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Annealing Effect of Local Anisotropy Field in Amorphous $Co_{66}Fe_4Ni_1B_{14}Si_{15}$ Ribbon

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The magneto-impedance (MI) has been measured in the annealed $Co_{66}Fe_4Ni_1B_{14}Si_{15}$ amorphous ribbon for the evaluation of anisotropy field. MI at the frequency of 10 MHz is related to the transverse permeability from rotational magnetization depending on the local anisotropy field. MI varies sensitively with the annealing temperature, reflecting the change of anisotropy field distribution. The local anisotropy fields evaluated from MI profiles are discussed in terms of the magnetic softness and microstructural change by the annealing.

1. Introduction

A lot of works on the magneto-impedance (MI) has been studied in the soft magnetic Co-, Fe-based amorphous and nanocrystalline alloys for the sensitive magnetic sensors, where MI is understood as the effect of magnetic field on transverse permeability to ac current direction [1, 2]. MI profile during a half cycle of magnetization for low operating frequency shows a broad maximum around zero field due to the dominant contribution from wall motion. As the frequency increases over a few hundreds kHz, the dip in the MI profile appears, showing two peaks split at the zero field. In this frequency range, the wall motion begins to be damped, in turns, the effect of rotational magnetization on MI is comparable to that of wall motion. The dip becomes profound as the frequency increases, being ascribed for by the fact that the rotational magnetization is responsible for MI profile.

It has been known that the effective anisotropy field plays significant role in MI where rotational magnetization is major contribution to the transverse permeability [1, 3]. In present work we investigate the variation of local anisotropy field in $Co_{66}Fe_4Ni_1B_{14}Si_{15}$ amorphous ribbon annealed at different temperatures, determined by analysis of MI profiles near the zero field.

2. Theoretical Background

The magneto-impedance (MI) of magnetic materials in ribbon geometry under a longitudinal prove current $I=I_o\, e^{j\omega t}$ in high frequency range, at which the skin depth becomes inferior to the sample thickness, can be written as [1]:

$$Z(\omega, H) \propto \sqrt{\omega\mu_t(\omega, H)} \tag{1}$$

where H is is the longitudinal dc field and μ_t is transverse magnetic permeability which consists of two parts of contributions:

$$\mu_t(\omega, H) = \mu_{dw}(\omega, H) + \mu_{rot}(\omega, H) \tag{2}$$

where μ_{dw} and μ_{rot} are transverse permeability originating from domain wall motion and magnetization rotation, respectively. The permeability from wall motion is dominant over the rotational magnetization in the low frequency range. As the frequency increases over a few MHz in the Co-based amorphous samples, the wall motion is nearly damped [4], and $\mu_{rot}(H)$ is only involved in the transverse permeability.

The H dependence of μ_{rot} can be known by calculating the transverse susceptibility χ_{rot} from the rotational magnetization. Consider the rotation of a single domain with uniaxial anisotropy as a simple model [5], as shown the coordinate system in Fig. 1. The external field H and probe current I act along the ribbon axis. The easy axis makes an angle θ_k from the transverse direction and H_t is transverse field produced by longitudinal prove current. The energy for magnetization M_s tilted away from easy axis by angle θ is written as

$$\begin{aligned} E &= K \sin^2\theta - M_s H_{ext} \sin(\theta + \theta_k) \\ &\quad - M_s H_t \cos(\theta + \theta_k) \end{aligned} \tag{3}$$

where K is the anisotropy constant.

The equilibrium angle can be determined by minimizing the energy, or by

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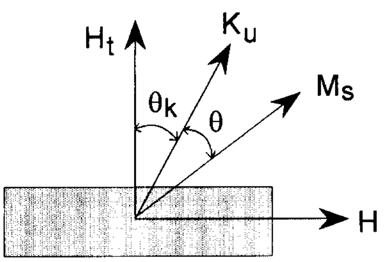

Fig. 1. Performance of feedback system to keep the interferometer signal constant (a) applied magnetic field, (b) interferometer signal and (c) feedback output.

$$\frac{\partial E}{\partial \theta} = K\,\sin(2\theta) - M_S H_{ext}\,\cos(\theta+\theta_k) + M_S H_t\,\sin(\theta+\theta_k) = 0 \qquad (4)$$

The rotational transverse susceptibility can be obtain by the relation

$$\chi_{rot} = \frac{\partial^2 E}{\partial H_t^2} \qquad (5)$$

After some partial derivative procedures with change of variables and taking small H_t field approximation, the Eq. (5) becomes

$$\chi_{rot} = \frac{M_s\,\sin^2(\theta+\theta_k)}{H_k\{h\,\sin^2(\theta+\theta_k)+\cos(2\theta)\}} \qquad (6)$$

where we defined anisotropy field $H_k=2K/M_s$ and $h=H/H_k$. It is a same result that is obtained by the precession of magnetic moment in dc frequency limit [1].

We can obtain $\chi_{rot}(h)$ numerically for a given θ_k from Eq. (4) and (6) as shown in Fig. 2. For the small angles θ_k, the susceptibilities exhibit peaks near $h=\pm1$, or $H=\pm H_k$. As θ_k increases, the value of h at the peak decreases and the peak eventually disappears for further increase of θ_k, giving monotonically decreasing χ_{rot} with h. In actural amorphous materials, there are inevitable residual stresses, leading to local variations in the anisotropy direction. In spite of the spatial distribution of θ_k, MI will shows peaks near because the local anisotropy near $H=\pm H_k$ transverse direction, $\theta_k\approx 0°$, gives most pronounced peaks in χ_{rot} as shown in Fig. 2.

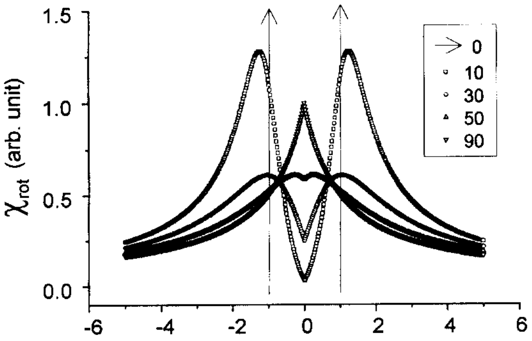

Fig. 2. Relative amplitude of the harmonics of magnetic induction for (a) φ=0°, (b) 40° and (c) 90°.

3. Experimental

The Co-based amorphous ribbons ($Co_{66}Fe_4Ni_1B_{14}Si_{15}$) have been annealed at various temperatures of 200-500 °C during 1 hour in 10^{-3} Torr. The absolute value of impedance Z is measured by HP4192A impedance analyzer using four terminal contacts under the longitudinal magnetic field, which is produced by 0.01 Hz triangular current applied to a Helmholtz coil. The magneto-impedance ratio is obtained from the relation

$$\Delta Z/Z(\%) = \frac{[Z(H)-Z_{sat}]\times 100}{Z_{sat}} \qquad (7)$$

where Z_{sat} is the impedance measured at H=6 Oe. MI ratio profile is obtained by measuring $\Delta Z/Z$ during the cyclic applied field.

4. Results and Discussion

Figures 3(a)-(c) show the x-ray diffraction (XRD) using

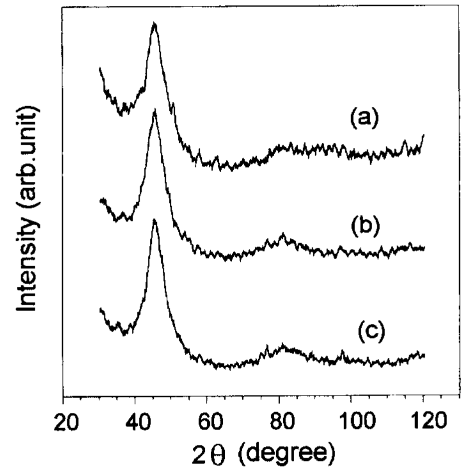

Fig. 3. x-ray diffraction in (a) as-quenched, (b) 400 and (c) 500 °C annealed samples.

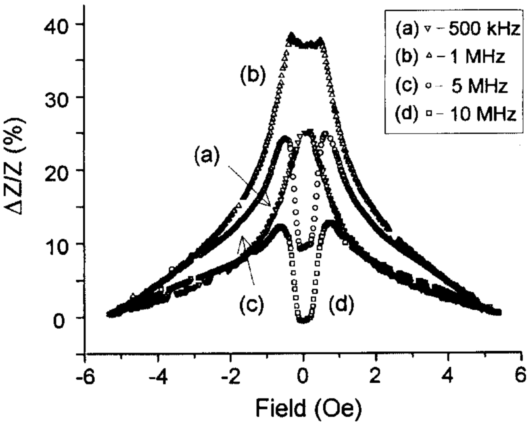

Fig. 4. MI profiles in as-quenched sample measured at various frequencies. (a) 500 kHz, (b) 1 (c) 5 (d) 10 MHz.

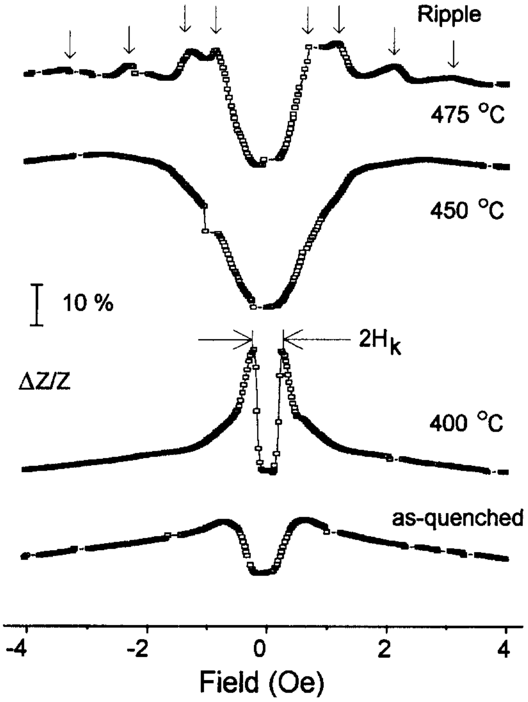

Fig. 5. MI profiles at f=10 MHz in annealed samples.

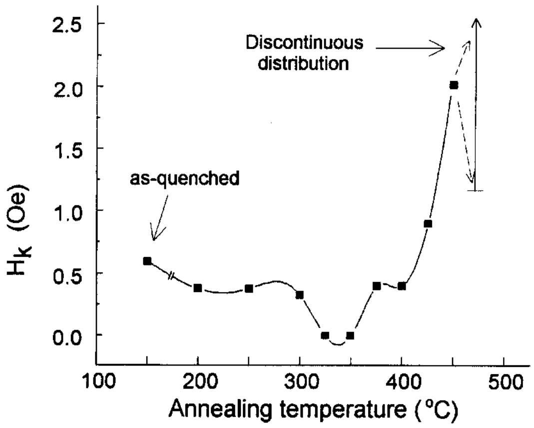

Fig. 6. Variation of the local anisotropy field with annealing temperature.

CuKα radiation in as-quenched, 400 and 500 °C annealed samples, respectively. There is no significant change in XRD patterns, indicating that most of sample volume is amorphous or nanocrystalline states after annealing up to 500 °C.

Figure 4 shows MI profiles at various frequencies of applied ac current in as-quenched sample. The monotonically decreasing MI with H at f=500 kHz, that is, single peak profile, reflects that the domain wall motion is dominant mechanism in MI because $\mu_{dw}(H)$ decreases with the field H. The MI ratio at high frequencies above 5 MHz increases initially with H to a peak and then fall with further increment. In this frequency range, the wall motion is nearly damped, then $\mu_{rot}(H)$ is responsible for MI. Hence the value of H for MI peak corresponds to the local anisotropy field H_k of the rotated domains, as described in section 2.

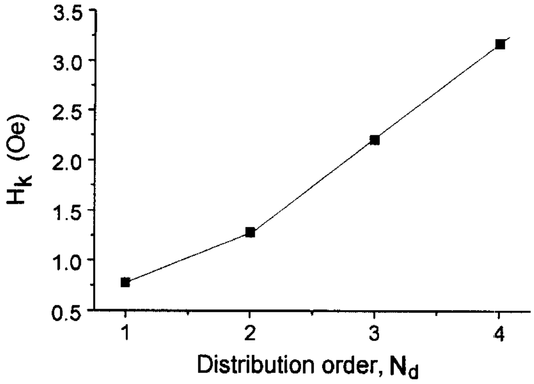

Fig. 7. Discontinuous distribution of anisotropy fields at 475 °C annealed sample.

Figure 5 shows the MI profile with annealing temperature T_a at f=10 MHz, of which frequency the rotational magnetization only contributes to MI. MI profiles show sensitive variation with annealing temperatures, accompanied with the change of field interval between two peaks, $2H_k$. In addition, the field sensitivity of MI ratio for the range of $H>H_k$ is higher for the sample of smaller H_k. For the samples of T_a=320, 350 °C, MI profiles show single peak at H=0, indicating H_k is nearly equal to zero. It is worth to noticing that there are ripples (several peaks) in MI profile at T_a=470 °C sample. For T_a=500 °C sample, MI decreases drastically, and so it is hard to observe the distinct MI peaks.

The variation of H_k with T_a, determined from MI profile in Fig. 5, is shown in Fig. 6. As T_a increases up to 350 °C, the H_k of 0.6 Oe in as-quenched sample decreases to be less than 0.03 Oe due to the increase of magnetic softness in the nanocrystalline state by the annealing. However, H_k increases for the further increase of T_a, due to the onset of microcrystallization. There is ambiguity to determine H_k at T_a=475 °C sample because of the several peaks in MI profile.

Several peaks at T_a=475 °C sample could indicate the existence of discontinuous distribution of anisotropy fields, corresponding the peak's order to the distribution order, N_d. The anisotropy field varies linearly with the distribution order from N_d=2, as shown in Fig. 7. Such a discontinuous distribution of H_k may reflect that the microstructure in the initial crystallization state causes the different values of anisotropy field.

5. Conclusion

We have evaluated the variation of anisotropy field H_k in the annealed $Co_{66}Fe_4Ni_1B_{14}Si_{15}$ amorphous by analyzing the measured MI profiles in terms of transverse permeability and domain dynamics. The decreasing H_k with the annealing temperature is ascribed for by the increase of magnetic softness, while the increasing H_k for the further increment of annealing temperature is associated with microstructural change by the annealing. The discontinuous distribution of H_k at 475 °C annealed sample may reflect that the microstructure in the initial crystallization state causes the different values of anisotropy field.

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