New techniques and results in the measurement of magnetostriction
J.E. Goldman

To cite this version:

HAL Id: jpa-00234406
https://hal.archives-ouvertes.fr/jpa-00234406
Submitted on 1 Jan 1951

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
NEW TECHNIQUES AND RESULTS IN THE MEASUREMENT OF MAGNETOSTRICTION

By J. E. GOLDMAN,
Westinghouse Research Laboratories and Carnegie Institute of Technology.

Introduction. — In 1947 [1], the writer proposed the use of electrical resistance strain gauges for the measurement of magnetostriction. This method offers certain notable advantages which will be enumerated below. Since that time, the technique of measurement has been refined, the accuracy and range improved; this has made possible measurements on materials and sample geometries not previously amenable to accurate measurement. This paper will be devoted to a description of the method of measurement and a survey of some of the more recent results obtained as part of a program for the study of magnetostrictive phenomena initiated in the writer's laboratory and more recently continued in a program under the writer's direction at Carnegie Institute of Technology [2]. The measurements on single crystals of iron-silicon are part of an unpublished dissertation by W. J. Carr, Jr. at the latter institution with the cooperation of Prof. Smoluchowski.

Experimental Technique. — Electrical resistance strain gauges operate on the principle that if a thin wire is stretched its resistance will undergo a change proportional to the degree of strain. The constant of proportionality is termed the gauge factor, i.e.

$$GF = \frac{\Delta R}{\Delta I}$$

and may vary from 1 to 13, depending upon the material, the magnitude of the stress and other factors. In our experiments we have used commercial Type A gauges manufactured in the United States by the Baldwin Locomotive Works. These gauges are of advance (60 cu, 40 ni) wire and at the magnitude of magnetic fields used, the magneto-resistive effect in this material is either negligible or small enough so that it can be compensated for without unduly impairing the accuracy. In practice the gauge is bonded to the sample with a cellulose-acetate cement. Commercial gauges as small as 1.5 mm in length are available permitting the measurement of magnetostriction on single crystals or other samples as small as 3 mm in diameter.

Measurements of the change of resistance of the active gauge are made with a conventional DC Wheatstone bridge in which all the arms of the bridge are made up of equivalent gauges that are bonded to non-magnetic material but with a coefficient of thermal expansion closely matching that of the material under test thus eliminating errors due to ambient temperature variations. The detector is a sensitive DC amplifier which has a 75 c chopper in the input, a 75 c narrow-band amplifier and a synchronous commutator at the output. The output signal is recorded on a 0-5 mA recorder. Full scale deflection on the recorder can be obtained with an input signal of \(10^{-7}\) V. A schematic circuit diagram is shown in figure 1.

The constancy of the gauge factor and the behavior of the bond at very low positive and negative strains (expansion and contraction) were checked by measuring the known elastic moduli of metal samples using this method. The system is readily calibrated in terms of strain by introducing a known change in resistance in the active arm of the bridge and noting the deflection of the recording milliammeter. With this arrangement and with drift as well as pick-up reduced to a minimum a strain sensitivity of the order of \(2 \times 10^{-8}\) mm scale deflection can be obtained.
This method of measurement has the following noteworthy advantages:

1. It can be applied to the measurement of magnetostriction on samples of a variety of shapes and geometries including extremely small single crystals that do not permit of ready measurement by other methods.

2. In the case of thin laminated samples, errors due to bending can be eliminated by applying gauges on both sides of sample and connecting them in series.

3. Regions over which strain measurements are made are small so that variables such as end effects, shearing stresses and non-uniformity are eliminated.

4. The effects of temperature variations and other ambient variables are eliminated. Adequate sensitivity and stability are available so that measurements can be made when the sample has attained thermal equilibrium thus minimizing errors resulting from temperature effects in the sample due to magnetocaloric effect and other magnetothermal effects.

5. A closed magnetic path may be used, thus assuring a greater uniformity of flux distribution and eliminating possible errors due to form effect.

6. Finally, and perhaps most significant, measurements are very readily made in two perpendicular directions thus eliminating to a great extent the uncertainty in the knowledge of the demagnetized state and errors in the interpretation of results due to the possible non-randomness in crystal orientation or in the initial distribution of domain directions. In the case of the single crystal measurements the sample is always saturated and only the direction of \( M_3 \) is varied with respect to the direction of strain measurement. Moreover, by measuring the strain simultaneously parallel and transverse to the direction of magnetization, the volume magnetostriction is very easily separated from the longitudinal magnetostriction, if one assumes that no first order volume change accompanies the latter. In this connection it may be pointed out that we have recently adopted this technique for the measurement of volume magnetostriction.

**Measurements on Single Crystals.** — Quantitative data on the behavior of the magnetostriction constants of alloys as a function of composition are available only in the case of the iron-nickel alloys [3] and a few isolated cases [4] where large single crystals have been made. In such cases as the iron-cobalt alloys, it is quite difficult to obtain sizeable single crystals and hence the significant single crystal magnetostriction data is not available. Using the above described technique we have made measurements on a single crystal of a 3o per 100 cobalt-iron alloy in the from of an oblate spheroid 3.5 mm in diameter and 0.3 mm in thickness [5]. The plane of the crystal was ascertained by taking a back-reflection X-ray picture and found to be approximately (411). A very fine strain gauge with active dimensions approximately 1.5 mm² was bonded onto the crystal in such a way that the direction-cosines of the gauge axis relative to the cubic axes are (0.93 ±, 0.21, 0.21). The crystal was placed in a magnetic field of 4000 Oe and the change in strain in the above fixed direction was measured as a function of the angle made by this direction with the direction of the field. The results are plotted in figure 2. Using the relation given by Becker [6] for the magnetostriction of a cubic single crystal as a function of the direction-cosines of the direction of strain measurement and the direction of magnetization, we have obtained for the single crystal constants

\[
\lambda_{100} = 1.5 \times 10^{-5} \quad \text{and} \quad \lambda_{111} = 8.5 \times 10^{-5}.
\]

Using Becker's relation for the polycrystalline saturation magnetostriction (assuming random crystal...
In excellent agreement with values obtained on a sample of this composition measured in our laboratory in such a way as to eliminate the uncertainty in knowledge of the initial domain distribution and in agreement with the value given by Snoek [7].

\[
\left( \frac{\Delta l}{l} \right)_{\text{sat}} = \frac{2 \lambda_{100} - 3 \lambda_{111}}{5} = 1.7 \times 10^{-3}
\]

in excellent agreement with values obtained on a sample of this composition measured in our laboratory in such a way as to eliminate the uncertainty in knowledge of the initial domain distribution and in agreement with the value given by Snoek [7].

The availability of such data has become, indeed, helpful in interpreting the mechanism of some reactions taking place in magnetic alloys. The writer in collaboration with Smoluchowski in some as yet unpublished work has endeavored to explain the mechanism of nucleation in Alnico V on this basis. It is proposed that the precipitate in this alloy is a phase rich in iron and cobalt of the approximate composition 30 per 100 Co. This is compatible with the hypothesis of Bradley and Taylor [8] and with the observations of Geisler [9] and fits the known optimum composition of Alnico V if one assumes that cobalt when added to the FeNiAl system simply behaves like iron. The measured low magnetostriction of such a phase in the [100] suggests that nuclei whose [100] axes make a small angle with the matrix grow preferentially and the magnetic anisotropy of the alloy results from the crystalline anisotropy of the precipitate. This data is also of further interest in making possible a quantitative interpretation of the effect of a magnetic field applied during recrystallization upon the recrystallized texture reported by Smoluchowski and Turner [10].

Recently, Carr [11] has made measurements of the single crystal magnetostriction constants of iron-silicon alloys as a function of silicon content. His results are shown in figure 3. These results are also of great theoretical interest, for, comparison of the data with other systems such as Fe—Al bring out the very significant difference in the behavior of the magnetic shells during alloying and is the subject of a separate treatment. Moreover, as will be shown below, this data makes possible a more quantitative evaluation of the distribution of domain directions in polycrystalline media.

**Measurements on Polycrystalline Materials.**

1. **Materials with Preferred Crystal Orientation.**

Information on the distribution of domain directions in a polycrystalline material can be obtained by means of magnetostriction measurements. A good example is afforded by the data on polycrystalline materials having a preferred grain orientation. The magnetostriction vs. B curve for oriented 3.25 per 100 silicon steel (Hipersil) is shown in figure 4. From Carr’s data shown in figure 3 we know the actual value of the single crystal constants for this composition. A check on the compatibility of the measurements is afforded by noting the measurement of the magnetostriction as measured with the sample magnetized transverse to the direction of rolling as shown in figure 5. The orientation of the crystalites in the material is as shown schematically in figure 6. Thus one would expect that when magnetized transverse to the rolling direction the magnetostriction would be positive until all the domains are magnetized at 45° to the direction of measurement, i.e. \( \frac{B_x}{B_y} = 1.4,000 \) gauss as observed.

At this juncture the material should behave substantially as a single crystal so that the magnetostriction resulting from turning the direction of magnetization from the [100] to the direction of the field i.e. [110], is [6]:

\[
\frac{\Delta l}{l} \approx -4.0 \times 10^{-6}
\]

in good agreement with \( \frac{\Delta l}{l} = -4.0 \times 10^{-6} \) in figure 6. From the actual values of the peak one may calculate
the anisotropy in the distribution of domains among the six possible easy initial directions.

Fig. 5. — Magnetostriction in Hipersil transverse to rolling direction.

The negative magnetostriction at low inductions is associated with the laminar character of the sample and is interpreted as being due to the extra magnetostatic energy if there is a component of magnetization normal to the plane of the sheet.

Fig. 6. — Orientation of crystals in Hipersil.

Thus if the crystal makes a small angle with the plane of the sheet, then during the steep portion of the magnetization curve when magnetization proceeds almost exclusively by means of $180^\circ$ boundary displacements there would result a component of magnetization normal to the sheet; accordingly, there are some "reverse" $90^\circ$ displacements in which domains initially magnetized antiparallel to the field change their directions by $90^\circ$ to neutralize the normal component. This is analogous to Stewart's interpretation of the negative effect of tensile stress on magnetization in the same alloy [12]. A similar effect is observed in a 50 per 100 Fe—Co alloy with preferred grain orientation as shown in figure 7. The negative strain at low inductions does not appear when the preferred grain orientation is not pronounced.

2. Magnetostriction and Order-Disorder. — Goldman and Smoluchowski [13] first discovered a relationship between magnetostriction and the state of order of an alloy. The original measurements were made on an alloy of Fe-Co by the technique described above. A theoretical interpretation was given for the effect in terms of the dipole-dipole interaction treatment of Becker. This required certain assumptions as to the character of the atomic moment in an alloy. Our original ideas have since been amplified by Smoluchowski and form the basis for some of the ideas presented in his paper elsewhere in this meeting. The writer has also extended the measurements of magnetostriction as a function of order to Ni$_3$Fe (permalloy) [14] where an increase by a factor of two is observed in the magnetostriction on ordering; and in the Fe—Al system [15]. The data on Fe—Al are shown in figure 8. The single crystal constants of Carr have also been found to be sensitive to thermal treatment—probably due to a variation of the state of order. It appears quite probable that the extreme sensitivity of the magnetic pro-
Properties of these three systems to thermal treatment is due primarily to the very large changes in magnetostriction that are produced.

Remarque de M. Street. — I should like to ask Dr Goldman for further information on two points of experimental technique. Firstly, is there any disadvantage in using A.C. bridge methods compared with the method described i.e. using a D.C. supply and a “chopped” D.C. amplifier? Secondly, in his measurements has it been found necessary to calibrate the resistance strain gauges in situ or is it found sufficient to accept the gauge factor in accurate measurements? I should like also to know if Dr Goldman has been able to make any measurements on reversible magnetostriction, i.e. the alternating strain produced by an alternating field applied at different points on the hysteresis cycle. It would appear that his form of apparatus would be extremely useful for such measurements.

Réponse de M. Goldman. — We feel we can obtain lower noise level with D.C. than with A.C. As to the calibration, in the initial stages of development of this method we checked the gauge factor given by the manufacturer by measuring the modulus of elasticity in standard samples. In general, we have found the manufacturer’s data to be quite accurate making a regular check of the gauge factor unnecessary.


Remarque de M. Hoselitz. — We have also been using strain gauges for magnetostriction measurements and the results obtained with strain gauges have been the same as those obtained with our optical lever method. In our experiments we were able to use an optical lever in fields up to 5 000 Oe.

REFERENCES.

[2] Supported by ONR.
[5] The Fe-Co crystal was very kindly loaned to us by Prof. L. W. McKechnie of Yale University and is part of the set used by J. W. Shih for the measurement of crystal anisotropy. Phys. Rev., 1934, 46, 136.
[9] Geisler A. H., to be published. We are indebted to Dr Geisler for making available to us a manuscript of his paper in advance of publication.