Effect of annealing on torsion giant impedance of Co-rich amorphous wires with vanishing magnetostriction

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Torsion giant impedance (TGI) ratio, $(\Delta Z/Z)_\xi$, has been measured in as-cast and annealed $(Co_{0.94}Fe_{0.06})_{72.5}B_{15}Si_{12.5}$ amorphous wire. Two-step current annealing has been employed: pre-annealing (550 mA, 2 min) plus current annealing under torsion stress (33 π rad/m, 450 mA, up to $t_{ann}=105$ min). Pre-annealing results in a drastic increase of $(\Delta Z/Z)_\xi$ (from 155% to 260%) and decrease of the asymmetry. The consequent annealing under torsion of pre-annealed sample gives rise to the appearance of significant asymmetry of the TGI. In this case $(\Delta Z/Z)_\xi$ has a tendency to achieve rather asymmetric shape with a sharp maximum at certain torsion ξ_m. The value of ξ_m depends on the time of annealing under torsion and on the applied torsion during the annealing. The asymmetric shape of the $(\Delta Z/Z)_\xi$ in as-cast state and after torsion annealing could be ascribed to the spontaneous or induced helical anisotropy, which can be compensated by the application of certain torsion stress. Evolution of $(\Delta Z/Z)_\xi(\xi)$ and ξ_m (ξ) as a function of annealing time reflects the kinetic of the induced magnetic anisotropy.
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INTRODUCTION

Giant magnetoimpedance (GMI) effect in amorphous wires has been intensively studied during the last decade owing to its excellent technological applicability. According to the classical approach, the origin of the GMI effect is related to the strong dependence of the electrical impedance of a ferromagnetic conductor on the axial applied magnetic field (H_z) when an alternating current of high enough frequency (f) is flowing along the sample. The nearly-zero magnetostriction amorphous wires exhibit the best conditions for the GMI effect owing to their specific magnetoelastic anisotropy with high circular permeability in the surface.[1,2]

Such high sensitivity of the electrical impedance to the dc axial magnetic field has been interpreted in terms of the classical skin effect of a magnetic conductor with scalar magnetic permeability, as a consequence of the change in the penetration depth of the alternating current caused by the dc applied magnetic field. The electrical impedance Z of a magnetic conductor in this case is given by[1,2]

$$Z=R_{dc}krJ_0(kr)/2J_1(kr), \tag{1}$$

with $k=(1+j)/\delta$, where $j=(-1)^{1/2}$, J_0 and J_1 are the Bessel functions, r is the wire's radius, R is the dc electrical resistance, and δ the penetration depth given by

$$\delta=(\pi\sigma\mu_\phi f)^{-1/2}, \tag{2}$$

where σ is the electrical conductivity, f the frequency of the current along the sample, and μ_ϕ the circular permeability assumed to be scalar. The dc applied magnetic field introduces changes in the circular permeability μ_ϕ. Therefore, the penetration depth also changes through and finally results in a change of Z.[1,2]

On the other hand, this circular permeability μ_ϕ, also depends on the applied stresses.[3–5] In this way, the electrical impedance of a magnetic conductor also drastically changes under applied stresses, giving rise to the stress impedance effect.[3–9] Such external stress could be of tensile or torsion origin. Consequently, a torsion or tensile impedance effect can be observed.[4–9]

It is also well known that peculiar magnetoelastic anisotropy is developed in amorphous wires owing to the internal stresses caused by the rapid quenching process during the fabrication. This magnetoelastic anisotropy is responsible for a peculiar domain structure of the amorphous wires, consisting of an internal axially magnetized core and an outer shell with high circular (in the case of nearly-zero magnetostriction constant) permeability.[10] It is clear that the electrical impedance behavior with the applied stresses depends on the magnetic anisotropy in the surface layer. On the other hand, stress annealing can induce macroscopic magnetic anisotropy. Therefore, it should be interesting to study the effect of the torsion annealing on the torsion impedance behavior.

In this relation, it was recently found that the

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torsion giant impedance (TGI) of the as-cast $(Co_{0.94}Fe_{0.06})_{72.5}B_{15}Si_{12.5}$ wire exhibits asymmetric torsion stress dependence. This TGI effect can be significantly enhanced and the asymmetry substantially reduced by the current annealing. Consequently, the aim of this paper is to study the effect of current pre-annealing on the TGI effect in the $(Co_{0.94}Fe_{0.06})_{72.5}B_{15}Si_{12.5}$ amorphous wire with vanishing magnetostriction.

EXPERIMENTAL DETAILS

Our experiments were carried out in a nearly-zero magnetostrictive amorphous wire of nominal composition $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$ with a diameter of 125 μm, kindly supplied by Unitika Ltd., Japan. Pieces 7 cm long were cut in order to carry out the impedance measurements. A special experimental setup with one fixed and another rotating clamps has been designed. In this way the wire ends were clamped to allow the application of torsion stress (ξ) when sinusoidal alternating current simultaneously flows along the wire.

The following current annealing procedure has been used: (1) pre-annealing at 550 mA (current density $j = 44$ A/mm^2) for 1 min duration and (2) current annealing at 450 mA (current density $j = 36$ A/mm^2) under the action of a torsion strain (up to applied torsion $\xi = 33\pi$ rad/m, which is equivalent to the 1.5 complete revolutions per sample length). Such experimental conditions have been elected in order to compare with experiments done in the same composition but without pre-annealing.[8,9] The duration t_{ann} of this current annealing was up to 105 min.

The impedance was evaluated by means of the four points technique flowing an alternating current along the wire with a frequency of 500 KHz and a driven current amplitude I of 25 mA to avoid the heating of the wire. The ac amplitude was measured by an ac sensing device CT-1.

When the torsion dependence of the impedance was investigated, we have defined the torsion impedance ratio (TI), $(\Delta Z/Z)_\xi$, by the expression

$$(\Delta Z/Z)_\xi = [Z(\xi) - Z(\xi_{max})]/Z(\xi_{max}), \tag{3}$$

where ξ_{max} is the maximum applied torsion stress ξ applied for the determination of this $(\Delta Z/Z)_\xi$. Measurements of TI with and without a longitudinal magnetic field, H, can be made.

Generally, torsion stress dependence of the total impedance Z and $(\Delta Z/Z)_\xi$ have a shape of decay beginning from some position corresponding to their maximum. This decay has certain saturation, indicating that after application some torsion Z and $(\Delta Z/Z)_\xi$ are almost independent of ξ. The position of the maximum can change after different treatments. In order to compare $(\Delta Z/Z)_\xi$ dependencies after different treatment when the position of maximum can be shifted from zero torsion, these dependencies have been compared when the saturation is reached.

EXPERIMENTAL RESULTS AND DISCUSSION

Pre-annealing treatment results in a drastic increase of the TGI ratio from 155% to 260%, as is shown in Fig. 1.

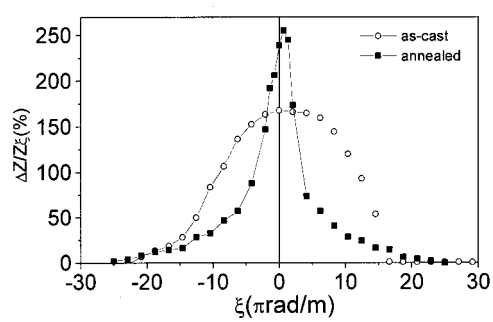

FIG. 1. Effect of the pre-annealing on the $(\Delta Z/Z)_\xi(\xi)$ dependence.

Besides slight asymmetry of the torsion dependence of $(\Delta Z/Z)_\xi$ with a broad maximum at around $\xi_m = 2.5\pi$ rad/m typical for the as-cast sample, disappears after pre-annealing. In addition, after pre-annealing $(\Delta Z/Z)_\xi$ shows a tendency to finally achieve sharp and almost symmetric shape with a maximum at almost zero torsion.

Subsequent joule heating under torsion produces the appearance of a significant asymmetry on the $(\Delta Z/Z)_\xi$ dependence with a maximum at certain torsion ξ_m. The evolution of $(\Delta Z/Z)_\xi$ dependencies with the time of current annealing t_{ann} as a parameter at fixed applied torsion (33 π rad/m) during the current annealing is presented in Fig. 2. As can be observed, ξ_m increases and $(\Delta Z/Z)_\xi$ gradually decreases with t_{ann}.

Figure 3 presents the evolution of $(\Delta Z/Z)_\xi(\xi)$ dependencies obtained after current annealing at 450 mA with a fixed annealing time (10 min) but under different applied stress ξ_{ann}. Similarly to the Fig. 2, this dependence shows an increase of the asymmetry with ξ. Moreover, the $(\Delta Z/Z)_\xi$ ratio shows some improvement under certain conditions of the current annealing. Comparing with previous results[8] the pre-annealing by Joule heating introduces some changes in the observed dependencies. A maximum $(\Delta Z/Z)_\xi$, ratio of 290% is obtained after optimal conditions of current annealing under torsion (see Fig. 3).

Regarding observed torsion impedance effect, it should be mentioned that high circular permeability and a GMI effect are observed mostly in samples with the nearly zero magnetostriction compositions. Thus, in order to have a sig-

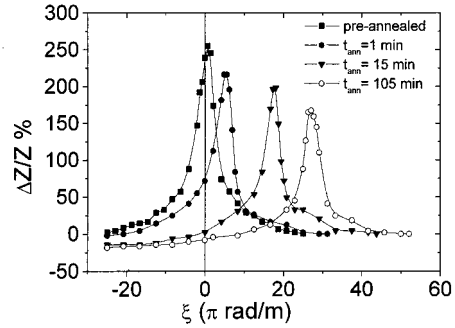

FIG. 2. Evolution of the $(\Delta Z/Z)_\xi(\xi)$ dependence of the pre-annealed wire with the torsion annealing time, t_{ann}, at fixed ξ.

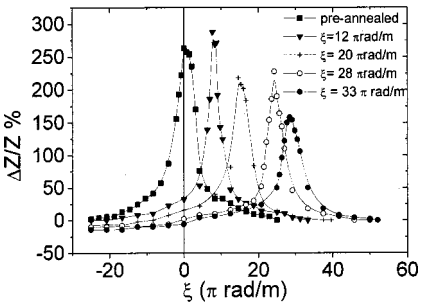

FIG. 3. Evolution of the $(\Delta Z/Z)_{\xi}(\xi)$ dependence of the pre-annealed wire with ξ_{ann} at fixed t_{ann}.

nificant GMI effect we are limited in the choice of the composition. On the other hand such compositions have minimal magnetoelastic coupling. Rather low magnetostriction values exhibited by these compositions could be explained assuming the existence of two kinds of short ordering, namely: (i) an ordered highly anisotropic phase centered around Fe atoms with positive magnetostriction, mainly due to anisotropic exchange mechanism and (ii) a disordered phase at Co-rich atoms with negative magnetostriction.[11] In fact such inhomogeneity can create enhanced stress sensibility exhibited by nearly zero amorphous wires.

There are two remarkable features of $(\Delta Z/Z)_{\xi}(\xi)$ dependencies presented in Figs. 1–3: (i) a slight asymmetry of this curve with respect to zero torsion in the as-cast state and (ii) a decrease of such asymmetry after pre-annealing and an increase of such asymmetry after current annealing under torsion with t_{ann} and ξ_{ann}. To explain this behavior it is necessary to consider the fact that the current annealing under torsion strain induces a helical magnetic anisotropy of magnetoelastic character. At the same time, such current annealing without stress gives rise to a relaxation of the complex internal stresses introduced during the fabrication process and the disappearance of the magnetoelastic anisotropy associated with such frozen-in stresses. The disappearance of the spontaneous asymmetry of $(\Delta Z/Z)_{\xi}$ (ξ) dependence associated with such frozen-in internal stresses and an improvement of $(\Delta Z/Z)_{\xi}$ ratio after current annealing has been observed also in Ref. 8. It means that the enhanced asymmetry found in Figs. 2 and 3 is clearly related to the application of torsion during current annealing.

Finally, the effect of the torsion stress annealing on the torsion dependencies of the Z/Z_{ξ} ratio found in this work could be generally related to two kinds of relaxation processes (annelastic and plastic)[12] invoked in the process of induction of the helical induced anisotropy in amorphous alloys. One of these processes can be attributed to the lower temperature and the other one to higher temperature. Regarding the interpretation of these two processes, we can suggest previously described reversible and irreversible contributions in structural relaxation of amorphous alloys with vanishing magnetostriction constan.[12] Thus, it has been assumed that the annelastic component has a recoverable character in the sense that it disappears during heat treatment while the plastic component is permanent,[12] being predominant in the samples annealed at elevated temperature.

CONCLUSIONS

The electrical impedance of the $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$ amorphous wire results in a great sensitivity to the applied torsion stress as well as to the torsion current annealing conditions. Current pre-annealing results in a more symmetric TI behavior and an increase of the $\Delta Z/Z_{\xi m}$ ratio. When the wire is submitted to torsion annealing a helical anisotropy is developed, increasing the asymmetry of the torsion impedance effect. As compared with as-cast state, a generally higher and sharper TI effect has been observed in annealed, under-torsion samples.

With respect to the effect of the thermal treatments on the TI effect, it has been observed that the shape of the maximum $\Delta Z/Z_{\xi m}$ ratio is quite different to that exhibited by the as-quenched sample, indicating that the stress distribution in pre-annealed or torsion annealed samples is narrower than that of as-cast wire.

The asymmetry of the $(\Delta Z/Z)_{\xi}$ in as-cast state and after torsion annealing could be ascribed to the spontaneous or induced (after torsion annealing) helical magnetic anisotropy, which can be compensated by the application of certain torsion stress. The evolution of $(\Delta Z/Z)_{\xi}$ (ξ) dependencies with torsion annealing reflects the kinetic of the induced magnetic anisotropy in the studied amorphous wire with vanishing magnetostriction constant.

ACKNOWLEDGMENT

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