REVIEW OF MAGNETOACOUSTIC RESIDUAL STRESS MEASUREMENT

TECHNIQUE FOR IRON-LIKE FERROMAGNETIC ALLOYS

M. Namkung, D. Utrata*, P. Langlois**,
P. W. Kushnick*** and J. L. Grainger****

NASA Langley Research Center
Hampton, VA 23665

INTRODUCTION

The stress dependence of the magnetoacoustic response in ferromagnets is based on two distinct, but not mutually independent, phenomena: stress dependence of domain structure and domain structure dependence of elastic modulus [1,2,3]. A difference in magnetoelastic energy density exists between two neighboring domains unless α, the angle between the uniaxial stress axis and magnetization vector, is the same for both domains. This difference is a net pressure acting on domain walls and, apparently, is non-zero only for 90° domain walls as long as α is different from 45° [4]. Application of uniaxial stress, hence, induces motion of 90° domain walls such that domains in iron-like ferromagnets align parallel (perpendicular) to the uniaxial tensile (compressive) stress axis. Producing local 90° domain wall motions, the same trend is valid for a stress wave propagating in these materials.

Motion of any non-180° domain wall always produces ε_{me}, magnetoelastic strain. When stress-induced, the sign of ε_{me} can be shown to be the same as that of the applied uniaxial stress [2]. The elastic modulus of a nonlinear solid can be expressed as

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_{el} + \Delta\varepsilon_{me}}$$

where $\Delta\varepsilon_{el}$ and $\Delta\varepsilon_{me}$ are direct elastic and magnetoelastic strains, respectivley, produced by the application of $\Delta\sigma$. The elastic moduli of

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* Association of American Railroads
3140 S. Federal St., Chicago, IL 60616

** UA-CNRS-ENSAM, Paris, France and
Virginia State University, Petersburg, VA 23803

*** PRC Kentron Inc., 303 Butler Farm Rd., Hampton, VA 23666

**** AS&M Inc., 107 Research Dr., Hampton, VA 23666

iron-like ferromagnets, thus, depends explicity on the state of 90^o domain walls, i.e., the more 90^o domain wall area available, the lower the elastic modulus is.

This paper presents new experimental results obtained for three types of carbon steel and pure iron samples, and a brief review of previous results.

ACOUSTIC MEASUREMENT TECHNIQUES

Two methods are available for measuring fractional changes in the propagation velocity of pulsed acoustic waves: (1) measuring the fractional frequency shift of a phase-locked acoustic signal, i.e., to force the phase difference between the reference and received signals to be constant [5], and (2) measuring the fractional phase difference between them while keeping the wave frequency constant [6]. The total phase difference between the reference and received signals is

$$\phi = 2\Pi fL/V$$

where f is the wave frequency, L is the total acoustic path length and V is the propagation velocity. With the above expression, the field-induced fractional frequency shift can be obtained as

$$\Delta f(B)/f = \Delta V(B)/V - \Delta L(B)/L$$

under the phase-locked condition, and the field-induced fractional phase shift can be obtained as

$$\Delta\phi(B)/\phi = \Delta L(B)/L - \Delta V(B)/V.$$

The strain term in the above expressions is due to macroscopic magnetostriction which is less than 10 parts per million (PPM) for various steels, and is negligible. Most of the experiments have been performed by measuring $\Delta f(B)/f$ mainly due to the maturity of the phase-locked acoustic technique.

MAGNETOACOUSTIC RESPONSE DUE TO MAGNETIZATION PARALLEL TO THE UNIAXIAL STRESS AXIS

The magnetization process due to a magnetic field applied parallel to the uniaxial stress axis can be found elsewhere [7]. The initial domain structure under compression is a combination of (1) domains separated mainly by 180^o walls that can be represented in a plane parallel to the stress axis and, (2) normal closure domains that can be represented in a plane perpendicular to the uniaxial stress axis. Upon the field application, the residual 90^o walls of the first type begin to expand at the same time the elastic modulus decreases. Such a trend continues until domain rotation begins to occur and beyond this point the modulus, in general, begins to increase.

When the material is under tension or unstressed, on the other hand, the elastic modulus should increase monotonically as the net magnetization increases over the domain wall motion and domain rotation regions, and approaches technical saturation. Having more 90^o domain walls initially, the total $\Delta f(B)/f$ obtained in the unstressed condition should be larger than that obtained under tension.

Experiments were performed on plain carbon steel samples of 1020, 1045 and 1095 by propagating 5 MHz compressional waves parallel to the uniaxial stress axis. Fig. 1 and Fig. 2 show the results of the 1020 steel sample under uniaxial tension and compression, respectively. The behavior of the Δf(B)/f curves under tension, being shifted downward as the stress amplitude increases, is seen to be consistent with what was predicted. The results in Fig. 2 show exactly the expected trend by showing a decrease in acoustic velocity as the moudulus decreases until domain wall motion expands the total area of 90° walls in the material. The inflection point of the Δf(B)/F curve under compression shifted downward as the stress amplitude increases.

The results for the 1045 steel sample, shown in Fig. 3, differ drastically from those for the 1020 steel sample, especially for the effect of tensile stress on the Δf(B)/f curves. Such effects of tensile

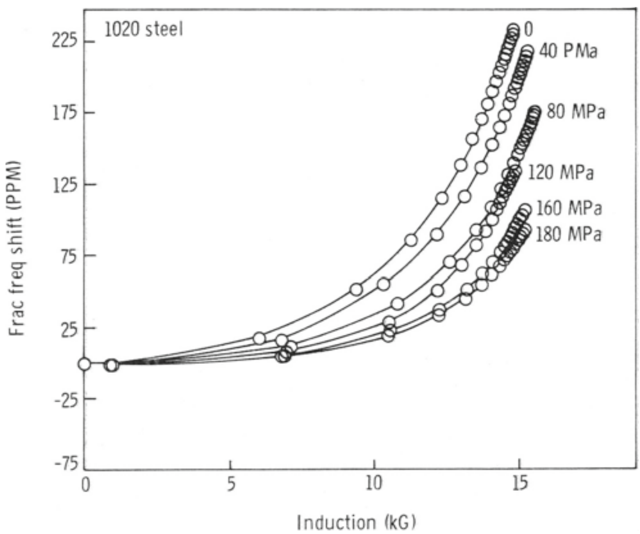

Fig. 1. Δf(B)/f curves obtained for the 1020 steel sample under uniaxial tension.

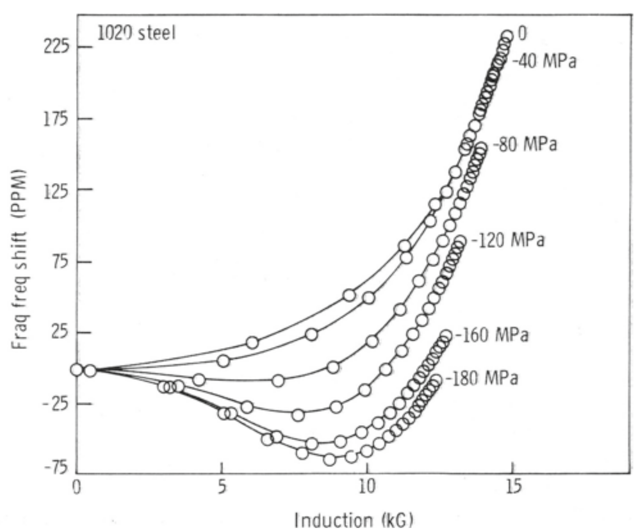

Fig. 2. Δf(B)/f curves obtained for the 1020 steel sample under uniaxial compression.

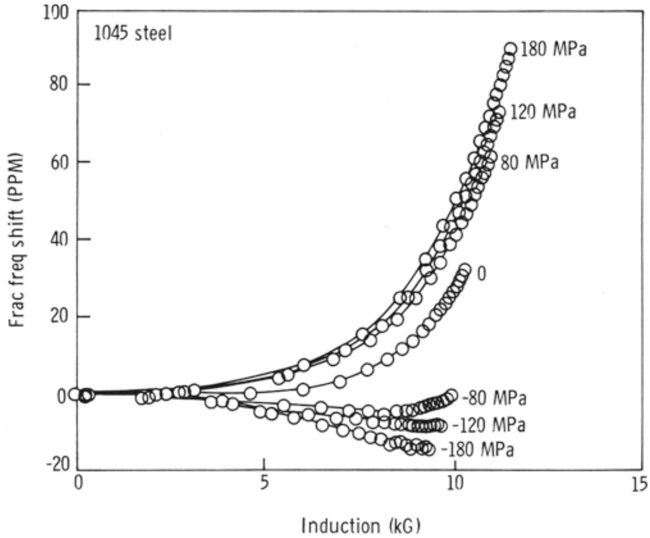

Fig. 3. $\Delta f(B)/f$ curves obtained for the 1045 steel sample.

stress can be explained in part by assuming that this type of steel possesses a high degree of local residual stress in the lattice which significantly lowers the mobility of 90^{o} domain walls. The motion of 90^{o} domain walls either by uniaxial stress or applied field becomes difficult in this sample. It is, therefore, possible that the presence of tensile stress merely helps the applied field remove 90^{o} domain walls and the curves shift upward as the stress amplitude is increased. Comparison of the curves obtained under maximum compression in Fig. 2 and Fig. 3 also provides some justification to the above assumption. This is because the $\Delta f(B)/F$ curve for the 1020 sample at -180 MPa shows the inflection point at about B = 8 kG whereas that for the 1045 steel sample is still decreasing. Thus it takes more applied field to expand the area of 90^{o} domain walls to its maximum in the 1045 steel sample.

The next two figures show the results obtained for the 1095 steel sample under tension and compression. The trend of stress effects in this sample is found to be very similar to that of the 1020 steel sample. Such a carbon content dependece of uniaxial stress effects on magneto-acoustic response has been known for the last few years but a detailed study is yet to be performed to find its origin. Nevertheless, it has been confirmed that there exists a certain range of carbon content in steel that show such an upward shift of $\Delta f(B)/F$ curves under uniaxial tension [7].

MAGNETOACOUSTIC RESPONSE DUE TO MAGNETIZATION PERPENDICULAR TO THE UNIAXIAL STRESS AXIS

Schematic representation of the magnetization process due to a magnetic field applied perpendicular to the uniaxial stress axis can be found elsewhere [8]. The general trend of uniaxial stress effects on $\Delta f(B)/f$ should be reversed from that seen for magnetization induced parallel to the uniaxial stress axis. There exists a basic differnce between these two magnetization schemes, i.e., the axial symmetry in the domain structure is preserved due to maganetization parallel to the unaixial stress axis, while it is not in the other case. Experiments have been performed previously using samples of 1020 and two different

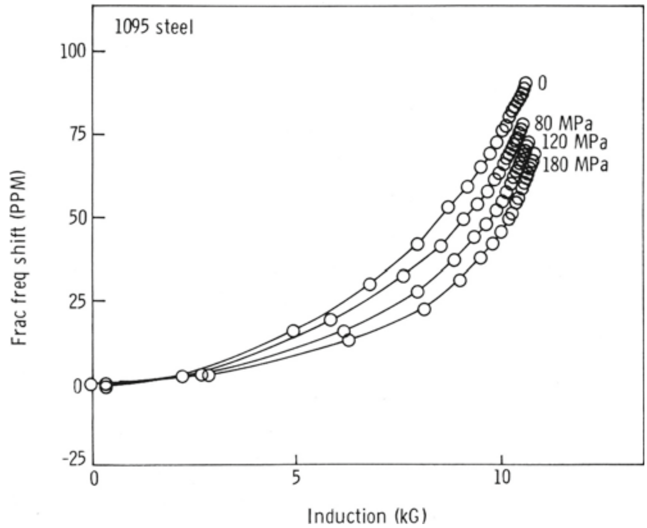

Fig. 4. $\Delta f(B)/f$ curves obtained for the 1095 steel sample under uniaxial tension.

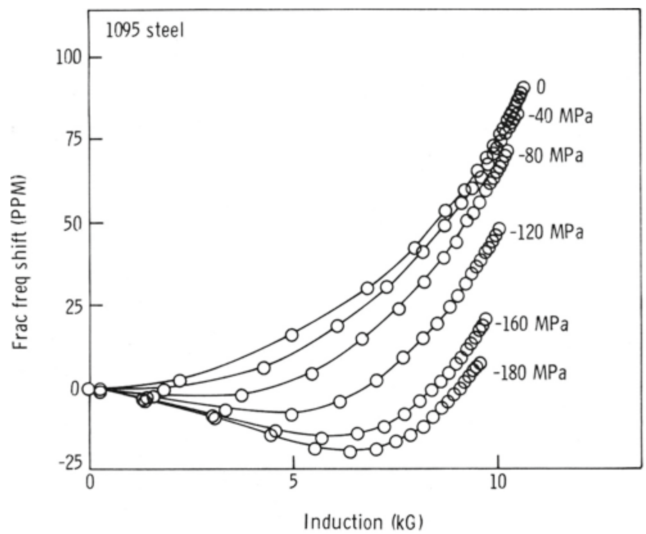

Fig. 5. $\Delta f(B)/f$ curves obtained for the 1095 steel sample under uniaxial compression.

types of railcar wheel steel. The results showed much smaller differences between the tension and compression curves in this case compared to that obtained by applying a magnetic field parallel to the uniaxial stress axis. Further, the initial negative slope of $\Delta f(B)/f$ has never been seen until a significant improvement was made to the acoustic instrumentation [6].

Acoustic shear waves have been proven to be more effective than compressional waves in differentiating the sign of the uniaxial stress with perpendicular magnetization. At least one mode of shear wave propagation, its wave vector perpendicular to both the magnetic field and uniaxial stress axes, and the polarization vector parallel to the stress axis, provides a negative initial slope under tension.

EXPERIMENTS AND RESULTS FOR PURE IRON

All the analysis made for these results have been based on the magnetic properties of pure iron. Therefore, it is necessary to perform experiments with a pure iron sample. Well annealed pure iron plates shaped as fatigue samples with a thickess of 6 mm were used for the measurement by propagating 2.25 MHz compressional waves perpendicular to the uniaxial stress axis which was also chosen as the magnetization axis.

The next two figures show the results obtained for two pure iron samples. These results show clearly the similar effects of tensile stress seen in the 1045 steel sample above, and railroad wheel and railroad rail steel samples. One can wonder why this happens, while the stress dependences of $\Delta f(B)/f$ are consistent with the magnetic properties of pure iron. A possible answer to this question is that domain wall movements are simply based on the magnetic properties of iron without considering the initrinsic local lattice residual stress state. It is well known that such local lattice stresses exists in ferromagnets absolutely free of metallurgical defects, i.e., vacancies, impurities, dislocations and so on. In addition, some experimental evidence shows that pure iron crystals contain a higher degree of local lattice stresses that some iron base alloys [9]. This means that the argument made for the tesile stress effect of $\Delta f(B)/f$ for 1045 steel may be applied to the case of pure iron.

Variation between the results of Fig. 6 and Fig. 7 is seen to be rather severe considering that these sample were prepared in a manner to achieve metallurgucally identical conditions. Assuming the sensitivity of $\Delta f(B)/f$ to small fluctuations, a study is being made to identify microstructural characteristics, especially, for the presence of texture variations in these samples.

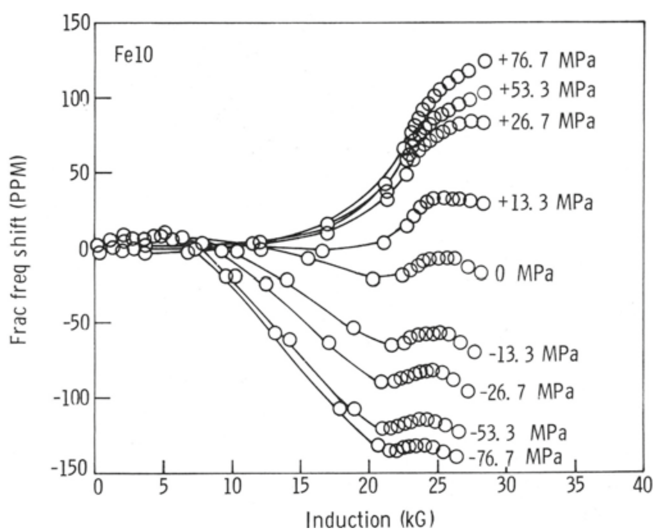

Fig. 6. $\Delta f(B)/f$ curves obatined for a pure iron sample by applying the magnetic field parallel to the stress axis and propagating compressional waves through the field axis.

Fig. 8 shows the Δf(B)/f and magnetizaation curves obtained in a pure iron sample under uniaxial compression. During reversible domain wall motion, Δf(B)/f shows very little change. No appreciable change in Δf(B)/f is seen untill about B=10 kG. Such an increase in induction is apparently contributed mainly by the 180° domain wall motions. Beyond this point, 90° domain walls abruptly jump over the pinning sites to expand the total area. These 90° domain walls travel as far as they can and domian rotaion process begins afterward. The minimum of Δf(B)/f under uniaxial compression occurs during the transition between domain wall motion and rotation regions.

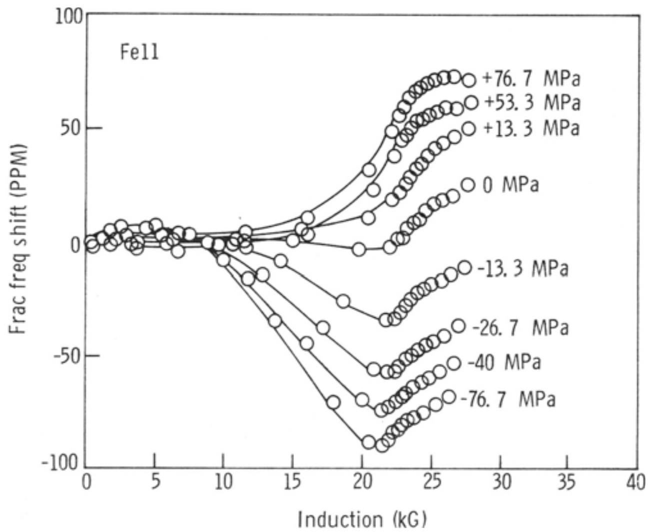

Fig. 7. Δf(B)/f curves obtained for another pure iron sample prepared under identical conditions.

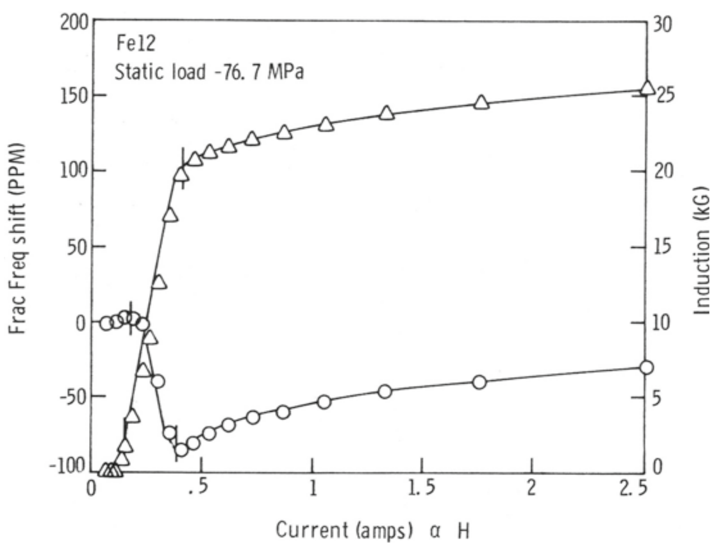

Fig. 8. Δf(B)/f and magnetiztion curves obtained for a pure iron sample.

SUMMARY AND FURTHER DISCUSSION

The present and previous experimental results on the subject indicate clearly that the magnetoacoustic response of ferromagnets involves various microstructural mechanisms. Nevertheless, the general effects of uniaxial stress on $\Delta f(B)/f$ are (1) the presence of an inital negative slope of $\Delta f(B)/f$ when net magnetization is induced parallel to the compressive stress axis, and (2) separation of the tension curve from the compression curve by the unstressed curve for a certain range of carbon content in steel.

As shown in Fig. 8, the portion of $\Delta f(B)/f$ carrying stress information coressponds to the domain wall motion region. All the theoretical analysis of magnetoacoustic interaction has been made for domain rotation and pure para process (well beyond technical saturation), and has never been made for the region of domain wall motion. The difficulty that limits the practical application of the technqiue, however, is induction of uniform magnetization of known magnitude in a region where the stress information needs to be otained. Hence, future devlopment should involve some extensive computational work on the magnetic field distribution in ferromagnetic objects as well as an effort to gain a deeper insight into the related physical processes.

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