

Capacitance bridge measurements of magnetostriction

Mark S. Boley,^{a)} Won C. Shin, David K. Rigsbee, and Doug A. Franklin

Department of Physics, Western Illinois University, One University Circle, Macomb, Illinois 61455

Magnetostriction effects were investigated for three different materials by using a simple, reproducible, and cost-effective method recently developed in our laboratory. The magnetostriction effects were generated by a large oscillating magnetic field produced by a high current 60 Hz ac welder power supply, capable of reaching saturation levels for the material, and then detected by a change in capacitance between a hollow cylindrical sample and a concentric brass ring. This capacitance change was continuously monitored at a high frequency rate by a standard laboratory capacitance bridge meter. The output voltage of the bridge was fed into a storage cathode-ray oscilloscope and its voltage versus time signals were then analyzed by a computer program. Two ferromagnetic rings, constructed of high-speed steels 4620 and 4340, which have proven applicability for use in magnetoelastic torque sensing, were used as the samples for investigating the magnetostriction effects, while a paramagnetic aluminum ring was used for the control sample. Our study showed that the 4340 ring, which had higher nickel, cobalt, and chromium content than that of the 4620 ring, had the largest magnetostriction effect, and that the aluminum ring displayed no magnetostriction effect, as was expected. We have found this experimental method to be both reproducible and sufficient to rank different ferromagnetic materials by their magnetostriction level, which is a significant consideration in producing effective magnetoelastic torque sensors. © 2002 American Institute of Physics. [DOI: 10.1063/1.1447512]

I. INTRODUCTION

Recently developed magnetoelastic torque-sensing technology¹ usually employs circumferentially magnetized shafts or rings of specially formulated alloy steels that have undergone unique processing treatments to enhance their efficiency.² Identifying these suitable alloys and assuring their appropriate sensor performance has proven to be an expensive and tedious process. In order to promote the widespread applicability of such devices, it is now essential to economically and reliably predict the suitability of additional specific alloys and processing treatments. Although the specification of mechanical properties of commercially available alloys is readily accessible, in the vast number of cases magnetic properties appear to be either unobtainable or unpublished. In particular, the magnetostriction level of the alloy is functionally one of the most important characteristics in determining its efficacy in torque-sensing technology.

Conventionally, rigorous measurements charting the change in dimensions of unconstrained, single-crystal samples were recorded as a saturating magnetic field was rotated through an angle of 90°. Such methods usually depended upon the use of complex mechanical or optical levers³ to measure changes in sample dimension on the order of one part per million (ppm). Besides the expense and delicacy of the measurement apparatus, the nonexistence of single crystal samples for the alloys under consideration, as well as the practical consideration that actual polycrystalline torque-sensing elements must be reproducible on a large scale, renders such classical measurements impractical. In 1920, Whiddington⁴ developed a system to measure minute magnetostrictive displacements in metallic alloys, which

formed one plate of a capacitor that was a portion of a two-oscillator circuit, by monitoring the beat frequencies between the oscillators. Almost forty years later, Thompson⁵ introduced the three-terminal method for the measurement of minute capacitances using a ratio transformer bridge, and this was shortly thereafter applied by White⁶ to the determination of thermal expansion coefficients. More recently, Rotter⁷ *et al.* have constructed a capacitance dilatometer cell, based on a tilted plate principle that requires numerical solutions of the capacitance equations, that when combined with a capacitance bridge circuit allows for high precision magnetostriction measurements in tiny single crystals. Additionally, Garshelis⁸ has adapted the two-oscillator method to perform a more simplistic bench-top magnetostriction measurement on polycrystalline steel alloys.

However, persistent difficulties with electronic circuit performance, oscillator calibration, and reproducibility of results in the latter case,⁸ as well as the complexity of numerical analysis and the nonexistence of single crystalline samples for such steel alloys in the former case,⁷ have prompted the development of a greatly simplified method utilizing standard laboratory equipment, but in a quite unconventional manner, for the purposes of ranking polycrystalline materials by their magnetostriction levels. Unfortunately, magnetostriction measurements in polycrystalline samples will likely not relate to one another in a linear, predictable manner, since it is nearly impossible to assume an initially isotropic arrangement of the domain structures. While such considerations may render the gathering of magnetostriction data at the ratio level questionable, the ranking of materials may be accomplished in a reliable manner using this scheme, thus allowing for the identification of additional suitable alloys for torque-sensing applications.

^{a)}Electronic mail: mbole@ccmail.wiu.edu

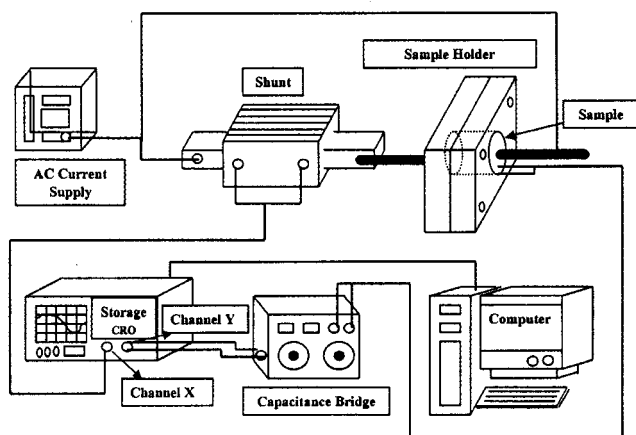


FIG. 1. Block diagram of the experimental setup for the capacitance bridge measurement of effective magnetostrictive strain.

II. THEORY

In order to initiate the magnetostrictive displacement in our sample rings, a sinusoidally oscillating circumferential magnetic field was produced by application of a large alternating current to a coaxial insulated conductor. According to classical magnetostriction theory,⁹ this results in a corresponding oscillatory variation in the radius of the sample ring, thus affecting its capacitance with a concentric non-magnetic holder according to the well-known formula for a cylindrical capacitor (where C is the capacitance of the device, l is the length, and r is the outer radius of the sample ring, and R is the inner radius of the holder):

$$C = \frac{2\pi\epsilon_0 l}{\ln(R/r)}$$

From this the effective magnetostrictive strain, $\lambda = \Delta r/r$, is calculated as follows:

$$\lambda = \frac{\exp[\ln R - (C/C + \Delta C)(\ln R - \ln r)] - r}{r}$$

where ΔC is the capacitance change as measured by the capacitance bridge meter, which is the only experimental input beyond the apparatus dimensions. The bridge meter operates on the principle of the Schering impedance bridge, the theory of which can be found in most upper level electromagnetics texts.

III. EXPERIMENT

Results obtained with three sample rings, of 9.45 mm outside radius and with 1.45 mm thick walls, of Al, steel alloy 4620 (with percent by weight — Ni 1.74, Mn 0.64, Al 0.28, Si 0.28, Mo 0.28, C 0.20, Cu 0.18, Cr 0.15, P 0.08, S 0.18, Sn 0.01, Co 0.010, and the balance is Fe), and steel alloy 4340 (with percent by weight — Ni 1.82, Cr 0.82, Mn 0.75, C 0.43, Mo 0.40, Si 0.33, Cu 0.07, V 0.069, Al 0.06, Co 0.014, and the balance is Fe) are reported here. Figure 1 shows the block diagram of the experimental setup. The

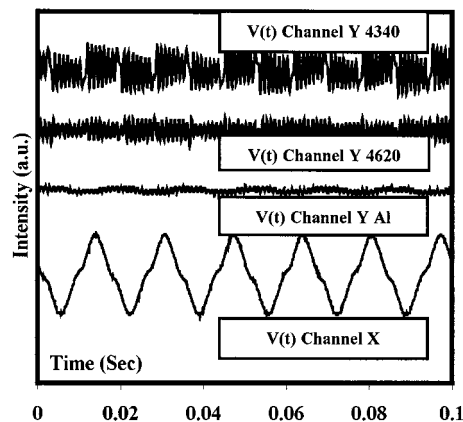


FIG. 2. Comparison of the CRO traces for the two magnetostrictive steel alloys and the control aluminum sample. The trace representing applied field is shown at the bottom.

large alternating current was provided by a 60 Hz power supply capable of sustained rms current values of up to 450 A, thus producing a large 60 Hz circumferential magnetic field in the sample ring. The current was continuously measured by the voltage across a calibrated resistance shunt and fed into the X channel of a storage CRO. The cylindrical capacitor formed by the sample rings insulated by rubber O rings from the nonmagnetic brass holder of inner radius 10.25 mm was connected to the capacitance bridge meter via shielded coaxial cable to minimize the effects of stray capacitance. The unique feature of the capacitance bridge meter as compared to modern solid-state capacitance measuring devices was its ability to almost instantaneously respond to changes in capacitance, which is a most crucial property for this experimental scheme. The rapidity of the response of the bridge meter and the corresponding density of capacitance change measurements within an oscillation cycle of the magnetic field is ideally limited only by the frequency of the minute alternating current used to balance the bridge. In our case, the 1000 Hz built-in ac sampling frequency was sufficient to convincingly demonstrate the effects of magnetostriction in the sample rings. The output voltage of the null detector of the bridge meter, which was calibrated to determine its approximately linear relationship with the capacitance change, was fed into the Y channel of the storage CRO. All voltage versus time signals collected were then downloaded to the computer for plotting and analysis. By differential comparison between the results obtained for the Al sample and the steel alloy samples any remaining effects of stray capacitance or capacitance drift could be removed from these signals; therefore, scope traces are shown in Fig. 2 for all three samples.

IV. RESULTS AND DISCUSSION

Figure 2 shows a comparison of the time-synchronized CRO Y traces obtained from the bridge meter for each of the three sample rings, demonstrating their effective magnetostrictive strains. The CRO X trace shown at the bottom of the figure represents the shunt voltage which is proportional to

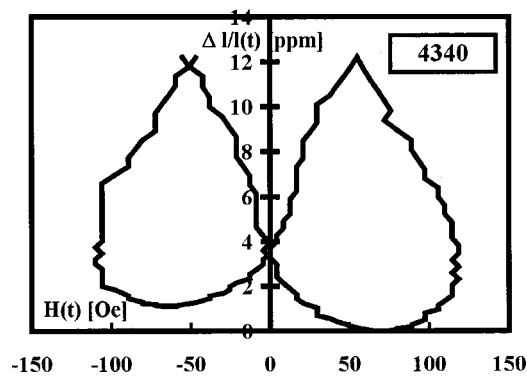


FIG. 3. Plot of the effective magnetostrictive strain in ppm vs applied magnetic field in oersteds for the 4340 alloy.

the oscillations of the current and the corresponding magnetic field. Clearly, the periodic nature of the top two traces and their dramatic pinching effects corresponding to the zero-field points of the cycle, apart from the small expected phase lag due to domain hysteresis, are compelling evidence of the magnetostrictive nature of the two steel alloys being observed. This is further accentuated by the absence of any features in the corresponding trace for the Al sample. The flat topping of the data in the top two traces likely indicates that rapid saturation has been reached in our steel alloys. It can be obviously seen from a comparison of the amplitudes of the Y traces that the 4620 alloy demonstrates a smaller magnetostrictive effect than the 4340 alloy. This is consistent with expectations¹⁰ based on alloy composition (higher percentages of Ni, Cr, and Co in 4340) and with experience in successful torque sensors only in the 4340 (300 M) material.²

Figures 3 and 4 are shown the graphs of effective magnetostrictive strain in ppm plotted as a function of applied magnetic field in Oe for the 4340 and the 4620 steel alloys, respectively. These figures represent the average of all cycles exhibited in the traces of Fig. 2. The relative heights in ppm of these two figures allow us to appropriately rank the materials by their magnetostriction. The shape of each graph is characteristic¹¹ of that observed for a classical λ -B graph in any magnetostrictive material.

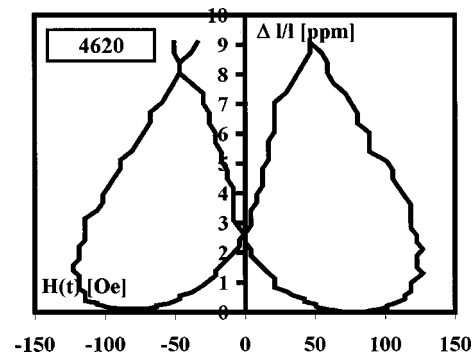


FIG. 4. Plot of the effective magnetostrictive strain in ppm vs applied magnetic field in oersteds for the 4620 alloy.

V. CONCLUSIONS

The ranking of materials with respect to their effective magnetostrictive strain has been accomplished using standard laboratory equipment, which represents a significant advancement in reliability, reproducibility, and incurred expense over previous measurements. This should appreciably broaden the class of available materials found to be suitable for use in torque-sensing applications, and increase our fundamental knowledge of their magnetic properties.

- ¹I. J. Garshelis and C. A. Jones, *J. Appl. Phys.* **85**, 5468 (1999).
- ²M. S. Boley, D. A. Franklin, and D. K. Rigsbee, *J. Appl. Phys.* **87**, 7073 (2000).
- ³S. R. Williams, *J. Opt. Soc. Am.* **14**, 343 (1927).
- ⁴R. Whiddington, *Philos. Mag.* **40**, 634 (1920).
- ⁵A. M. Thompson, *IRE Trans. Instrum.* **7**, 245 (1958).
- ⁶G. K. White, *Cryogenics* **1**, 151 (1961).
- ⁷M. Rotter, H. Muller, E. Gratz, M. Doerr, and M. Loewenhaupt, *Rev. Sci. Instrum.* **69**, 2742 (1998).
- ⁸I. J. Garshelis, C. A. Jones, D. K. Rigsbee, and D. W. Cripe, *International Magnetics*, IEEE 2000 Conference.
- ⁹R. M. Bozorth, *Ferromagnetism* (Van Nostrand, Princeton, NJ, 1951), p. 627.
- ¹⁰R. M. Bozorth, *Ferromagnetism* (Van Nostrand, Princeton, NJ, 1951), p. 657–684.
- ¹¹R. M. Bozorth, *Ferromagnetism* (Van Nostrand, Princeton, NJ, 1951), p. 633.