UNIAXIAL STRESS EFFECTS ON THE LOW-FIELD MAGNETOACOUSTIC INTERACTIONS IN LOW AND MEDIUM CARBON STEELS

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INTRODUCTION

In the past, we have shown that the low-field magnetoacoustic technique is capable of detecting uniaxial compression in steel components without necessiating a calibration standard [1,2]. This is because the initial slope of the ΔF(B)/F curve (fractional frequency change of phase-locked acoustic waves as a function of net magnetic induction) is negative only under compression and positive otherwise, when the specimens are magnetized along the static unaxial stress axis.

The presence of the negative initial slope under compression has been confirmed in numerous steel samples having different carbon contents, grain sizes and mechanical and thermal treatment histories. Such a stress dependence of ΔF(B)/F curves has been explained by a model based on the uniaxial stress-induced domain structure rearrangement and domain structure-dependent elastic modulus. The quantitative stress effects on ΔF(B)/F varies from one type of steel to another. Especially, an interesting effect of uniaxial tensile stress has been found in medium-carbon steels which was attributed to the role of microscopic residual stresses on ΔF(B)/F almost certainly common to these steels [3].

The previous experiments mainly utilized bulk compressional and Rayleigh surface waves, with the induced magnetization parallel to the uniaxial stress axis. It is expected, however, that experiments under different conditions will provide more vital information on the ΔF(B)/F behavior and its uniaxial stress dependence. In this paper, we present the results obtained for low- and medium-carbon steel samples by using bulk shear waves and the induced magnetization perpendicular to the unaixal stress axis.

MAGNETIZATION PROCESS AND ELASTIC MODULUS CHANGES

Assuming that a sample is structurally isotropic, the domain structure should possess a cylindrical symmetry under a uniaxial stress

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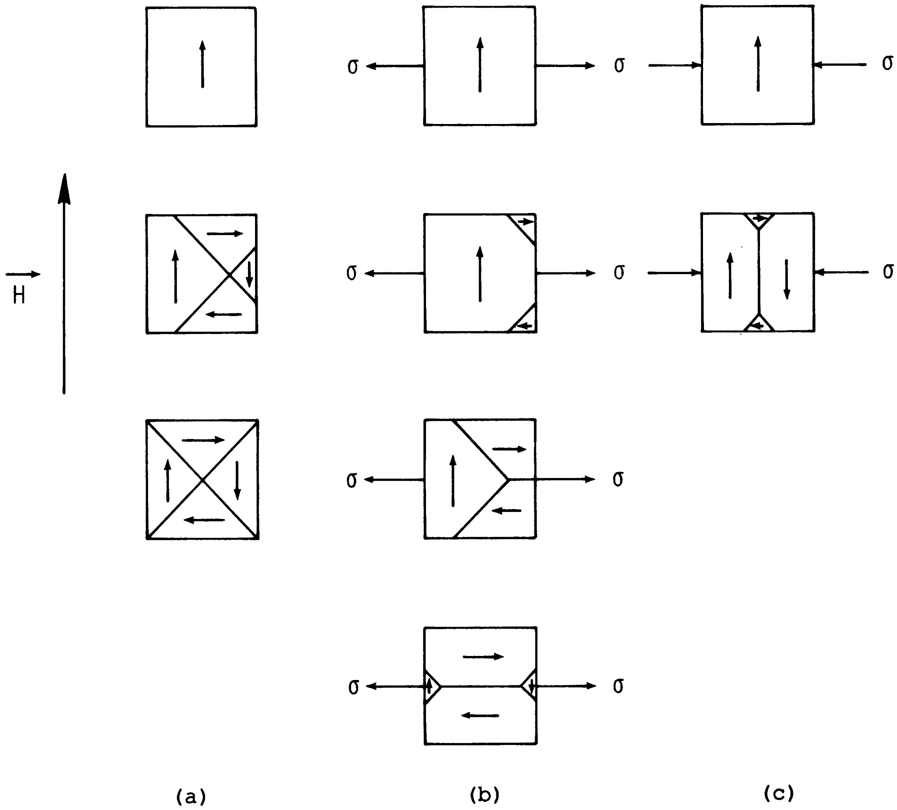

Fig.1. Domain wall motions due to application of external field perpendicular to the cylindrical axis of a rod sample when unstressed and uniaxially stressed.

applied in the cylindrical axis. Such a symmetry in the domain structure is preserved when an external field is applied in the stress axis but it is not otherwise. Figure 1 shows the domain structure changes due to external field applied perpendicular to the uniaxial stress axis. The majority of domain walls in the demagnetized state are 180-degree walls both under tension and compression. Most of the volume of a steel sample is occupied by the domains aligned parallel to stress axis under tension and perpendicular to the stress axis under compression to reduce the magnetoelastic energy. A fraction of residual domains, which are bounded mainly by 90-degree walls, always exists in impure materials because of the pinning effects of lattice defects. When a magnetic field is applied perpendicular to the stress axis, the domains having lower Zeeman energy begin to grow by moving domain walls in a certain way. Under a particular condition, the residual domains act as seed domains (Fig.1 b).

The 90-degree domain walls of iron or steel respond to uniaxial stress by moving their position, and thus produce an extra strain called the magnetoelastic strain. It is also well known that the sign of magnetoelastic strain is always the same as that of direct elastic strain regardless of the sign of magnetostriction coefficient [4]. Hence, the role of 90-degree domain walls in these ferromagnets is to reduce the elastic modulus. The acoustic wave velocity change during the magnetization process in the material, therefore, depends mainly on the state of 90-degree domain walls.

The expansion of the area of 90-degree domain walls due to a magnetic field applied perpendicular to the tensile stress axis described in Fig.1 is only a special case. The magnetic filed is generally not parallel to the magnetization vector in the residual domains with lowest Zeeman energy. In addition, the stress-induced easy magnetization axis is along the tensile stress axis for polycrystalline iron and steel. Hence, expansion of 90-degree wall area under tension in this case is less active than it is in the case of magnetization parallel to the compressive stress axis which results in a decrease of elastic modulus. Nevertheless, this increase of 90-degree wall area should decrease the elastic modulus somewhat.

EXPERIMENTS

Three types of steel samples have been used in these experiments. A 1020 steel sample was used as a typical low-carbon steel sample. Medium carbon steel samples were cut from the rim of heat-treated (class C) and un-heat-treated (class U) railroad wheels containing about .7 wt. % of carbon. The samples were first machined as cylidrical bars of 3.175 cm in diameter and 25.4 cm in length. The center portion of each sample was further machined to form a rectangular cross-section of 1.75 cm x 2 cm. Uniaxial stress was applied in the cylindrical axes of the samples.

To induce magnetization perpendicular to the uniaxial stress axis, a closed magnetic circuit was formed through the sample with pole pieces having rectangular cross-sections directly touching the sample except a small air gap (< 2 mm) on one side of the sample. Parts of these end pole pieces were machined to the sample thickness (1.75 cm) and tapped to match the cross-section of the outer poles surrounded by a pair of magnetizing coils. The pickup coil was placed on the one of the end pieces right next to the sample and it was assumed that the magnetic flux distribution is the same in the sample as it is in the end pole pieces. Other detailes of experiment can be found elsewhere [1,2].

RESULTS

The following designation of shear wave propagation mode is used for convenience:

- Mode 1 ; shear wave polarization vector perpendicular to the uniaxial stress axis.
- Mode 2 ; shear wave polarization vector parallel to the uniaxial stress axis.

The magnetic feild was applied parallel to the wave propagation vector, which was perpendicular to the stress axis for both cases.

Figure 2 shows the mode 1 results for the 1020 steel sample. The $\Delta F(B)/F$ curve obtained without external load increased almost linearly after magnetic induction reached about 4 kG. Curves begin to shift downward from the unstressed one both under tension and compression. The amount of downward shift is larger under tension than it is under compression but there is no initial negative slope obsreved. The mode 2 results for the 1020 steel are shown in Fig.3. The overall stress effects on the shape of the $\Delta F(B)/F$ are very similar to that seen in the previous figure but the amount of shift in the stressed curves are larger here.

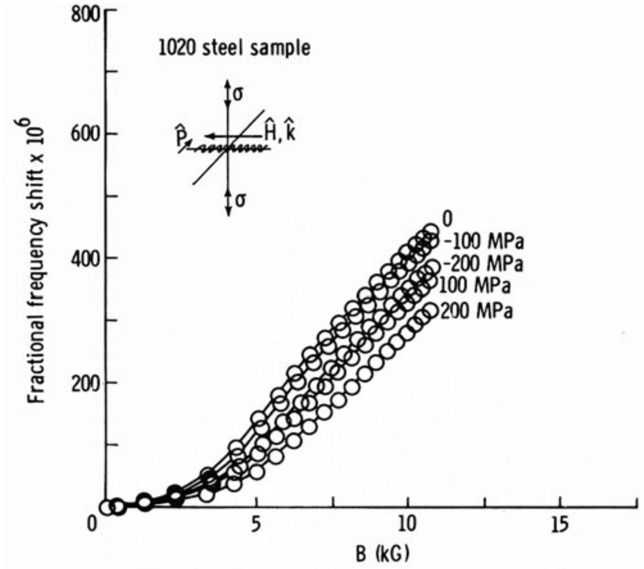

Fig.2. The results for the 1020 steel sample with shear wave mode 1.

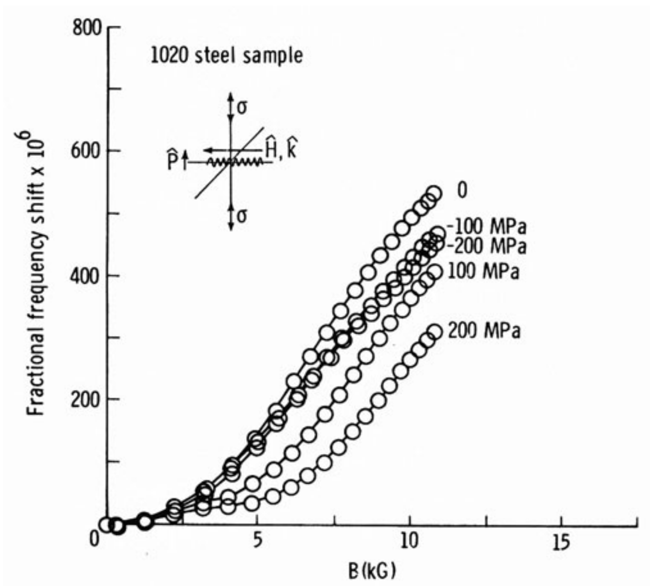

Fig.3. The results for the 1020 steel sample with shear wave mode 2.

Figure 4 shows the mode 1 results obtained for the sample cut from an untreated (class U) railroad wheel. The stress effects in this sample are markedly different from those in the previous sample, as evidenced by shifting ΔF(B)/F curves in opposite directions under opposite signs of applied uniaxial stress. It is shown in Fig.5 that such stress effects are reversed when the shear wave polarization is rotated by 90 degrees. It is also noteworthy that the unstressed curves in these two figures overlap to each other almost exactly which suggests that the material is probably structrually isotropic and free of residual stress.

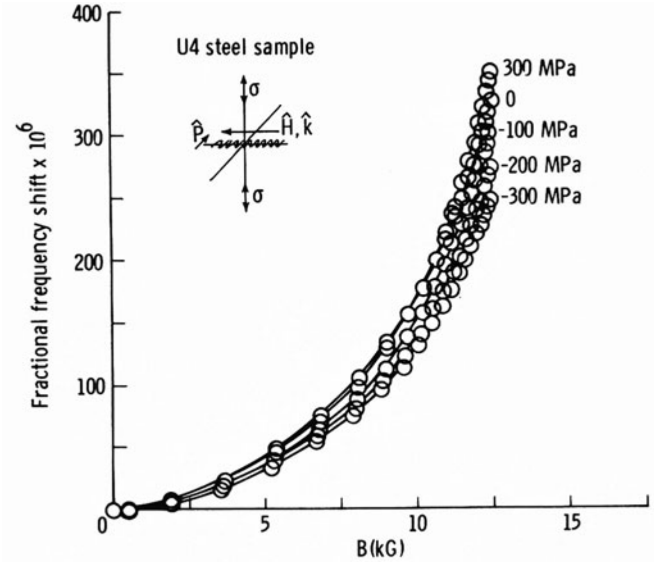

Fig.4. The results for the untreated railroad wheel steel sample with shear wave mode 1.

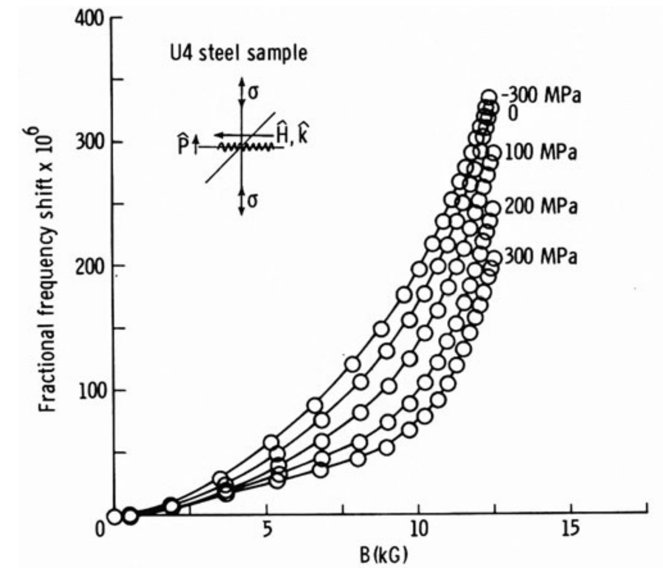

Fig.5. The results for the untreated railroad wheel steel sample with shear wave mode 2.

The next two figures show the results for the sample cut from a heat treated (class C) railroad wheel. The overall effects of uniaxial stress in this sample are consistent with those seen in the class U sample even though the magnitudes of shifting the curves are much smaller in this case.

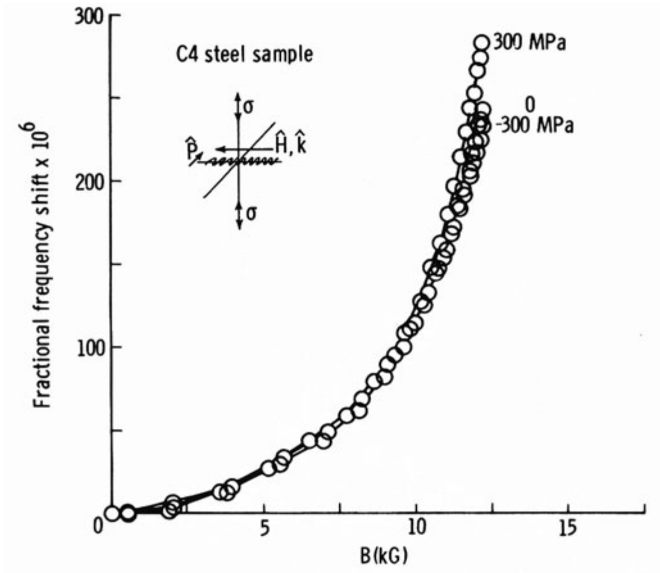

Fig.6. The results for the heat treated railroad wheel steel sample with shear wave mode 1.

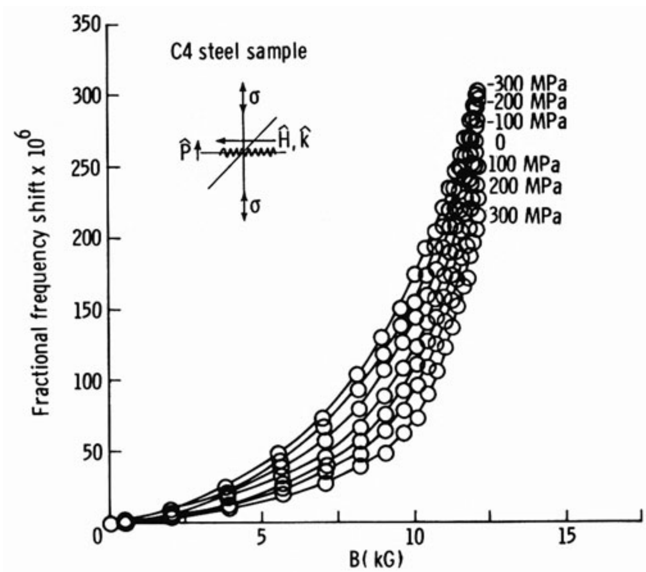

Fig.7. The results for the heat treated railroad wheel steel sample with shear wave mode 2.

DISCUSSION

Acoustic wave propagation velocities in crystalline solids are not simple functions of experimentally measurable parameters. The presence of ferromagnetism and uniaxial stress impose more complexity to the matter. In addition, the effect of a varying ferromagnetic state on the acoustic properties is observed in this experiment. Hence, to simplify the effects of magnetic field, the discussion will concentrate on the elastic modulus, which is assumed to behave in the same way as the acoustic wave velocity.

In the previous papers [1,2], the presence of negative initial slope of $\Delta F(B)/F$ in steel samples due to magnetization parallel to the compressive stress axis was explained adequately by the 90-degree domain wall growth model. As indicated in Fig.1 (b), negative initial slope should appear due to magnetization perpendicular to the tensile stress axis but it is not found in the results. Such a distinction in the two magnetization schemes neccesiates re-evaluation of the assumptions made for the model discription and further discussion on other possible effects.

The linear strain of tetragonal deformation of unit cells by magnetostriction is on the order of 10^{-5}. The macroscopic uniaxial stress-induced linear strains during the experiments are on the order of 10^{-3}. The model assumes implicitly that the components of these two strain tensors are linearly superimposed and hence the unit cells are still slightly elongated along the magnetization axis under stressed state. The uniaxial stress effects on intrinsic ferromagnetic properties can be estimated by the change in the saturation magnetization, M_s, which is about 1700 G at room temperature. According to the slope of forced magnetostriction obtained by Calhon *et al.*, $\Delta M_s/\Delta\sigma$ measured along the [100]-axis of pure iron is about 2.3×10^{-3} G/ MPa [5]. This suggests that the local electronic structure is not much affected by uniaxial stress to create any appreciable alteration in the magnetostrictive properties.

It is also assumed that 90-degree domain walls in a stressed state responds to the stress wave (acoustic wave) in the same way as it does in the unstressed state. Schneider *et al.* studied the effects of biaxial stress in steels [6]. They confirmed that the net pressure on 90-degree domain walls is proportional to the effective stress which is a mere algebraic sum of principal stresses in the two orthogonal axes. Therefore, the contribution of 90-degree walls to the elastic modulus should not be affected whether the material is prestressed or not.

The common fact in the two magnetization schemes is that 90-degree domain walls begin to expand with the application of external field. The difference is that the external field expands the domains where unit cells are uniaxially deformed in opposites. The model, in fact, pays attention only to the role of 90-degree domain walls during the magnetization process and the effect of domain bulk itself has not been taken into account at all.

The acoustic velocity in a ferromagnet is anisotropic depending on its polarization and propagation directions with respect to the magnetization vector. This phenomenon is called the morphic effect. Mason has shown that the fractional velocity anisotropy in nickel single crystals is on the order of 10^{-3} [7]. This value is an order higher than that of total $\Delta F(B)/F$ observed in this experiment for steels. The morphic effect itself is expected to be modified by the presence of uniaxial stress. The magnetoelastic effect is typically smaller in iron than in nickel and it is expected to be much smaller in steel. Consequently, the morphic effect would be much smaller in steel than in nickel. Even so, one cannot exclude the contribution of this term to the elastic modulus during the magnetization process.

The other effect to be considered is the role of interstitial carbon atoms which selectively occupy certain octahedral sites of the body-centered cubic lattice when the material is uniaxially stressed. Since the lattice distortion adjacent to these impurities is rather severe, they also cause anisotropy in the elastic modulus. In addition, these impurity atoms interact with the ferromagnetic state. Although the contributions of morphic effect and carbon interstitials have yet to be studied, they seem to have counter-effected the role of 90-degree walls on the elastic modulus when the sample is magnetized perpendicular to the tensile stress axis.

The sign of uniaxial stress determines the manner in which the $\Delta F(B)/F$ curve shifts with respect to the unstressed curve for railroad wheel samples, depending on the shear wave polarization, while 1020 steel sample shifts the curves downward only. Such a difference in uniaxial stress effects in previous experiments had been attributed to rather severe microscopic residual stresses present in medium-carbon steels, and the domain wall model worked well. It is, however, not very clear whether the same interpretation can be applied to the present results due to the complications involved in the magnetization process. Nevertheless, it has been shown clearly that there exists characteristic discrepancy in the uniaxial stress effects on the low-field magnetoacoustic interactions between low and medium-carbon steels.

The shear wave polarization dependence of the uniaxial stress effect on $\Delta F(B)/F$ indicates that the elastic modulus variations alone cannot acount for all the effects on the acoustic wave velocity. While a rigorus theoretical development is needed to support the experimental observation, such a polarization dependence is certainly a very promising feature for applying this test methodology for practical residual stress characterization.

CONCLUSION

In this paper, we present new low-field magnetoacoustics experimental results obtained for low- and medium-carbon steels. The measurements were made by applying an external field perpendicular to the uniaxial stress axis. In this configuration, the initial slope of $\Delta F(B)/F$ curve were expected to be negative under tension, but this did not happen. The absence of initial negative slope is most probably due to effects of magnetic domain volume (morphic effect) and/or the interstitial carbon atoms that inhibit the domain wall effect. The shear wave polarization dependence of uniaxial stress effect on $\Delta F(B)/F$ curves has been found to differentiate the sign of uniaxial stress in medium carbon steels.

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