Journal of Optoelectronics and Advanced Materials Vol. 4, No. 2, June 2002, p. 361 - 365

MAGNETO-MECHANICAL EFFECT IN CIRCULAR FIELD IN $Fe_{77.5}Si_{7.5}B_{15}$ AMORPHOUS WIRES

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The magneto-mechanical damping behaviour of a stress-relieved $Fe_{77.5}Si_{7.5}B_{15}$ amorphous wire subjected to circular DC magnetic field was examined in torsion mode by the inverted pendulum method. Strain amplitude-dependent maxima of the internal friction vs magnetic field were observed. As Barkhausen pulses were detected during free oscillations, the damping mechanism was attributed to irreversible strain-activated 90º Bloch wall motion. The results are interpreted within the framework of a potential function model by considering the coupling between the domain walls and the internal stresses associated to the defects of the amorphous structure.

(Received February 14, 2002; accepted May 15, 2002)

Keywords: Internal friction, Magneto-mechanical damping, Potential function model

1. Introduction

The mechanical vibration damping capacity of solids usually known as the “internal friction” is quantitatively expressed through the coefficient Q, the quality factor [1].

The magnetostrictive ferromagnets exhibit a specific loss mechanism, the “magneto-mechanical damping” (MMD), a contribution to the internal friction attributed to the irreversible magnetization processes periodically activated by the elastic strain. It is evaluated by extracting from the total damping the term of non-magnetic origin, currently measured with the sample at magnetic saturation:

$$Q_m^{-1} = Q^{-1} - Q_{sat}^{-1} \quad (1)$$

The MMD coefficient (2) is dependent both on vibration amplitude and on applied magnetic field, showing a maximum in both cases thus suggesting equivalent effect of the elastic stress and of the magnetic field acting on the non-180º Bloch walls which were identified to cause energy loss through irreversible jumps [2,3,4]. The damping behaviour of the crystalline magnetostrictive metals has been widely investigated [5,6,7,8] but rather few results concerning the magnetic amorphous alloys were reported in the litterature. Among the latter, in [9] MMD maxima vs longitudinal field exhibited by $Fe_{77.5}Si_{7.5}B_{15}$ amorphous wires were reported. A similar behaviour, but under circular magnetic field conditions is reported in the present work for the same composition. The experimental data are discussed in terms of an energetic model based on the “potential function” concept [10,11].

2. Experiment

A sample of length *l=55mm* and diameter *d=135µm* was cut from an amorphous wire of nominal composition $Fe_{77.5}Si_{7.5}B_{15}$ produced by the in-rotating water spinning method. Annealing for *15min*. at *450ºC* in silicon oil bath significantly reduced the large native stresses (currently of tens of MPa [12] in magnitude). The effect of the thermal relaxation is confirmed by the important coercivity decrease (from *9.4* to *1.3 A/m*) and by vanishing single Barkhausen jump-type magnetization reversal during magnetic hysteresis cycling [13]. Using the Villari effect [14], a valuae of $29x10^{-6}$ of the saturation magnetostriction constant was found in the relaxed state of the sample. Q^{-1} measurements were carried out by the inverted torsion pendulum method. For torsion angles not exceeding *0.1rad*, a Hall effect-based transducer converted the specific strain (γ) at the surface of the wire into a signal:

$$u_{\gamma}(t) = C_{\gamma}\gamma(t) + u_o \tag{2}$$

where $C_{\gamma}=(5.68\pm0.07)10^4$ *V/rad* is the calibration constant and $-1mV < u_o < +1mV$ is an error voltage mainly caused by eventual Hall probe missorientation. The vertical component of Earth's field was compesated by by means of a field coil. As a direct measure of the magnetization rate of change during oscillation, a signal $e_M(t)$ was obtained by linear amplification of the emf induced in a pick-up coil coaxial with the sample. Simultaneous records of γ(t) and $e_M(t)$ were performed at constant H_{φ} by analog-to-digital conversion; in Fig.1 the experimental procedure is illustrated.

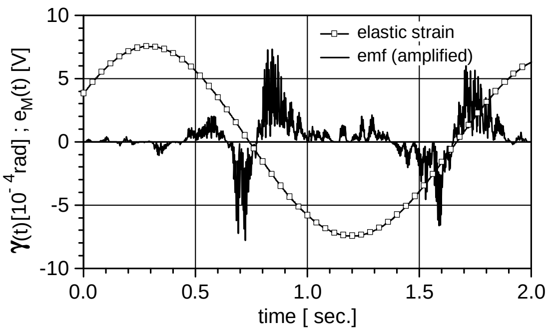

Fig. 1. A sequence (≈*2000* data points) from a joint record of the elastic strain γ(t) and of the amplified emf $e_M(t)$. The circular field strength at the sample surface was H_{φ} = *20A/m*.

The induced signal $e_M(t)$ consists in trains of Barkhausen pulses originating in irreversible domain wall jumps periodically activated by the elastic strain, suggesting that the magneto-mechanical damping mechanism consists in elastic energy conversion into Joule heat by the as-induced micro-eddy currents [2]. The dependence of Q^{-1} on the strain amplitude (Γ) was obtained by using a least-square fitting procedure based on stepwise exploring the vibrograms with the user-defined function:

$$u_{\gamma,i}(t)=C_{\gamma}\,\Gamma_i\,\exp\left(\frac{1}{4\pi}\ln\left(1-2\pi Q_i^{-1}\right)\omega_i\,t\right)\sin(\omega_i\,t+\alpha_i)+u_{o,i} \tag{3}$$

where the index "i" reffers to succesive full oscillation periods. The H_{φ} dependence of the MMD coefficient at constant Γ was then extracted. A set of three representative examples corresponding to the highest observed damping are shown in Fig.2.

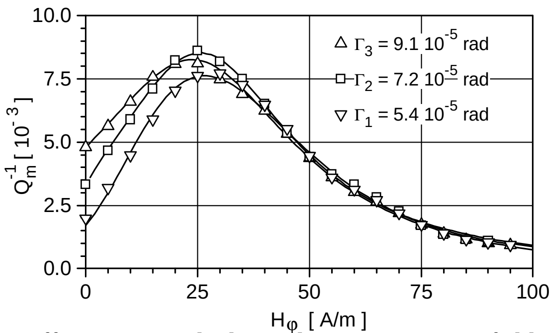

Fig. 2. MMD coefficient vs applied circular DC magnetic field at three different strain amplitude values. The solid lines connecting the measured points were generated using the model proposed in the following section.

The curves exhibit maxima slightly shifting towards lower field strength with increasing strain amplitude. A relatively significant damping, increasing with Γ, is also observed in zero circular field. The maximum damping values, both observed by us and reported in [9], are one order of magnitude lower than those observed in crystalline magnetostrictive metals.

3. Discussion

The simultaneous action of the applied mechanical stress and magnetic field will cause, during the free oscillations, periodic domain wall motion, either reversible or irreversible. Since the position of the 180º wall is not sensitive to tension or compression, the case of 90º Bloch walls will be considered only, oriented at an angle β with respect to the transverse plane (Fig. 3.a). The defects of the amorphous structure (quasi-dislocations, free volumes, higher density regions [15]), still present after moderate annealing, generate an internal stress pattern on which the wall position is dependent. As previously done for polycrystalline metals [10,11], the corresponding interaction will be taken into account by introducing a random profile "potential function" P(ξ) where ξ is the wall abscissa along the local motion direction (Fig.3.b).

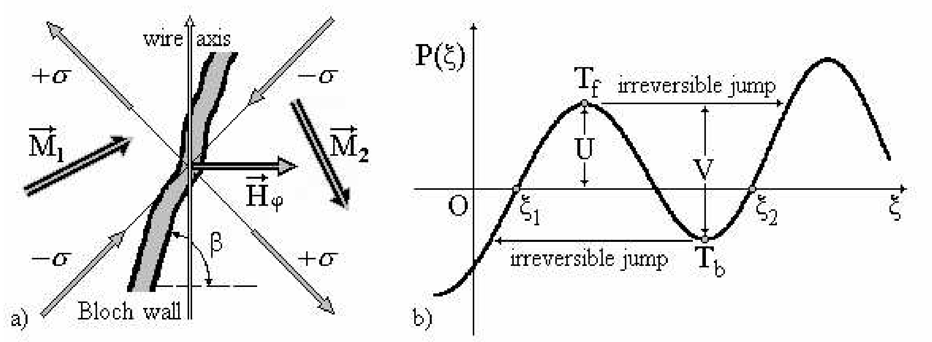

Fig. 3. A) Two domains of magnetization vectors $\mathbf{M_1}$ and $\mathbf{M_2}$, separated by a 90º wall making the angle β with the transverse plane, subjected to torsion and circular magnetic field; b) the assumed local profile of P(ξ); t he abscissae ξ_1 and ξ_2 correspond to intrinsic equilibrium positions.

The equilibrium of a domain wall in the absence of external forces is consistent with the conditions

$$P(\xi)=0 \quad ; \quad \frac{\partial P}{\partial \xi}>0 \tag{4}$$

Introducing the quantities:

$$\eta = 3\lambda_S G\cos(2\beta)\Gamma \quad ; \quad \rho = \sqrt{2}\mu_o M_S \cos(\beta) H_\varphi \tag{5}$$

where λ_S is the saturation magnetostriction, G is the shear modulus, μ_o is the vacuum permeability and M_S is the spontaneous magnetization, for a given set of the local parameters "U" and "V" of the potential function, a 90° wall will perform cyclic irreversible jumps activated by the elastic strain if:

$$\begin{cases} \rho \le U \le \eta + \rho \\ 0 \le V \le \eta - \rho + U \end{cases} \tag{6}$$

The associated energy loss δW is an increasing function of the energetic distance between the jump treshold points (T_f and T_b in Fig.3.b). A first order approximation

$$\delta W \propto V \tag{7}$$

will be assumed.

The dissipation at the whole body scale will result by adding contributions from all the similar events. In order to carry out this evaluation, the following assumptions will be considered:

i) – the amorphous wire exhibits a "core-shell" domain structure [13]; correspondingly, only the superficial region of the sample containing magnetic domains separated by 90º walls will have contribution to MMD, which is in agreement with the observed low damping. It is also assumed that the parameters (6) will not exhibit significant changes within the "shell" zone of the wire.

ii) – the quantities U and V are statistically independent but their mean values are related by:

$$\langle V \rangle = 2\langle U \rangle \tag{8}$$

and obey the same distribution law [12]. A general peak-type analytical form:

$$F_m(x) = C_m\left(\frac{x}{q_m\langle x \rangle}\right)^m \exp\left[-\left(\frac{x}{q_m\langle x \rangle}\right)^m\right] ; \qquad m > 0 \quad x = U, V \tag{9}$$

where the parameters C_m and q_m depend on m and <x>, will be considered.

It is convenient to introduce the normalized energetic quantities

$$u = \frac{U}{q_m\langle V \rangle} = \frac{1}{2}\frac{U}{q_m\langle U \rangle} \quad ; \quad v = \frac{V}{q_m\langle V \rangle} \quad ; \quad h = \frac{\rho}{q_m\langle V \rangle} \quad ; \quad s = \frac{\eta}{q_m\langle V \rangle} \tag{10}$$

in terms of which the conditions (7) become:

$$\begin{cases} 0 \le v \le s - h + u \\ h \le u \le s + h \end{cases} \tag{11}$$

and the distribution function (9) takes, corresponding to the variables U or V, one of the forms:

$$f(u) = 2^{m+1} c_m u^m \exp\left(-(2u)^m\right) \; ; \; f(v) = c_m v^m \exp\left(-v^m\right) \quad , \quad c_m = q_m\langle V \rangle C_m \tag{12}$$

iii) – the distance between successive local maxima of $P(\xi)$ is considered small relative to the size of the magnetic domains; the number of walls is then smaller than the number of the available stable equilibrium positions ξ_1, ξ_2,…(see Fig.3.b). However, the higher the potential barrier the more probably in such a position a Bloch wall will be found. An empiric probability function

$$p(u) = 1 - \exp\left(-ru^n\right) \qquad ; \quad r, n > 0 \tag{13}$$

will be regarded as a weigthing factor when adding up contributions from all the possible events causing magnetomechanical damping.

Under these assumptions, a qualitative prediction of the MMD coefficient dependence on strain amplitude ($\Gamma \propto s$) and circular magnetic field ($H_\varphi \propto h$) results as:

$$Q_m^{-1} \propto \frac{1}{s^2} \int_g^{s+h} \left(1 - \exp\left(-ru^n\right)\right) u^m \exp\left(-(2u)^m\right) du \int_0^{s-h+u} v^{m+1} \exp\left(-v^m\right) dv \tag{14}$$

Appropriate choice of the distribution and probability parameters will lead to good agreement between theory and experiment. Thus, the solid lines in Fig.2 resulted by assuming m=1, n=7/2 and r=1 and choosing three values s_1, s_2 and s_3 in the same ratio as the amplitudes Γ_1, Γ_2 and Γ_3.

4. Conclusions

The magneto-mechanical damping behaviour of a stress-relieved $Fe_{77.5}Si_{7.5}B_{15}$ amorphous wire subjected to circular DC magnetic field was examined. Maxima vs both strain amplitude and field intensity were observed. The strain-activated irreversible jumps of 90° Bloch walls were identified as basic dissipation mechanism. The results were discussed in terms of an energetic model based on a conservative potential function ascribed to the effect of the internal stresses on domain wall motion.

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