Magnetoelastic resonance in single-crystal Fe+3% Si

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The absorption of sound was measured in single-crystal Fe+3% Si at frequencies 15–55 MHz in the temperature interval 300–1200 °K. Sound-absorption maxima of the resonant type were observed on the slow shear waves propagating in the [110] direction. An estimate of the resonance frequencies shows that the maxima are due to the predicted [1] interaction of elastic waves with surface magnetostatic oscillations.

Observation of natural magnetoelastic resonances (MAR) in ferromagnetic materials entails great experimental difficulties, since these resonances should as a rule be manifest at rather high frequencies, at which the nonmagnetic sound-absorption mechanisms (thermoelastic, dislocation, Akhiezer-type, etc.) are large. Consequently, natural MAR have been observed so far only in yttrium iron garnet crystals[2] as a result of the interaction of elastic and volume spin waves. There exists, however, one possibility of realizing natural MAR in ferromagnetic metallic crystals, namely by increasing the sample temperature and accordingly by decreasing the anisotropy constant K_1. Under these conditions, one should expect MAR at frequencies $\sim 10^8$ Hz in the temperature region where $K_1 \to 0$.

We have performed in this connection high-temperature measurements of the sound absorption coefficient α in single-crystal Fe + 3% Si in the [110] direction, on longitudinal and two shear waves. The measurement procedure is described in[3]. Figures 1 and 2 show the results of the measurements of α in the [110] direction on slow and fast shear waves, respectively. Since the domain structure of an Fe + 3% Si crystal cut in the [110] direction consists of a certain number of domains in the form of flat plates with maximum surface normal to [110] and with magnetization vectors in the directions [100] and [010], the fast shear wave (displacements in the wave parallel to [001]) do not interact with the spin waves. Accordingly, the maxima of α are of the relaxation type and are due to the intruded carbon atoms. This is well confirmed by estimates of the diffusion activation energy and the relaxation time, calculated from the temperature shift and position of the maxima with increasing frequency. Slow shear waves do not interact with point defects of this type, [4] and the observed maxima of α have a magnetic nature (high-temperature sound absorption in nonferromagnetic cubic metals at frequencies 10^7–10^8 Hz was investigated in[4]). At 55 MHZ (Fig. 1), two maxima of α are distinctly separated on the slow shear waves. At lower frequencies, the separation of the maxima is worse. The positions of the maxima with higher temperatures do not depend on the frequency and are caused by losses to eddy currents due to the displacement of the domain walls. [5] It can be shown that in this case $\alpha_{e.c.} \sim M_0/K_1$, and this ensures the appearance of a frequency-independent maximum in the region of $K_1 \approx 0$ [5] (M_0 is the spontaneous magnetization of the domains). The low temperature maxima of α depend on the frequency and are of the nonrelaxation type, since they shift to the right along the temperature axis when the frequency is lowered. This is evidence of a decrease of the resonant frequency with increasing temperature, owing to the decrease of K_1.

It follows from the results of the theory of[1] that the presence of domain boundaries leads to the appearance of two types of magnetoelastic resonances—volume and surface. The frequency ω_0 of the volume magnetoelastic resonance in a multidomain sample does not differ from that in a one-domain sample (at sufficiently large domain dimensions) and is equal to

$$\omega_0 = 2\gamma\left[\frac{K_1}{M_0}\left(\frac{K_1}{M_0} + 4\pi M_0 \sin\theta\right)\right]^{1/2}.$$

(Here γ is the gyromagnetic ratio and θ is the angle between the sound propagation direction and the domain magnetization.) Numerical estimates of ω_0 at the temperature of the low-temperature maximum of α ($T = 700$ °K, $K_1 \approx 0.2 \times 10^5$ erg/cm^3, $M_0 \approx 1.6 \times 10^3$ G, $\theta = 45$°) yield $\omega_0 \approx 5 \times 10^9$ sec$^{-1} \gg \omega_{ac} = 3 \times 10^8$ sec^{-1}. A decrease of ω_0 by taking the higher "geometric" frequencies ω_g into account ($\omega_g = sq_{l_0}$; $q_{l_0} = l(\pi/D)$; $l = 0.1, 2, \ldots s$ is the speed of sound, and D is the dimension of the domain) can hardly be expected because of the scatter in the domain dimensions at high tempera-

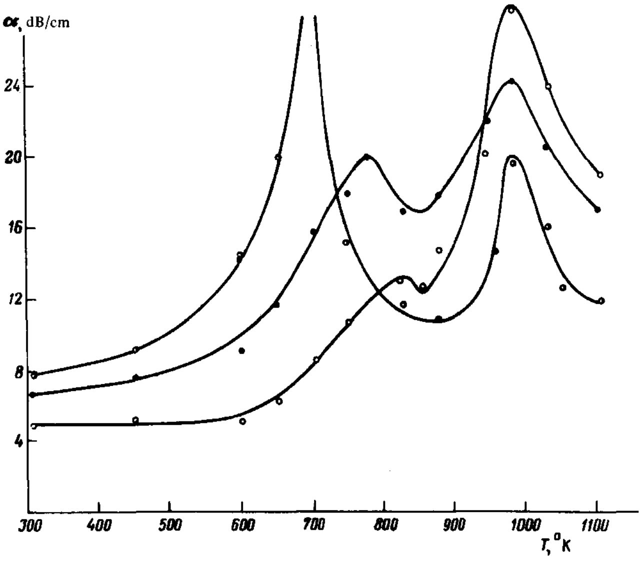

FIG. 1. Temperature dependence of the coefficient of sound absorption by slow shear waves: ◑—55 MHz, ●—35 MHz, ○—15 MHz.

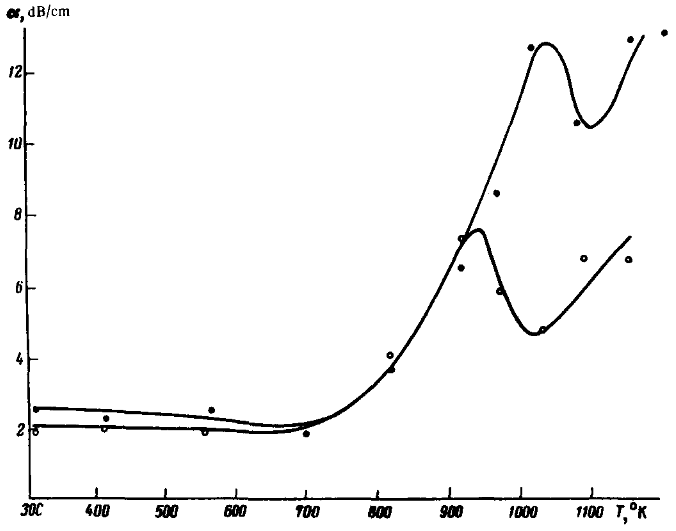

FIG. 2. Temperature dependence of the coefficient of sound absorption by fast shear waves: ● —55 MHz, ○—15 MHz.

tures and small K_1, when the domain dimensions are determined mainly by random internal stresses. The resonant properties of such a system should manifest themselves very weakly.

A different, surface type of resonance, present only in multidomain structures, appears at frequencies $\omega_s = 2\gamma(K_1/M_0)$. Using the obtained numerical values for constants, we obtain $\omega_s \approx \omega_{ac}$. Thus, the observed MAR can be considered to be of the surface type. Further increase of the temperature, by decreasing K_1, shifts the resonance region towards lower frequencies. With decreasing K_1, however, internal stresses begin to assume a major role, and this greatly broadens the resonance line and decreases its amplitude. An indirect confirmation of the fact that the observed maxima of α are due to surface MAR is provided by experiments performed at increased pressure on the sample, since the mechanical stresses increase the crystal energy via the magnetoelastic constants. An increase of the pressure to 3 atm raises the maximum of α at 55 MHz by 30–40°C.

It was also established that MAR exerts a distinct influence on the velocity of slow shear waves (Fig. 3), where a characteristic change in the velocity was observed in the resonance region (55 MHz). This change was not observed in measurements at low frequencies (15 MHZ), where the resonance condition was not satisfied. Outside the resonance region, no differences were observed in the behavior of the speed of sound measured at different frequencies. It should be noted that the errors in the measurements of the speed in the MAR region are very high and can amount to several percent, this being the consequence of the strong distortion of the waveform of the received signals. For fast shear waves, the speed of sound decreases monotonically with rising temperature.

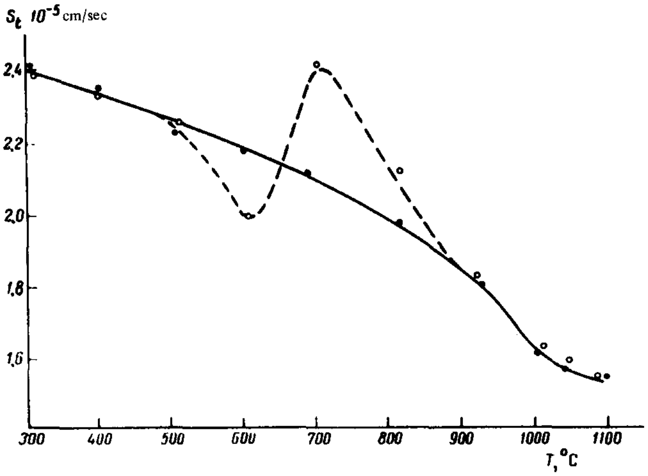

FIG. 3. Temperature dependence of the speed of sound for slow sheer waves ● —15 MHz, ○—55 MHz.

We emphasize that the theory of[1] was developed for the case when the displacement vector in the wave is parallel to the domain magnetization, whereas the geometry of our experiments was somewhat different. The agreement between the experimental and theoretical results for different geometries seems to indicate that the conclusion that surface MAR with $\omega = \omega_s$ exist is quite general in character.

We note in conclusion that measurements on longitudinal waves revealed no MAR. It is difficult to conclude from the experimental results that in the given geometry there is no interaction at all between the surface magnetic and the elastic waves, or that the MAR is masked by other effects, inasmuch as maxima of α are also observed for longitudinal waves and are due to the intruded carbon and to excitation of microeddy currents in the sample.

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