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Abstract

It was recently reported that the addition of nonmagnetic Ga increased the saturation magnetostriction (λ_{100}) of Fe over tenfold while leaving the rhombohedral magnetostriction (λ_{111}) almost unchanged. To determine the relationship between the magnetostriction and the magnetization we measured the temperature and stress dependence of both the magnetostriction and magnetization from −21 °C to +80 °C under compressive stresses ranging from 14.4 MPa to 87.1 MPa. For this study a single crystal rod of $Fe_{0.81}Ga_{0.19}$ was quenched from 800 °C into water to insure a nearly random distribution of Ga atoms. Constant temperature tests showed that compressive stresses greater than 14.4 MPa were needed to achieve the maximum magnetostriction. For the case of a 45.3 MPa compressive stress and applied field of 800 Oe, the maximum magnetostriction at 80 °C decreases from its value at −21 °C by 12.9%. This small magnetostrictive decrease is consistent with a correspondingly small 3.6% decrease in magnetization over the same temperature range. This well-behaved temperature response makes this alloy particularly valuable for industrial and military smart actuator, transducer, and active damping applications. The measured value of Young's modulus is low (~55±1 GPa) and almost temperature independent. The large magnetostriction over a wide temperature range combined with the nonbrittle nature of the alloy is rare.

Keywords

iron alloys, gallium alloys, ferromagnetic materials, magnetostriction, alloying additions, magnetisation, Young's modulus

Disciplines

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Comments

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I. INTRODUCTION

Galfenol alloys, i.e., iron substituted with nonmagnetic gallium ($Fe_{1-x}Ga_x$ where $13 \leqslant x \leqslant 23$ at. %) have recently been shown to exhibit large magnetostrictions, approaching 400 ppm at room temperature, with low saturating fields of several hundred oersted. The saturation magnetostriction (λ_{100}) is over tenfold that of nonsubstituted Fe, yet the rhombohedral magnetostriction (λ_{111}) remains almost unchanged.[1] A proposed model describing the magnetostriction mechanism of the alloy consists of pairs of Ga atoms situated along the cube edges of the bcc α-Fe crystal structure.[2] Concentrations of Ga higher than 21 at. % lead to the development of low-energy long range ordered DO_3 or B2 crystal structures and a corresponding reduction in the magnetostrictive capability.[3] This ordering phenomenon and disruption of the magnetostrictive response were formerly observed in aluminum-substituted iron.[4,5]

Galfenol's large magnetostrictive capability and high maximum relative permeability ($\mu_r \sim 300$) coupled with its robust mechanical characteristics (compared to the typical rare earth-Fe_2 magnetostrictive materials) make it potentially well suited for transducer applications in severe mechanical environments.[6] To advance the understanding of Galfenol's magnetomechanical characteristics that are relevant to its implementation in transducer applications, this work examines the effects of temperature and compressive stress on the alloy's magnetization and magnetostrictive responses to applied magnetic fields. Since it is important to assess the force output capability of a transducer under dynamic and mechanically blocked conditions,[7,8] the Young's modulus of demagnetized Galfenol was also measured.

II. EXPERIMENTAL METHOD

This study utilized a single crystal $Fe_{0.81}Ga_{0.19}$ rod (6.35 mm diameter by 23.7 mm long) extracted from a single crystal ingot grown at 2 mm/h using the modified Bridgman technique. The ingot was annealed at 1000 °C for 168 h and afterward water quenched from 800 °C to obtain a nearly random Ga distribution throughout the crystal lattice. Using back reflection Laue diffraction, the rod was oriented and sectioned from the ingot with a [100] crystal axis aligned within 0.5° of the rod's longitudinal axis.

To evaluate the magnetomechanical response of Galfenol under controlled conditions, a thermally regulated transducer was used to test the specimen at constant temperatures ($\pm 1\,°C$) ranging from $-21\,°C$ to $+80\,°C$. Minimizing demagnetizing effects of the low aspect ratio sample, annealed low carbon steel end pieces served as interfaces between the sample and the steel transducer housing to form a complete magnetic circuit. The end pieces also functioned as the load path through which a free hanging weight assembly imposed constant longitudinal compressive load conditions

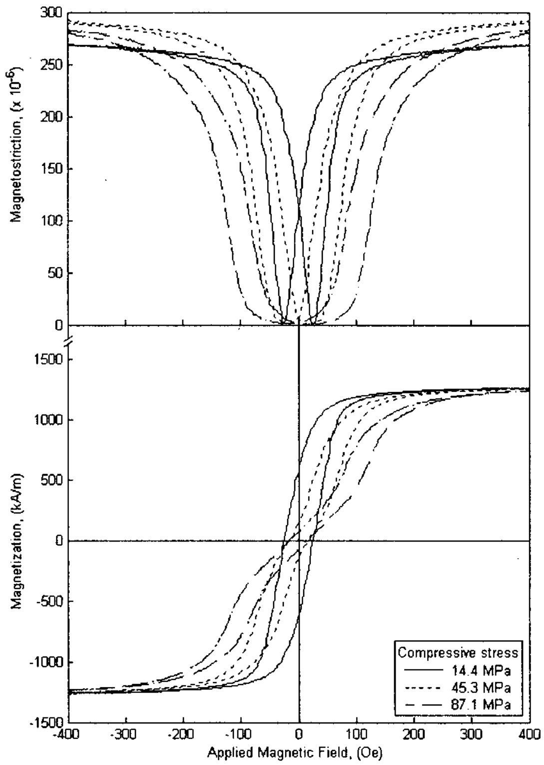

FIG. 1. Applied magnetic field dependencies of the magnetostriction and magnetization of $Fe_{0.81}Ga_{0.19}$ at 80 °C for various compressive stresses. All measurements were made at 0.05 Hz in a flux-closed transducer.

up to 87.1 MPa. Applied magnetic fields (coaxial with the rod's longitudinal axis) were generated with a solenoid surrounding the specimen and steel end pieces. The sample's magnetization was recorded using a sense coil and fluxmeter while the magnetostriction was measured with strain gauges. Two strain gauges were used, each with an active area of 6.1×1.9 mm, and were positioned on opposing sides of the rod at mid-length.

For each combination of stress and temperature examined, the sample was stabilized at the desired temperature under constant stress and subsequently demagnetized with a 1.0 Hz, 5% geometrically decaying sinusoidal field. The magnetization and magnetostriction responses were then recorded while the sample was subjected to a 0.05 Hz, 800 Oe amplitude sinusoidal applied magnetic field.

III. RESULTS

Figure 1 shows the magnetostriction and magnetization developed due to an applied magnetic field at a temperature of 80 °C. This figure highlights the effect of stress on Galfenol's magnetomechanical response. As the magnitude of compressive stress is increased, attaining equivalent levels of magnetostriction requires larger applied magnetic fields. The 14.4 MPa stress condition exhibits less strain for applied fields above 300 Oe due to inadequate stress and thus incomplete pre-alignment of magnetic moments perpendicular to the rod's longitudinal axis. The maximum magnetostrictions obtained for this temperature (near maximum magnetization with an applied field of 800 Oe) were 273 ppm for the 14.4 MPa stress condition and 298 ppm for both the 45.3 MPa and 87.1 MPa stress conditions. Notably, 95% or more of the maximum strain for each stress level was developed with applied fields of 400 Oe or less. Figure 1 also demonstrates that the magnetization reaches 95% or more of the maximum magnetization (1265 kA/m at 800 Oe) at 80 °C for all load cases with fields less than 300 Oe. Below 200 Oe the decreasing slope of the magnetization versus applied field curve indicates that increasing stress levels reduce the permeability. In this case the maximum relative permeability decreases sixfold from $\mu_r\sim360$ to $\mu_r\sim60$ for the 14.4 MPa and 87.1 MPa stresses, respectively. The hysteresis in the magnetostriction and magnetization plots of Fig. 1 occurs for two primary reasons. The sample experiences domain wall pinning due to crystal defects and the transducer itself generates a 12 Oe hysteresis in the applied magnetic field due to remanence of the steel housing.

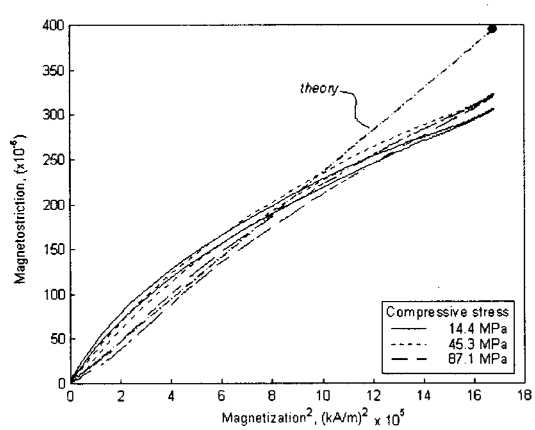

FIG. 2. Magnetization squared dependencies of the magnetostriction of $Fe_{0.81}Ga_{0.19}$ at 22 °C for three compressive stresses.

Figure 2 provides some insight into the sample's magnetization process. Here, the magnetostriction is shown as a function of the magnetization squared for three compressive stress levels at 22 °C. Assuming sufficient stress to dominate the magnetostriction process and to align all the magnetic moments with the [100] easy axes perpendicular to the rod's longitudinal axis at zero field, one would expect the theoretical linear plot indicated. This follows from the relationship $\lambda=(3/2)\lambda_s(M/M_s)^2$, which describes the magnetostriction λ generated by the magnetization M where λ_s and M_s are the conventional saturation magnetostriction and magnetization values, respectively.[9] This relationship assumes that the magnetization proceeds by moment rotation from the perpendicular [100] easy axes into the [100] easy axis parallel to the rod's longitudinal axis. The slope of the theoretical trace is based on values of $(3/2)\lambda_s=395$ ppm (determined at room temperature by orthogonal saturating applied fields) and $M_s=1313$ kA/m that were previously measured by Clark *et al.* using a (010) disk cut from the same Galfenol ingot used in this study.[10] The fact that the experimental traces of Fig. 2 are nonlinear indicates that the stress anisotropy generated by these compressive stresses were insufficient to cause the magnetization processes to occur solely by 90° moment rotation even at 87.1 MPa. Additionally, the maximum λ values

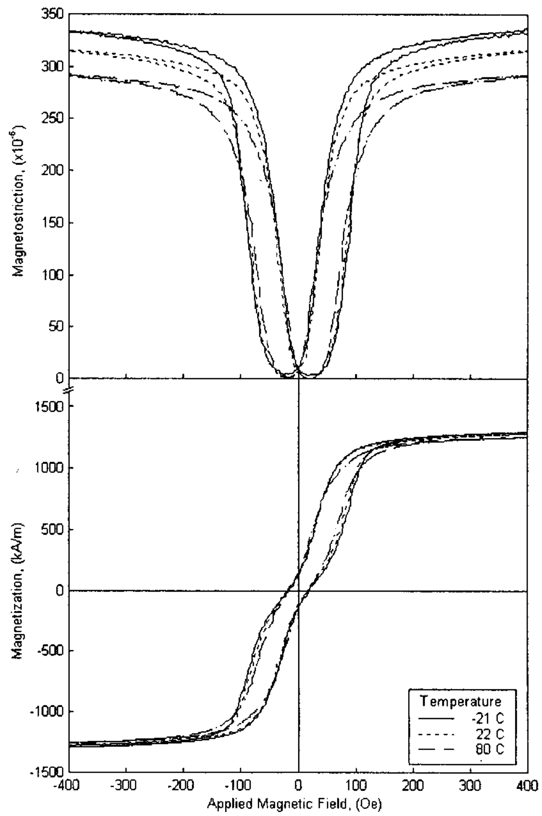

FIG. 3. Applied magnetic field dependencies of the magnetostriction and magnetization of $Fe_{0.81}Ga_{0.19}$ at 45.3 MPa for three temperatures.

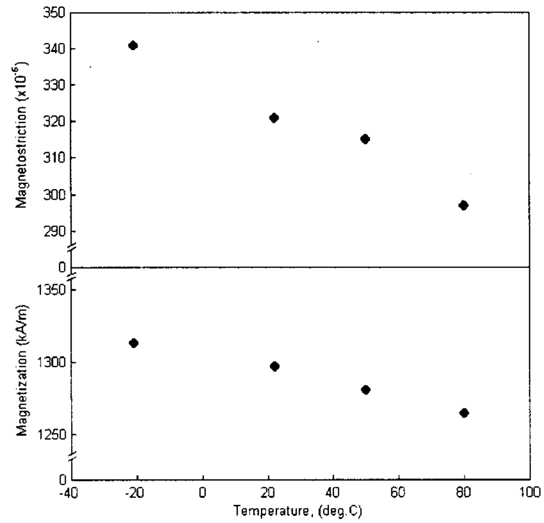

FIG. 4. Temperature dependencies of the maximum magnetostriction and magnetization of $Fe_{0.81}Ga_{0.19}$ for a 45.3 MPa compressive stress and 800 Oe applied field.

for both the 45.3 MPa and 87.1 MPa stress conditions at this temperature were identically 320 ppm, which suggests that the $(3/2)\lambda_s$ value of 395 ppm may be unattainable even with further increases in compressive stress.

The effects of temperature on the magnetostriction and magnetization versus applied magnetic field relationship were measured for the 45.3 MPa compressive stress condition. Figure 3 illustrates that the magnetization exhibits only a small reduction with increasing temperature. Likewise, the magnetostriction experiences only a small reduction with increasing temperature for applied fields above 100 Oe. The small and consistent nature of the temperature dependencies suggests that no anomalous changes in the anisotropy constants K_1 or K_2 or the magnetostriction constants λ_{100} or λ_{111} are occurring. Figure 4 shows the maximum magnetostriction and magnetization values at an 800 Oe applied field and 45.3 MPa stress as a function of temperature. The maximum magnetostriction declines 12% from 340 ppm at $-21\,°C$ to 298 ppm at $80\,°C$. Similarly the maximum magnetization declines 3% from 1313 kA/m to 1265 kA/m. These temperature dependencies of maximum magnetostriction and magnetization are consistent with the trends (previously measured up to $27\,°C$) for $Fe_{0.83}Ga_{0.17}$ and $Fe_{0.82}Ga_{0.18}$.[1,11]

To supplement the knowledge of the magnetic and magnetostrictive properties of Galfenol, the value of Young's modulus of $Fe_{0.81}Ga_{0.19}$ was measured. The sample's strain (in a demagnetized state at each stress level) was obtained over a 7.2 to 87.1 MPa compressive stress range. The modulus is nearly temperature independent with a value of $\sim 55 \pm 1$ GPa. This modulus is lower than the high stress low field value of ~ 77 GPa reported for single crystal $Fe_{0.85}Ga_{0.15}$.[1]

The large magnetostriction, high permeability and temperature insensitivity discussed in this paper combined with previously observed robust mechanical properties make Galfenol an attractive alloy for transducer, active vibration control and variable damping applications where the material is employed as an active structural material.

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[1] A. E. Clark, J. B. Restorff, M. Wun-Fogle, T. A. Lograsso, and D. L. Schlagel, IEEE Trans. Magn. **36**, 3238 (2000).
[2] J. R. Cullen, A. E. Clark, M. Wun-Fogle, J. B. Restorff, and T. A. Lograsso, J. Magn. Magn. Mater. **226**, 948 (2001).
[3] A. E. Clark, M. Wun-Fogle, J. B. Restorff, T. A. Lograsso, and J. R. Cullen, Proc. 8th Joint Intermag Conf., San Antonio, TX, Jan. 7–11, 2001.
[4] R. C. Hall, J. Appl. Phys. **30**, 816 (1959).
[5] H. J. Birkenbeil and R. W. Cahn, J. Appl. Phys. **32**, 362S (1961).
[6] A. E. Clark, M. Wun-Fogle, J. B. Restorff, T. A. Lograsso, A. R. Ross, and D. L. Schlagel, Proc. Actuator 2000 Conference, Bremen Germany, June 19–21, 2000.
[7] F. T. Calkins, Ph. D dissertation, Iowa State University, Ames, Iowa, 1997.
[8] R. A. Kellogg and A. B. Flatau, Proc. SPIE **3668**, 184 (1999).
[9] B. D. Cullity, *Introduction to Magnetic Materials* (Addison-Wesley, Reading, MA, 1972), Chap 8.
[10] A. E. Clark, M. Wun-Fogle, J. B. Restorff, and T. A. Lograsso, Mater. Trans. **43** (2002) (to be published).
[11] N. Kawamiya, K. Adachi, and Y. Nakamura, J. Phys. Soc. Jpn. **33**, 1318 (1972).