MAGNETO-MECHANICAL EFFECT IN CIRCULAR FIELD IN  
\text{Fe}_{77.5}\text{Si}_{7.5}\text{B}_{15} \text{ AMORPHOUS WIRES} \\

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The magneto-mechanical damping behaviour of a stress-relieved \text{Fe}_{77.5}\text{Si}_{7.5}\text{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 90° 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.

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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:

\[
Q_m^{-1} = Q^{-1} - Q_{\text{sat}}^{-1}
\]  

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-180° 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 literature. Among the latter, in [9] MMD maxima vs longitudinal field exhibited by \text{Fe}_{77.5}\text{Si}_{7.5}\text{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 $l=55\text{mm}$ and diameter $d=135\mu\text{m}$ was cut from an amorphous wire of nominal composition Fe77.5Si7.5B15 produced by the in-rotating water spinning method. Annealing for 15 min. at 450°C 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 value of $29\times10^6$ 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 0.1 rad, a Hall effect-based transducer converted the specific strain ($\gamma$) at the surface of the wire into a signal:

$$u_\gamma(t) = C_\gamma \gamma(t) + u_o$$

where $C_\gamma=(5.68\pm0.07)10^4 \text{ V/rad}$ is the calibration constant and $-1mV<u_o<+1mV$ is an error voltage mainly caused by eventual Hall probe misorientation. The vertical component of Earth’s field was compensated 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 $\gamma(t)$ and $e_M(t)$ were performed at constant $H_\phi$ by analog-to-digital conversion; in Fig.1 the experimental procedure is illustrated.

Fig. 1. A sequence ($\approx2000$ data points) from a joint record of the elastic strain $\gamma(t)$ and of the amplified emf $e_M(t)$. The circular field strength at the sample surface was $H_\phi=20\text{A/m}$.

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 ($\Gamma$) was obtained by using a least-square fitting procedure based on stepwise exploring the vibrograms with the user-defined function:

$$u_{\gamma,i}(t) = C_\gamma \Gamma_i \exp\left(\frac{1}{4\pi}\ln\left(1-2\pi Q^{-1}_i\right)\right)\omega_i t \sin(\omega_i t + \alpha_i) + u_{0,i}$$

where the index “$i$” refers to successive full oscillation periods. The $H_\phi$ dependence of the MMD coefficient at constant $\Gamma$ was then extracted. A set of three representative examples corresponding to the highest observed damping are shown in Fig.2.
Magneto-mechanical effect in circular field in Fe$_{77.5}$Si$_{7.5}$B$_{15.5}$ amorphous wires

The curves exhibit maxima slightly shifting towards lower field strength with increasing strain amplitude. A relatively significant damping, increasing with $\Gamma$, 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 180° wall is not sensitive to tension or compression, the case of 90° Bloch walls will be considered only, oriented at an angle $\beta$ 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” $P(\xi)$ where $\xi$ is the wall abscissa along the local motion direction (Fig. 3.b).

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

$$P(\xi) = 0 ; \quad \frac{\partial P}{\partial \xi} > 0 \quad (4)$$
Introducing the quantities:

\[ \eta = 3\lambda_s G \cos (2\beta) \Gamma; \quad \rho = \sqrt{2\mu_o M_s \cos \beta} H \]

where \( \lambda_s \) is the saturation magnetostriction, \( G \) is the shear modulus, \( \mu_o \) 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:

\[ \begin{align*}
\rho & \leq U \leq \eta + \rho \\
0 & \leq V \leq \eta - \rho + U
\end{align*} \]

The associated energy loss \( \delta W \) is an increasing function of the energetic distance between the jump threshold points \( (T_f \text{ and } T_b \text{ in Fig.3.b}) \). A first order approximation

\[ \delta W \propto V \]

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 90° 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:

\[ \langle V \rangle = 2 \langle U \rangle \]

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

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

where the parameters \( C_m \) and \( q_m \) depend on \( m \) and \( \langle x \rangle \), will be considered.

It is convenient to introduce the normalized energetic quantities

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

in terms of which the conditions (7) become:

\[ \begin{align*}
0 & \leq v \leq s - h + u \\
h & \leq u \leq s + h
\end{align*} \]

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

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

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 \( \xi_1, \xi_2, \ldots \) (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
Magneto-mechanical effect in circular field in Fe$_{77.5}$Si$_{7.5}$B$_{15}$ amorphous wires

\[ p(u) = 1 - \exp\left(-ru^n\right) \quad ; \quad r, n > 0 \]  \hspace{1cm} (13)

will be regarded as a weighting 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 ($H_\phi \propto h$) results as:

\[ Q_m^{-1} \propto \frac{1}{s^2} \int \left[ \left(1 - \exp\left(-ru^n\right)\right)u^n \exp\left(-(2u)^m\right)du \right]_0^{s-h+u} \int \exp\left(-v^m\right)dv \]  \hspace{1cm} (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 $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$.

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.

References