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Dependence of Sound Velocity on Magnetic Field Intensity and Orientation in Iron

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The velocity of 10-MHz sound waves in iron single crystals has been measured as a function of magnetic field intensity and orientation at room temperature. Changes of the order of 0.1% in the velocity with the field intensity and orientation were observed. Within a phase of $\pi/2$, a $\cos^2\theta$ dependence on orientation was observed. A comparison is made with previous results on nickel.

I. INTRODUCTION

The magnetoelastic interaction in a ferromagnetic single crystal can be detected by ultrasonic measurements. This interaction between the magnetization and the lattice causes a variation in the velocity of an acoustic wave. Experimentally, a change in the transit time of an ultrasonic wave is obtained as a function of the applied magnetic field intensity or orientation. Since the dimensional changes due to magnetostriction are too small to account for the measured change in transit time, this change is attributed here to a variation in the elastic constants which, of course, does not eliminate magnetostrictive strains as a contribution to the net effect.

Our measurements, reported here on single-crystal iron at room temperature, include the functional dependence of the elastic constants on both magnetic field intensity and orientation. A saturation effect is reached below 10 kOe in all cases. The magnitude of the change in elastic constants is $\lesssim 0.2\%$.

The same order of magnitude was found in nickel,[1] though saturation is not reached in all cases. A comparison of the iron and nickel data is made and discussed. Hopefully, the data will provide a further understanding of the properties of ferromagnetic materials.

II. EXPERIMENTAL PROCEDURE

The ultrasonic pulse-echo technique is well suited for the detection of small changes in the elastic constants. In this experiment a 10-MHz pulse is introduced into the sample via a quartz transducer glued onto one of two flat parallel surfaces. The same transducer then detects the repeatedly reflected pulse and feeds the signals (echoes) into a broad-band amplifier. The nth echo is then fed into an oscilloscope triggered by a 1-μsec marker fed through a variable-decay gate. Time changes of 0.2 nsec can be determined on the nth echo which magnifies changes on the first echo n times. Thus, using the 10th echo of a wave with a transit time of 10 μsec, a time change of 2 parts in 10^6 is detectable.

A Varian No. V-3703 electromagnet, capable of producing uniform fields up to 13 kOe, was calibrated, through the current in the field coils, by a Rawson rotating coil gaussmeter. The magnet could be rotated through 180°.

The iron single crystals used were those employed by Rotter and Smith.[2] They are right circular cylinders with faces normal to [110] direction. The length-to-diameter ratios are approximately one. The sample holder consisted of a hollow stainless-steel tube on which was mounted a rotatable hollow copper cylinder in which the crystal was glued. Rotation of the sample or magnet allowed the field direction to be rotated from $[\bar{1}10]$ to [001] (case I); [110] to [001] (case II); [110] to $[\bar{1}10]$ (case III).

Three independent modes were propagated in the [110] direction: longitudinal, $C'_{11}=\frac{1}{2}(C_{11}+C_{12}+2C_{44})$; transverse, $C=C_{44}$ (polarization $\parallel$ [001]); and transverse, $C'=\frac{1}{2}(C_{11}-C_{12})$ (polarization $\parallel$ $[\bar{1}10]$). The wave polarizations and field direction are defined in Fig. 1. Hereafter, the notation C-i, where C is the elastic constant and i = I, II, or III, will specify the mode and case under consideration. The zero-field room-temperature values for the elastic constants are,[2] in units of 10^{12} dyn/cm^2, $C'_{11}=2.994$, $C=1.164$, and $C'=0.4838$.

Since the demagnetized state in a ferromagnet is not reproducible, it was at first considered necessary to choose a better zero-field reference state. Thus, before data were taken for a particular field direction, the field was increased to 12 kOe in that direction, then reduced to zero. The consequent state of residual magnetization of the sample was chosen as the zero-field reference state. Further investigation, however, showed that the demagnetized state as the zero-field reference, gave the same results for Δt at saturation, a difference occuring only in the approach to saturation. Thus, as long as the discussion is restricted to results above saturation, the zero-field state seems inconsequential.

The dependence of transit time on field orientation was obtained at constant saturation fields by

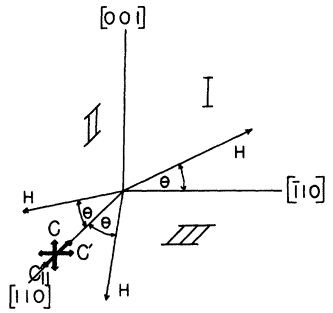

FIG. 1. Mode polarizations and magnetic field orientation cases.

rotating the crystal for case I and the magnet for cases II and III.

III. RESULTS

The measured changes in the transit time of the three elastic waves propagated in the [110] direction, with magnetic field aligned along major directions of crystals, [1̄10], [001], [110], are shown in Fig. 2. The data have been normalized by dividing by the zero-field transit time. Results shown are from measurements made on echoes 10, 12, and 15. Dashed lines indicate a smooth curve through the data. The estimated error in $\Delta t/t$ above saturation is 0.1×10^{-4}.

Since the elastic constant for each wave may be determined as the density times the wave velocity squared, the fractional change in elastic constants may be written as

$$\frac{\Delta C}{C}=\frac{-\Delta V}{V}+2\frac{\Delta L}{L}-2\frac{\Delta t}{t},$$

where V and L are the crystal volume and length, respectively, and t is transit time. Since the volume and linear magnetostriction[3] are at least two orders of magnitude smaller than the measured change in transit time, the fractional change in elastic constants is -2 times the data. Also, the fractional change in velocity, by the same reasoning, can be obtained by reversing the sign of the data.

The saturation field of about 5–7 kOe is readily explained by sample shape and size. Simple calculation shows the demagnetization field to be of this magnitude. Below saturation the data are dependent on the domain growth and rotation. The discrepancy between data for $\Delta t/t$ on demagnetized samples and those with residual magnetization is as large as 10^{-4} at 4 kOe but above saturation the discrepancy is within the estimated error.

Further evidence that the mechanism below saturation is domain growth can be drawn from measurements of echo amplitude vs field intensity. The amplitude of an echo increases, from zero field to saturation, by more than an order of magnitude, thereafter remaining constant. There are no phase or shape changes in an echo during the experiment. The reason for the large attenuation at zero field is thought to be scattering from domain walls.

The value above saturation of the fractional change in transit time is considered, for the purposes of this paper, to be constant in all cases. Measurements on the C' wave were extended to 22 kOe with

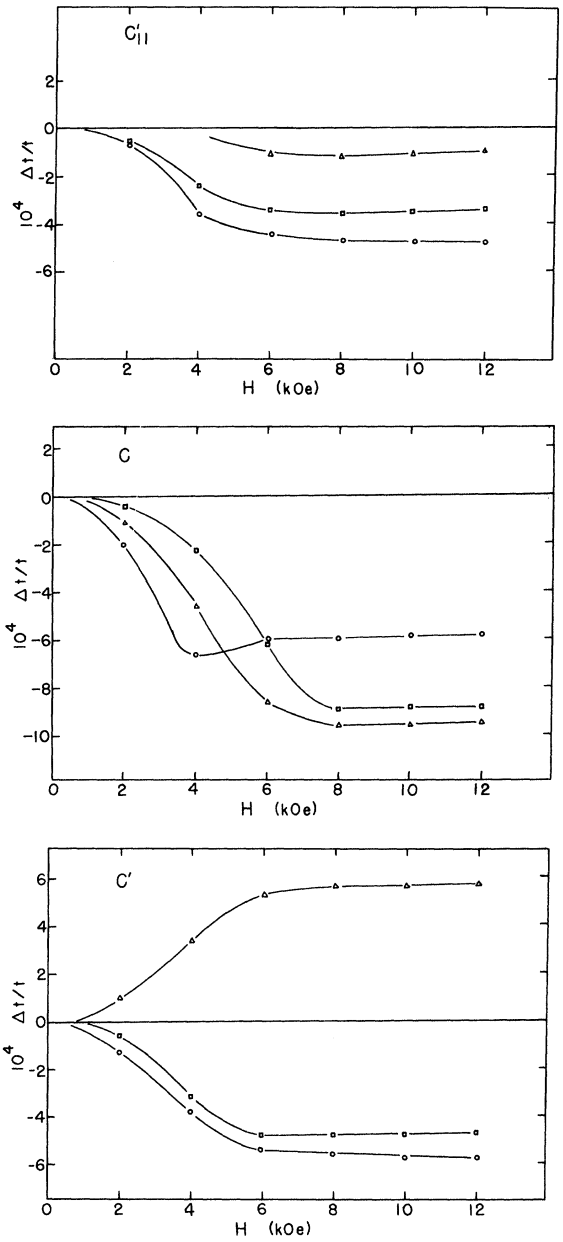

FIG. 2. Fractional change in transit time of C'_{11}, C, and C' modes in iron as a function of external magnetic field. □: $H\parallel[1\bar{1}0]$; △: $H\parallel[001]$; ○: $H\parallel[110]$.

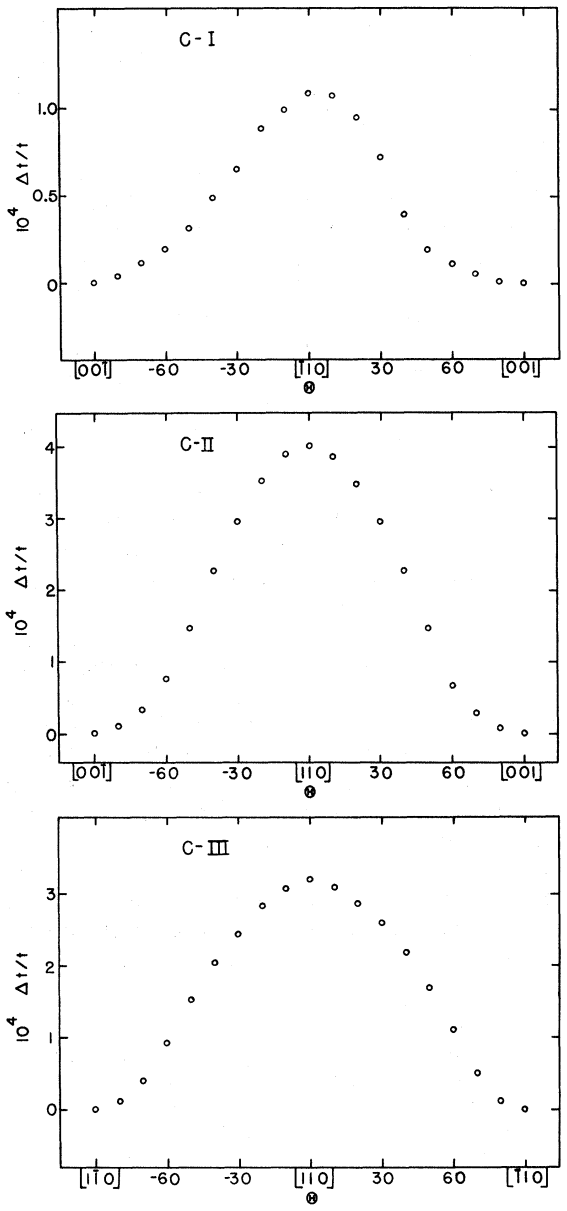

FIG. 3. Normalized angular dependence of C-mode transit time vs saturation-field orientation for all three cases. $\Delta C/C = -2\Delta t/t$.

no measurable change in value of $\Delta t/t$. The absolute fractional change in transit time is, in all cases, less than 0.1%

Due to the smallness of the effect of magnetization on the longitudinal wave, the angular dependence of the transit time was not investigated further. The dependence of a transverse acoustic velocity on field orientation was determined by varying orientation of a constant 10- or 12-kOe field as in cases I–III defined in Fig. 1. The normalized results are shown in Figs. 3 and 4. The maximum changes vary from 1 to 12 ($\times 10^{-4}$). No difference was noted between data taken at 10- and 12-kOe fields. The data were not corrected for actual direction of magnetization. Amplitude changes with orientation of the magnetic field were too small to be detected.

The angular data for $\Delta t/t$ obtained in this experiment can be approximated by a $\cos^2\theta$ curve for the C wave and a $\sin^2\theta$ curve for the C' wave, though the fit is not good for C-I and C'-III, which are of smallest amplitude for each mode and thus have largest error.

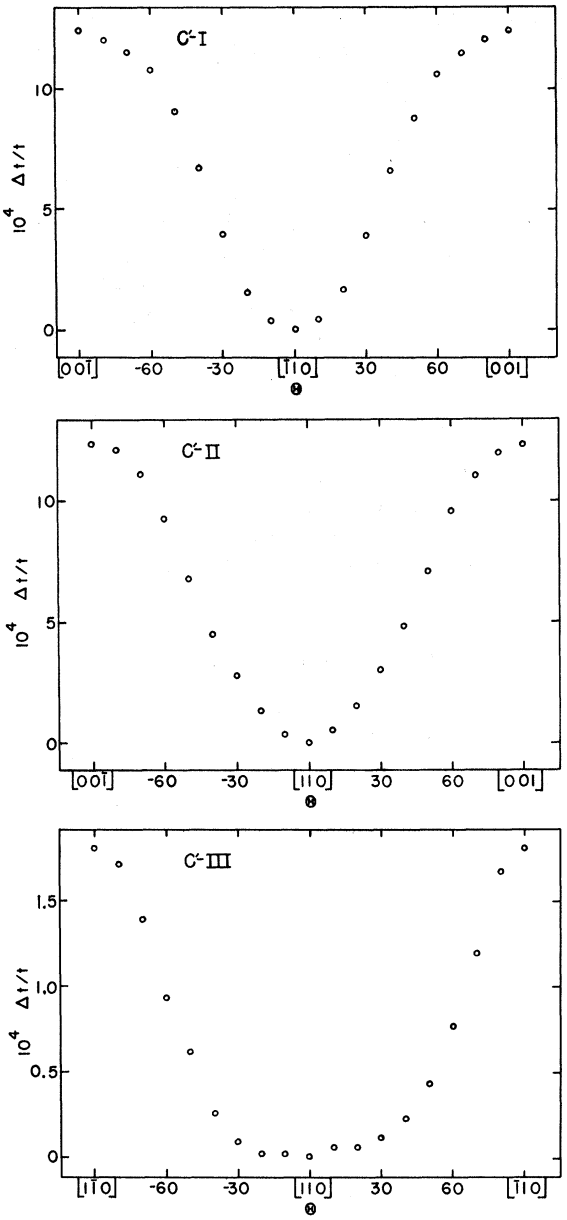

FIG. 4. Normalized angular dependence of C'-mode transit time vs saturation-field orientation for all three cases. $\Delta C'/C' = -2\Delta t/t$.

IV. DISCUSSION

The results obtained for iron are compared with previous work on nickel since no other similar experiment on iron has been reported. Mason[4] developed a phenomenological theory with an expansion of the enthalpy in powers of magnetization and stress. The terms of second power in both variables lead to a functional dependence of the elastic constants on the direction of magnetization, commonly called the morphic effect. The resultant equations predict no change for C'-III, which is in disagreement with our measurements, as can be seen in Fig. 4(c). The failure of this prediction, as well as the inability to arrive at a consistent fit for the rest of the data, led to the abandonment of the morphic effect as a suitable explanation of the effect observed in iron.

Alers *et al.*[1] applied a magnetoelastic theory, developed by Simon,[5] to their nickel data with some success. In this theory the magnetostriction, above saturation, causes stresses which change the direction of the magnetization, and which, by producing additional strains, make the effective elastic modulus appear reduced. The resultant dependence of the elastic constants on magnetization direction is given by the form

$$\Delta C/C = Af(\theta) ,$$

where $A = 9C\lambda^2(\chi/I_s^2)$ and $f(\theta)$ is the trignometric function appropriate to each case. C is the elastic constant under consideration, λ stands for the magnetostrictive constants[3] (λ_{111} for C mode; λ_{100} for C' mode), I_s is the saturation magnetization (1714 G for iron), and χ is the susceptibility (approximated by I_s/H in the nickel paper). $f(\theta)$ is derived as $\cos^2\theta$ for C'-I, II and C-III; $\sin^2\theta$ for C-I; and $\cos^2 2\theta$ for C-II and C'-III, where θ, for each case, is defined in Fig. 1. It should be recalled that $\sin^2\theta$ and $\cos^2\theta$ differ by a phase of $\pi/2$ or, put another way, they differ by sign and reference zero. The point is stressed since in the data for nickel, C-III actually seems to fit a $\sin^2\theta$ function if A is positive. If this is so, the iron and nickel data agree, in functional form, in four cases: C-I, III and C'-I, II. (Note that $\Delta C/C$ has $\sin^2\theta$ dependence for C mode and $\cos^2\theta$ dependence for C' mode. There is, for iron, no indication of a $\cos^2 2\theta$ dependence.)

The theory predicts the same maximum change for each case ($A = 2.2\times10^{-4}$ for the C mode, $A = 1.7\times10^{-4}$ for the C' mode). This is not observed for iron. Also, the magnitude of the observations is larger for the C' mode.

If χ is approximated as I_s/H then the amplitude of the effect should decrease with increasing field. The measurements made at 10 and 12 kOe show no such decrease. In fact, extension of the field to 22 kOe for the C' mode shows a constancy of the saturation magnitude. A major difference between the iron and the nickel data would seem to be the lack of saturation of the nickel data in some directions.

Neither the morphic effect nor the theory of Simon give the functional form for the magnetoelastic interaction as observed ultrasonically in iron.

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[2]C. A. Rotter and Charles S. Smith, J. Phys. Chem. Solids 27, 267 (1966).

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[4]W. P. Mason, Phys. Rev. 82, 715 (1951).

[5]G. Simon, Z. Naturforsch. 13A, 84 (1958).