]

Fig.7 Domain pattern and its change caused by a longitudinal field for ribbon with pinned walls.

Fig.8 shows the core loss per cycle of the toroidal samples as a function of frequency. Open and solid points are for samples with transverse anisotropy and with pinned walls introduced by re-annealing, respectively. The maximum induction was kept at 1kG($4\pi M$). It is seen that the re-annealing decreases core loss markedly over all the frequency range. The losses in the samples with pinned walls are about 40% and 64% of those of the sample with the transverse anisotropy measured at 100kHz and 5MHz, respectively. The loss value at 1MHz of the pinned wall sample is also lower than that of the Mn-Zn ferrite(pc40, TDK). It is inferred from Fig. 6 that the decrease in loss is ascribed to the low eddy current loss owing to magnetization rotation.

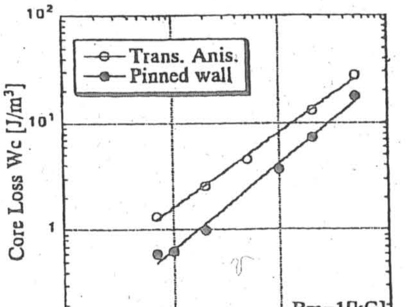


Fig.8 Core loss as a function of frequency.

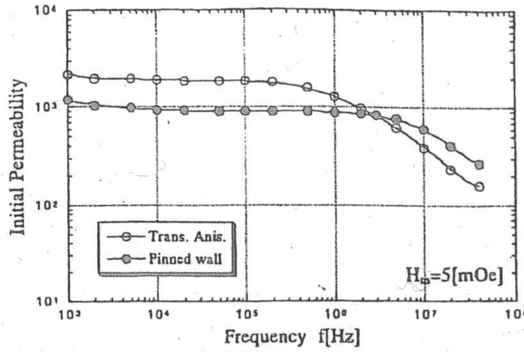


Fig.9 Initial permeability as a function of frequency.

Fig.9 shows the initial permeability:μ_i as a function of frequency for both toroidal samples. The sample with pinned walls has better high frequency characteristics. This seems also to be ascribed to magnetization rotation as the major magnetization process. It is not clear at present why the sample with pinned walls shows lower μ_i at lower frequency.

IV. Summaries

Magnetization process of Fe-Co based amorphous ribbons in the hard axis of induced anisotropy, i.e., the transeverse direction of ribbon, was studied by domain observation. The results are summarized as follows, 1) Domain wall displacement as well as magnetization rotation occur in a field applied in the hard axis owing to re-arrangement of energy balance between magnetostatic and wall energies. 2) The wall displacement can be restrained by re-annealing of the ribbon with no applied field which causes wall pinning. 3) The wall pinning treatment decreased core loss of toroidal samples markedly and improved high frequency characteristics of initial permeability, which can be ascribed to the decreased eddy current loss due to magnetization rotation.

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