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Electromagnetic-acoustic coupling in ferromagnetic metals at liquid-helium temperatures

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Electromagnetic-acoustic coupling at the surface and in the bulk of ferromagnetic metals at liquid-helium temperatures has been studied using electromagnetically excited acoustic standing-wave resonances at MHz frequencies in a number of ferromagnetic metals and alloys of commercial interest. The experimental results are compared with similar measurements at room temperature in the same and in different samples as well as with existing theoretical descriptions of the phenomenon.

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INTRODUCTION

Electromagnetic-acoustic coupling in ferromagnetic metals has been the subject of a large number of experimental and theoretical studies in recent years.[1-10] Most of the studies, however, have concentrated almost exclusively on the temperature range from room temperature up to the Curie point. As a result, very few quantitative studies of electromagnetic-acoustic coupling in ferromagnetic metals at low cryogenic temperatures have been carried out, and a number of important features of the phenomenon, such as the effect of material composition on low-temperature magnetostrictive-acoustic coupling, have remained completely uninvestigated. Apart from the intrinsic importance which a more thorough study of low-temperature electromagnetic-acoustic coupling in ferromagnetic materials would possess, such a study would also be of considerable interest from a practical point of view as cryogenic applications of ferromagnetic metals become increasingly common and would, in addition, provide a more critical test of the various theoretical models which have been developed phenomenologically to explain electromagnetic-acoustic coupling in ferromagnetic materials at room temperatures. It is the purpose of this article to report a detailed study of the electromagnetic-acoustic coupling in a number of ferromagnetic metals and alloys of commercial interest at liquid-helium temperatures. In particular, both bulk and surface electromagnetic-acoustic coupling have been investigated in detail in several ferromagnetic metals of significantly different composition and the experimental results compared both to similar measurements in the same samples at room temperatures as well as to existing theoretical descriptions.

EXPERIMENTAL METHOD

The electromagnetic-acoustic coupling was studied using a cw acoustic standing-wave resonance spectrometer.[10] The acoustic standing-wave resonances were both excited and detected electromagnetically using flat spiral coils mounted close to opposite sides of flat ferromagnetic metal plates. The use of a noncontact electromagnetic method of acoustic excitation and detection made it possible to carry out completely strain-free measurements of the acoustic generation as a function of dc magnetic field at liquid-helium temperatures. The selection of flat spiral coils[11] permitted a greater sensitivity than that obtainable with flat linear coils, as well as eliminating the necessity of correcting for possible changes in the sensitivity due to the magnetic field dependent rotation of the plane of polarization of the acoustic wave through the ferromagnetic samples. The choice of a standing-wave resonance technique was advantageous in allowing the electromagnetic-acoustic coupling to be studied simultaneously both in the bulk and the surface from the acoustic resonance itself by using a relatively simple experimental system. Thus, the acoustic attenuation α and the velocity of sound, v, in the bulk of the sample could be found from the linewidth $(\Delta f)_{\rm res}$ and the resonance frequency $f_{\rm res}$ of the acoustic standing-wave resonances[10] while the magnitude of the electromagnetic-acoustic coupling in the rf skin depth of the sample is directly proportional to the amplitude of the acoustic standing-wave resonances corrected for the acoustic attenuation within the bulk of the sample. In our case, it was convenient to measure the amplitude of the acoustic standing-wave resonances from the derivative of the signal S transmitted through the sample with respect to frequency f

$$\left(\frac{dS}{df}\right)_{\rm res} \equiv \left|\left(\frac{dS}{df}\right)_{\rm res,max} - \left(\frac{dS}{df}\right)_{\rm res,min}\right|, \tag{1}$$

where $(dS/df)_{\rm res,max}$ and $(dS/df)_{\rm res,min}$ are the maximum and the minimum, respectively, in the resonance change observed in dS/df at acoustic standing-wave resonance frequencies. Additional information about the electromagnetic-acoustic coupling at the surface of the sample could also be obtained from the line shape of the acoustic standing-wave resonances as described below.

EXPERIMENTAL RESULTS

We report here the results of measurements of the electromagnetic-acoustic coupling at liquid-helium temperatures in three different alloys of ferromagnetic metals chosen to illustrate the range of behavior possible at cryogenic temperatures. Measurements for several sample geometries and acoustic polarizations as well as for other ferromagnetic alloys were also carried out, but since the results are qualita-

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tively similar in all cases, we concentrate here primarily on the most extensive meaurements carried out for low MHz transverse acoustic waves propagating perpendicular to ca. 1-mm-thick flat polycrystalline plate samples of nickel, corronel, and inconel. The external dc magnetic field was also oriented along the same propagation (i.e., sample normal) direction.

At magnetic fields appreciably above the saturation field, it is expected that the Lorentz mechanism will be the dominant method of acoustic excitation[2,3] leading to a quadratic dependence of the amplitude of the acoustic standing-wave resonances measured in the transmitted signal $(dS/df)_{res}$ on the effective dc magnetic field within the skin depth where the acoustic excitation takes place. From Fig. 1(a), it can be seen that the amplitude of the low-temperature acoustic excitation for the polycrystalline samples studied is, in fact, very accurately proportional to the square of the *external* dc magnetic field at higher magnetic fields. The same quadratic dependence on the external magnetic field has previously been obtained for pure nickel single crystals at liquid-helium temperatures[12] as well as for a wide variety of polycrystalline and single-crystal ferromagnetic samples at room temperatures[2,3,5,8,9] showing that the electromagnetic-acoustic coupling within rf skin depth at higher magnetic fields is fully insensitive to the distribution of magnetizing fields within the skin depth over an extremely wide range of temperatures and values of the skin depth itself.[13]

In contrast to the high-field case, however, the amplitude of the acoustic excitation at lower magnetic fields is strongly temperature dependent. Thus the simple quadratic high-field dependence of the amplitude of the acoustic excitation observed here for nickel polycrystalline samples [Fig. 1(a)], as well as for previous measurements of nickel single crystals at liquid-helium temperatures, is in direct contrast to the large maximum in the amplitude of the acoustic excitation observed at room temperature in the same samples[10] (and in a wide variety of other ferromagnetic metals)[2-9] for magnetic fields comparable to or less than the magnetic saturation field. This experimental disappearance of the low-field maximum in the amplitude of the acoustic excitation can be qualitatively understood in terms of theoretical models which attribute the maximum to the presence of an additional magnetostrictive mechanism of acoustic excitation within the skin depth at lower magnetic fields,[2-6,8,9] Such a magnetostrictive mechanism of acoustic excitation would, in principle, be expected to exhibit a maximum at magnetic fields comparable to or less than the saturation field for which a maximum in the longitudinal or transverse differential magnetostriction occurs and would, at the same time, be expected to be less effective in high-conductivity samples, e.g., nickel at liquid-helium temperatures, where the rf skin depth within which magnetostrictive stresses act coherently on the lattice are smaller. This suggests that a maximum in the amplitude of the acoustic excitation, characteristic of a magnetostrictive-acoustic coupling within the skin depth, should also be observable at low cryogenic temperatures in high-resistivity ferromagnetic metals for which the rf skin depth were relatively large. From Fig. 1(a), it can be seen that an appreciable low-field maximum in the amplitude of the acoustic excitation is in fact observed for a high-resistivity inconel polycrystalline sample whose rf skin depth is large enough to include a significant fraction of the sample thickness at liquid-helium temperatures as shown by the large magnetic field variation of the electromagnetic background signal transmitted through the same sample [Fig. 1(b)] at a frequency differing from the acoustic standing-wave frequency. The exact form of the low-field maximum in the amplitude of the acoustic excitation in inconel, as indicated by the field dependence shown in Fig. 1(a) for magnetic fields above and below the magnetic field where the maximum occurs, differs somewhat from that expected on the basis of phenomenological models of the magnetostrictive excitation of acoustic waves. It should be noted that such models are quantitatively valid only in the case where the magnetostrictive-acoustic interaction is determined solely by reversible domain notation in single domain samples, conditions which are not satisfied for the low-temperature measurements in inconel. The low-field maximum in the amplitude of the acoustic excitation is, however, clearly of magnetostrictive nature since a 90° ($\pm$ 10°) phase shift[14] in the line shape of the acoustic standing-wave resonance is experimentally observed in inconel between measurements above and below the saturation field. Such a 90° phase shift would in fact be expected to result from the 45° phase difference betwen the rf electric and magnetic fields in the skin depth responsible for the electromagnetic-acoustic excitation[14] at high and low magnetic fields, respectively, where the Lorentz and magne-

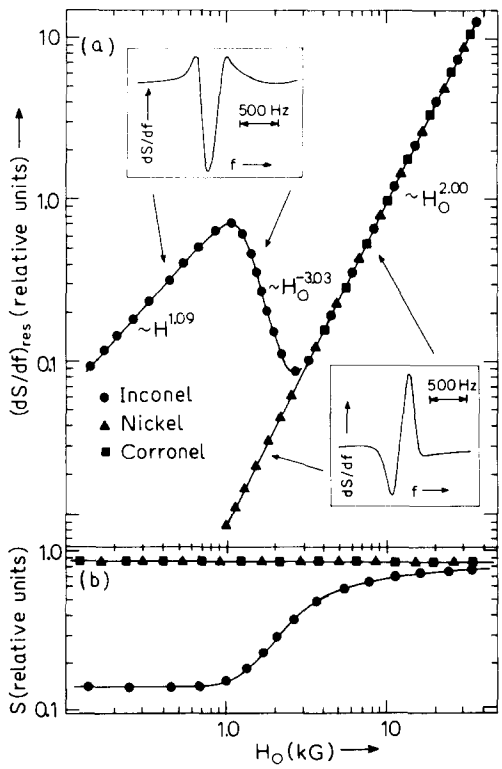

FIG. 1. (a) Amplitude, $(dS/df)_{res}$, of the acoustic standing-wave resonance measured from the derivative of the rf transmitted signal S with respect to the frequency f (as defined in the text) as a function of the external dc magnetic field H_0. The amplitude has been normalized to unity at a magnetic field of 10 kG. (b) Amplitude of the transmitted rf signal S at a frequency away from the acoustic standing-wave resonance.

tostrictive processes are dominant. It is worth noting that no phase shift in the measured line shape of the acoustic standing-wave resonance is observed above or below the magnetic saturation field at liquid-helium temperatures in the nickel polycrystalline sample for which a simple quadratic Lorentz field dependence of the amplitude of the acoustic excitation obtains [Fig. 1(a)] at all fields studied.

As indicated above, information about the electromagnetic-acoustic coupling within the bulk of ferromagnetic metals at liquid-helium temperatures can be obtained from measurements of the acoustic standing-wave resonance frequency f_{res} determined by the velocity of sound and the sample thickness. Such bulk properties would be expected to exhibit a much weaker temperature variation than the amplitude of the acoustic standing-wave resonance itself due to magnitude of the magnetostrictive-acoustic coupling within the skin depth at the surface of the sample. Measurements of the magnetic field dependence of the acoustic resonance frequency at room[10] and liquid-helium temperatures in nickel single and polycrystals [Fig. 2(a)[11,12]] are in fact essentially temperature independent,[15] although the exact magnitude of the very strong magnetostrictive-acoustic field variation cannot be quantitatively accounted for by present theories as noted before.[12] The different magnetic field dependences of the acoustic standing-wave resonance frequency observed in inconel and corronel at liquid-helium temperatures [Figs. 2(b) and 2(c)] are much smaller than that observed in nickel and differ substantially from each other as well as from the simple quadratic field dependence expected for Lorentz electromagnetic-acoustic coupling within the bulk of nonferromagnetic metals.[16] In addition, the decrease in the acoustic standing-wave resonance frequency for increasing magnetic fields observed in corronel and inconel (for magnetic fields from ca. 1 to 10 kG) can only be explained by an increase in the sample thickness for increasing magnetic fields if the electromagnetic-acoustic coupling in the bulk is determined by standard Lorentz or magnetostrictive models which predict a value of the velocity of sound which increases monotonically with the external magnetic field.

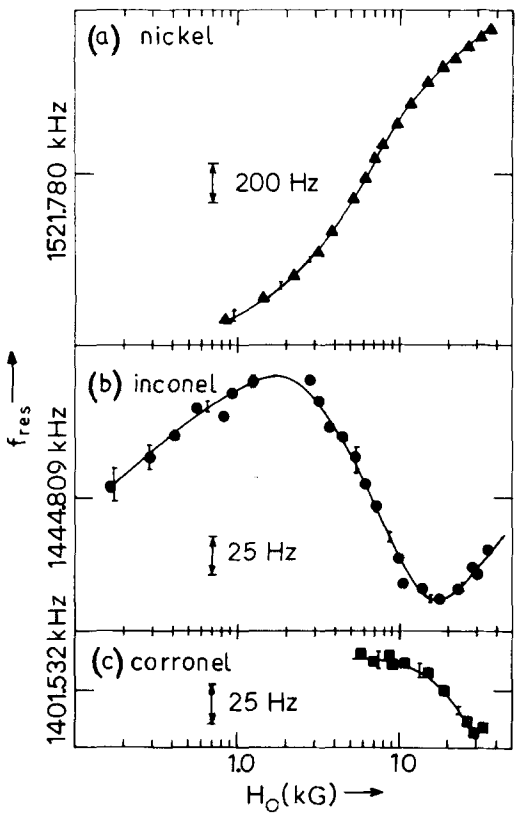

FIG. 2. Acoustic standing-wave resonance frequency f_{res} as a function of the external dc magnetic field H_0. The measurements were carried out simultaneously and in the same samples for which the amplitude of the acoustic standing-wave resonances shown in Fig. 1(a) were measured.

CONCLUSION

In contrast to room-temperature measurements the electromagnetic excitation of acoustic waves in the majority of ferromagnetic metals at very low cryogenic temperatures is accurately described by a single Lorentz mechanism of electromagnetic-acoustic coupling within the rf skin depth. Only in the case of relatively high-resistivity ferromagnetic metals is an additional magnetostrictive mechanism of acoustic excitation appreciable and only at magnetic fields comparable to the magnetic saturation field. On the other hand, the low-temperature field dependence of the velocity of sound is effectively dominated by magnetostrictive-acoustic coupling within the sample bulk which is only weakly temperature dependent but which depends very strongly in both magnitude and form on the particular ferromagnetic metal in question. In contrast to the Lorentz mechanism of electromagnetic-acoustic coupling which can be regarded as well understood quantitatively in ferromagnetic metals (with the possible exception of the experimental insensitivity to the distribution of magnetizing fields within the rf skin depth), magnetostrictive-acoustic coupling is quantitatively described by existing theories only over a comparatively limited range of magnetic fields.

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[13]This result holds for a change in the size of the rf skin depth by a factor of 20–30. The skin depth itself was also much smaller than either the acoustic wavelength on the sample thickness.
[14]The uncertainty in the measured phase shift results from the fact the line shape deviates slightly from a simple Lorentzian form. The phase shift in the line shape of the acoustic standing-wave resonance is expected to be twice that occurring in the corresponding acoustic displacements themselves since the acoustic standing-wave resonances measured here are both excited and detected electromagnetically.
[15]The temperature independence ($\pm$ 15%) in the form of the magnetic field dependence of the acoustic standing-wave resonance frequency is also found to occur in special sample orientations (avoided in all measurements reported here) for which anomalous extrema in the velocity of sound and in the acoustic attenuation are observed: R. A. Gordon and C. M. Larsen, Solid State Commun. **34**, 937 (1980).
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