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INTERNAL FRICTION AND HARMONIC GENERATION IN IRON

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Résumé - Le frottement intérieur du fer armco recuit a été mesuré près de 20 kHz dans un domaine de déformation atteignant 5×10^{-4} . Le frottement de Granato-Lücke dans l'état aimanté ainsi que le frottement suivant la loi de Rayleigh dans l'état désaimanté ont été observés. Des ondes harmoniques, produites par les déplacements de dislocations et aussi ceux des parois de Bloch, ont été mesurées jusqu'à l'ordre cinq.

Abstract - The internal friction of annealed Armco iron was measured near 20 kHz for strain amplitudes as high as 5×10^{-4} . Granato-Lücke damping was observed in the magnetized state, as was Rayleigh law damping in the demagnetized state. Harmonic waves produced by the motion of dislocations and domain walls were measured up to the 5th order.

I - INTRODUCTION

It is well established that the main sources for the internal friction in ferromagnetic materials vibrating with strain amplitudes ϵ_0 up to $\approx 10^{-3}$ are of magneto-mechanical origin [1,2]: stress-induced motion of the domain walls and rotation of the magnetization vector, the losses being referred to as magnetomechanical damping Q_m^{-1} . However, Q_m^{-1} is never seen alone. To separate Q_m^{-1} from other contributions, two measurements must be made on the specimen: one in zero field with the specimen demagnetized, and another in a saturating field. The corresponding damping values will be referred to as Q_0^{-1} and Q_S^{-1} respectively; from these one obtains Q_m^{-1} by subtraction: $Q_m^{-1} = Q_0^{-1} - Q_S^{-1}$. At frequencies less than 100 Hz, the behavior of Q_m^{-1} with increasing ϵ_0 for iron of various degrees of purity is well known: for $10^{-5} \leq \epsilon_0 \leq 10^{-3}$, a linear region (the Rayleigh region) is seen followed by a peak [3]. The model of Smith and Birchak, SB [4], based on an exponential distribution of internal stresses, gives a good description of the behavior of Q_m^{-1} vs. ϵ_0 with the slope of the linear region inversely proportional to the square of the internal stress. The dislocation damping measurements in iron, again at frequencies less than 100 Hz [3,5], show Q_S^{-1} to be ϵ_0 -independent up to about $\epsilon_0 = 10^{-4}$ after which it increases at a continually faster rate following the form described by Granato and Lücke (GL) [6]. The amplitude dependence arises from nonlinear mechanisms, which should also generate acoustic harmonics. Such harmonics have been measured in the kHz [7] and MHz [8] ranges for metals other than iron, although in the MHz range only at very low $\epsilon_0 \leq 10^{-6}$. The simultaneous measurement of damping and harmonics provides us with new insights into the dynamics of domain walls and dislocations. We report here measurements of internal friction and acoustic harmonics, up to the 5th order, for annealed armco Fe, over the large range of strain amplitudes $10^{-6} \leq \epsilon_0 \leq 5 \times 10^{-4}$.

EXPERIMENTAL APPARATUS

The transducer-step-transformer, TST, used to drive the system in steady state longitudinal vibration, and also to measure the damping of the specimen, has been described in detail elsewhere /9/. Our specimens were made of commercially pure iron, armco iron with less than 0.1% C content, having a dumbbell shape and, like the TST, tuned to a longitudinal resonance frequency of 22.5 kHz. After machining, the specimens were normalized at 900°C for one hour, then annealed at 700°C for four hours in an Argon atmosphere, which gave equiaxed grains of about 120µm in average size and magnetic domain widths in the range 10-40µm. A water-cooled solenoid provided an axial field up to 1000 Oe. A small (5 x 5 x 1 mm) LTZ-1 piezoelectric transducer cemented to the bottom of the specimen monitored the state of the specimen itself; this signal was filtered to reduce the fundamental by 40dB, to permit observation of the small harmonic signals without overloading the spectrum analyzer.

EXPERIMENTAL RESULTS

The specimen damping and harmonic amplitudes were measured as a function of ϵ_0 for both the demagnetized and the magnetically saturated states. Fig 1 shows a typical curve of Q_m^{-1} vs. ϵ_0 for an annealed specimen in the demagnetized state; a linear region is seen to extend up to $\epsilon_0 = 1.0 \times 10^{-4}$, followed by an upturn in Q_m^{-1} . When the saturating field is applied, the damping remains amplitude-independent up to $\epsilon_0 \leq 1 \times 10^{-4}$ then giving an amplitude dependence that, in a GL plot of $\log(\epsilon_0 Q_s^{-1})$ vs. ϵ_0^{-1} , Fig.2, exhibits two linear regions. The results for the harmonics are shown in Fig.3, for a demagnetized specimen, and in Fig.4 for a magnetically saturated specimen. The appearance of the harmonics is not accompanied by noticeable changes in the behavior of either Q_m^{-1} or Q_s^{-1} ; thus for a demagnetized specimen the harmonics begin to appear when Q_m^{-1} is in the linear range while for the magnetized specimen the second harmonic appears in the ϵ_0 -independent region. Plots of $\log A_n$ vs. $\log \epsilon_0$ allow us to test whether the n-th harmonic exhibits or an m-power law dependence on the strain amplitude of the form $A_n \propto \epsilon_0^m$. In demagnetized specimens the second harmonic A_2 has $1.3 \leq m \leq 2.5$, with m close to 2.0 in most cases, whereas for the third harmonic A_3 , $2.0 \leq m \leq 5.4$, with m scattered all over within the stated limits. When the specimen is magnetically saturated, the power-law relation for A_2 is at first $1.7 \leq m \leq 2.3$, but when $\epsilon_0 \geq 3 \times 10^{-4}$, A_2 departs from the power law and exhibits a broad peak in the region of amplitude dependence for Q_s^{-1} . A_3 for the saturated specimens does not exhibit a power law behavior, instead a dip in the value of A_3 is observed in the region $1.5 \times 10^{-4} \leq \epsilon_0 \leq 2.6 \times 10^{-4}$. The fourth and fifth harmonics were also observed but, because they don't appear until $\epsilon_0 \geq 1.5 \times 10^{-4}$, not enough data were collected to characterize them in detail.

ANALYSIS OF EXPERIMENTAL RESULTS

Damping - The slope θ_R of the linear region in Fig.1 is approximately equal to 25 and compares well with the values obtained for specimens of similar characteristics: $\theta_R \approx 40$ at 20 Hz /10/ and $\theta_R \approx 30$ at 50 kHz /11/; allowing for differences in heat treatment and purity among the specimens compared, the constancy of θ_R for a frequency variation greater than 10^3 is striking. This constancy confirms the hysteretic nature of the magnetomechanical losses in the Rayleigh region, since a notable characteristic of hysteretic behavior should be of independence frequency. At low ϵ_0 , the SB model gives

$$Q_m^{-1} \approx \frac{4K\lambda_s}{3\pi\epsilon_i^2} \epsilon_0 \quad (1),$$

where K is a constant which depends on the hysteresis loop, has a maximum value of 3, and is usually of the order of 1/4, λ_s is the saturation magnetostriction, for iron $\lambda_s \approx 7 \times 10^{-6}$, ϵ_i is the average of the absolute value of the internal strain in the specimen. Using $\theta_R = 25$, we obtain from eq.(1), $\epsilon_i \approx 4 \times 10^{-4}$, which is four to eight times larger than the corresponding values for high purity iron /12,13/ and is very

likely due to the internal stresses produced by the inclusions and C-interstitials since a similar shift to higher ϵ_1 - values has been observed with increased C-content /12/. The slope of the linear region can thus be used to make an evaluation of the internal stress. The ϵ_0 - independence seen for Q_s^{-1} at low ϵ_0 in Fig.2 is well known /3,10,12/, and, assuming dislocations are the main source for this damping probably indicates that the dislocations remain pinned and undergo viscous oscillations; as ϵ_0 increases beyond a certain value, there will be hysteretic losses corresponding to a mechanism of continuous breakaway and repinning of dislocations. The GL model corresponds to this description, giving dislocation damping of the form

$$Q^{-1} = \frac{C}{\epsilon_0} \exp(-D/\epsilon_0), \quad (2)$$

where C and D are constants depending on the dislocation density, the distance between impurity pinning points, and dislocation network pinning points. If eq.(2) is satisfied then $\log(\epsilon_0 Q_s^{-1})$ vs. ϵ_0 should exhibit a linear region of negative slope; the fact that two such regions are seen, Fig.2, probably arises from edge dislocations having, for the same ϵ_0 , greater amplitude of oscillation than the screws and so there will be a GL breakaway first for edges and then, at higher ϵ_0 , for screws. The suggestion that the amplitude dependent part of Q_s^{-1} comes from dislocations is reinforced by the analysis of the harmonics below.

Harmonics - It is surprising at first to see that the harmonics for the demagnetized and for the magnetically saturated specimens do not show as drastic a change as the damping, but we must remember that the damping, being inherently positive is the sum of positive contributions from all sources, while the harmonic signal is a sum of contributions with phases from all the sources. The phases being unknown at present, they might, at one extreme, be all the same, or at the other extreme all cancel, the expected result being somewhere between these limits. Now our measurements show that $A_2 \propto \epsilon_0^2$ holds for $\epsilon_0 > 2.5 \times 10^{-4}$ almost independently of the state of magnetization of the specimen, leading us to attribute the second harmonic in this range to lattice anharmonicity /14/; at higher ϵ_0 , $\epsilon_0 > 2.5 \times 10^{-4}$, A_2 shows a broad peak in a magnetically saturated specimen, Fig. 4, suggesting that the dislocation motion contributes to A_2 with a different phase, which would correspond to an increase in dislocation loop length as they breakaway from some pinning points /8,14/. Also the dip seen for the third harmonic, Fig.4, appears to be caused by the edge and screw dislocations contributing to A_3 with opposite phases and weighing factors that lead to cancellation at a particular value for the average dislocation loop length L_c , which is reached as the stress-induced breakaway takes place /8/.

Conclusions - The linear region for the magnetomechanical damping has been observed in the kHz range, the value of its slope both confirms the frequency independence of its hysteretic nature and allows for an estimate of the internal stresses to be made in ferromagnetic specimens. Harmonics are generated both from magnetomechanical and dislocation sources, but the second harmonic is primarily due to lattice anharmonicity, the broad peak for A_2 and the dip for A_3 seen for magnetized specimens, coupled with the GL type of ϵ_0 -dependence for Q_s^{-1} , indicates that dislocations are the likely sources of these effects.

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Fig.1.- Magnetomechanical damping for an annealed specimen.

Fig.2.- Granato-Lucke plots for annealed and lightly deformed specimens

Fig.3.- Harmonic spectrum for the demagnetized state. The details vary with each run.

Fig.4.- Harmonic spectrum for the magnetically saturated state, representative of all specimens.