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Abstract

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Keywords

Ames Laboratory, Cobalt, Ferrites, Torque, Magnetic field measurements, Magnetic fields

Disciplines

Electromagnetics and Photonics | Engineering Physics | Materials Science and Engineering

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Temperature dependence of the magnetomechanical effect in metal-bonded cobalt ferrite composites under torsional strain

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Metal-bonded cobalt ferrite composites are promising candidates for torque sensors and other magnetostrictive sensing and actuating applications. In the present study, the temperature dependence of the magnetomechanical effect in a ring-shape cobalt ferrite composite under torsional strain has been investigated in the temperature range of −37 to 90 °C. The changes of external axial magnetic field were measured as a function of applied torque. Magnetomechanical sensitivity of $\Delta H_{\mathrm{ext}}/\Delta\tau = 65\ \mathrm{A\,N^{-1}\,m^{-2}}$ was observed with a magnetomechanical hysteresis of $\Delta\tau = \pm 0.62$ N m at room temperature (22 °C). These were then measured as a function of temperature. Both decreased as the temperature increased throughout the entire range. The magnetomechanical hysteresis became negligible at temperatures higher than 60 °C, above which there was a linear change in external magnetic field with applied torque. These temperature dependences are explained by the changes of magnetostriction, anisotropy, spontaneous magnetization, and pinning of domain walls caused by the availability of increased thermal energy. © *2000 American Institute of Physics.* [S0021-8979(00)94408-6]

I. INTRODUCTION

Noncontact magnetostrictive torque sensors are candidates for steering sensors for electromechanical automotive steering systems. These will replace the costly and fuel inefficient hydraulic power steering systems currently in use.[1–3] The requirements for the magnetostrictive materials are a high magnetoelastic response, low magnetomechanical hysteresis (mmh), adequate mechanical strength to sustain overtorque of 150 N m, and sufficient temperature stability of the magnetomechanical response to allow it to operate over a temperature range of −40 to 85 °C. Metal-bonded cobalt ferrite composites have been shown to have sufficient magnetoelastic response for torque sensors and other magnetostrictive sensing and actuating applications.[4] These materials have magnetostriction $\lambda_s > 200\times 10^{-6}$ with strain derivative $(d\lambda/dH)_{\max} \approx 1.3\times 10^{-9}\ \mathrm{A^{-1}\,m}$, and average sensitivity $\Delta H_{\mathrm{ext}}/\Delta\tau = 65\ \mathrm{A\,N^{-1}\,m^{-2}}$ at room temperature (22 °C). In addition, the materials have adequate mechanical properties and corrosion resistance for the application. However, very little is known about the temperature dependence of the magnetomechanical response in these materials. Only a few studies have reported any results on the temperature dependence of magnetostriction or anisotropy of cobalt ferrites.[5–7] Due to the fact that the magnetizations of the sublattices of ferrites have opposite signs and different temperature dependence,[8] the temperature dependence of the magnetic properties of ferrites, such as saturation magnetization and anisotropy can be complicated.[9] Metal-bonded cobalt ferrite composites are even more complex systems due to the metal additives and different processing from pure cobalt ferrite.[10] In this study, we report results on the temperature dependence of the magnetomechanical response of a cobalt ferrite composite due to torque.

II. EXPERIMENTAL DETAILS

A metal-bonded cobalt ferrite composite (98 vol % $\mathrm{CoO\cdot Fe_2O_3}$ + 2 vol % $\mathrm{Ag_{0.97}Ni_{0.03}}$) was pressed and sintered in the form of a ring, then brazed onto a stainless steel shaft. The sample was first magnetized circumferentially to remanence, a configuration that has been used by Garshelis *et al.*[11–13] In the present study this was achieved using a narrow gap electromagnet. The changes of external axial magnetic field with torque were then measured using a specially designed magnetic torque sensor test bed.[14] The coercivity, remanence, and saturation magnetization were also measured in the temperature range from −40 to 100 °C, using a Quantum Design MPMS superconducting quantum interference device (SQUID) magnetometer.

Measurements below ambient temperature were performed with the sample immersed in a refrigerated heat-transfer fluid. Ethanol water solution (75 vol % ethanol + 25 vol % water) was used as the cooling medium. The torque response was measured at a variety of temperatures from 22 down to −37 °C. Measurements above ambient temperature were performed with the sample immersed in water which was heated in a separate tank and circulated using a centrifugal pump. During each measurement, the temperature was kept constant to within range of ±0.2°. Finally, the torque

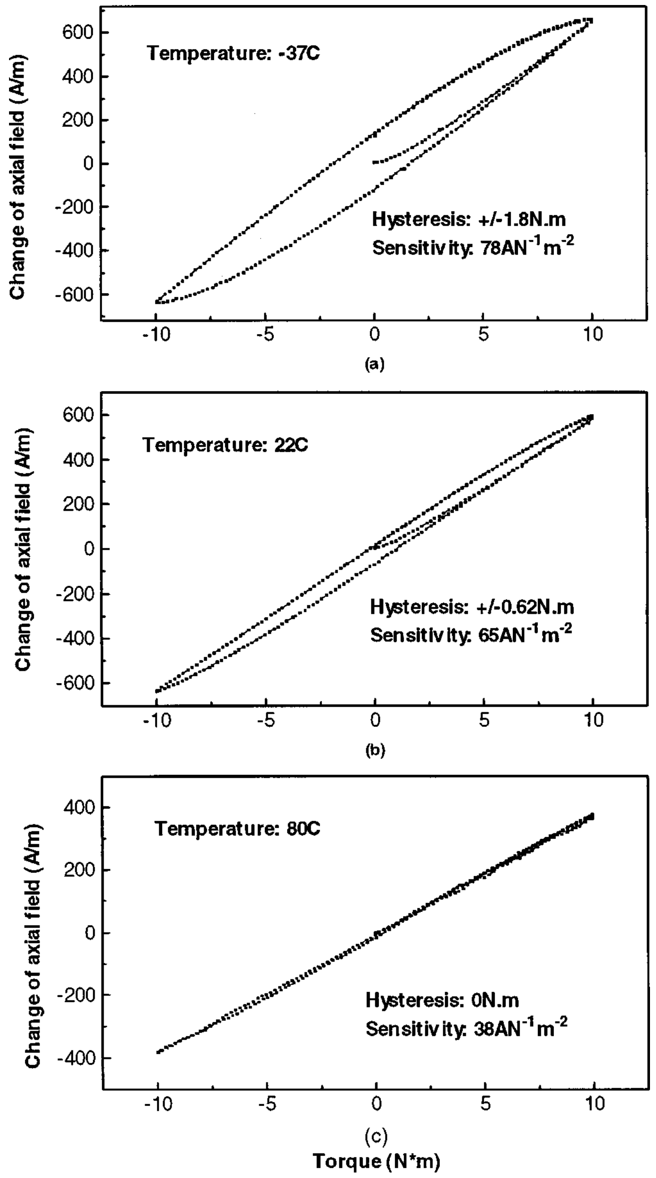

FIG. 1. The magnetomechanical torque responses at three typical temperatures. In this study, the mms is defined as the slope of the linear portion of the external axial field vs torque plot $\Delta H_{\mathrm{ext}}/\Delta\tau$. The mmh is defined as the width of the field vs torque loop at zero field $\Delta\tau$. Results are shown at: (a) −37 °C; mms=78 A N^{-1} m^{-2}, mmh=±1.8 N m. (b) 22 °C; mms=65 A N^{-1} m^{-2}, mmh=±0.62 N m. (c) 80 °C; mms=38.4 A N^{-1} m^{-2}, mmh is negligible.

response was measured after the sample had cooled back down to 22 °C.

III. RESULTS

In this study, magnetomechanical sensitivity $\Delta H_{\mathrm{ext}}/\Delta\tau$, is defined as the slope of the linear portion of the axial field versus torque plot and the mmh as the width $\Delta\tau$ in newtons per meter of the magnetomechanical hysteresis loop when H_{ext} is zero. The results of torque tests at −37, 22, and 80 °C are shown in Figs. 1(a)–1(c). The temperature dependence of the magnetomechanical sensitivity and mmh over the range −37 to 90 °C are plotted in Fig. 2.

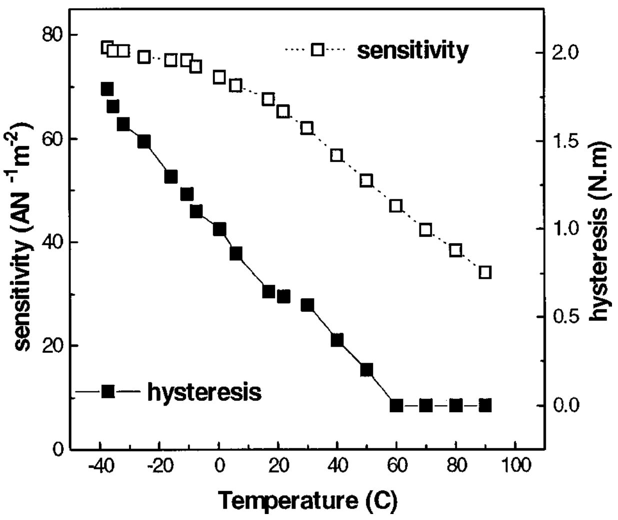

FIG. 2. The temperature dependence of the magnetomechanical effect of the ring-shaped cobalt ferrite composite under torsional strain in the temperature range of −37 to 90 °C. The empty squares represent mms and the filled squares represent mmh.

The magnetomechanical sensitivity (mms), $\Delta H_{\mathrm{ext}}/\Delta\tau$, decreased from 78 A N^{-1} m^{-2} at −37 °C to 65 A N^{-1} m^{-2} at 22 °C and to 34 A N^{-1} m^{-2} at 90 °C. It decreased approximately linearly with increasing temperature as shown in Fig. 2. The decrease in sensitivity was 56% (on average 0.4% per degrees Celsius). The mmh also decreased from ±1.8 to ±0.62 N m as the temperature increased from −37 to 22 °C and to less than ±0.1 N m at 60 °C. Over the range −37 to 60 °C the hysteresis decreased linearly with temperature giving a decrease of 0.02 N m per degrees Celsius (on average 1% per degrees Celsius). Interestingly, the mmh remained close to zero as the temperature increased beyond 60 °C, giving a magnetomechanical response $\Delta H_{\mathrm{ext}}/\Delta\tau$ that was linear and reversible.

The torque response was also measured after the sample had been heated to 90 °C and cooled back to 22 °C. The mms and mmh were 48 A N^{-1} m^{-2} and ±0.6 N m, respectively. As a result of thermal cycling the mms had decreased by about 26%, while the mmh returned to its earlier value. These results showed some significant thermal hysteresis in the sensitivity, while the mmh appeared to be unaffected by thermal cycling.

M–H hysteresis loops were measured over a similar temperature range as the magnetomechanical response. The coercivity, remanence, and saturation magnetization decreased with temperature in the range from −40 up to 100 °C, as shown in Fig. 3. The coercivity changed from 14.4 to 4.4 kA/m (a total of 69%, or 0.5% per degrees Celsius), the remanent magnetization changed from 70 to 26.5 kA/m (a total of 62%, or 0.44% per degrees Celsius), and the saturation magnetization changed from 445 to 387 kA/m (a total of 13%, or 0.09% per degrees Celsius).

IV. DISCUSSION

It is known that the sensitivity of the magnetomechanical effect is related to magnetostriction.[15] The temperature dependence of magnetostriction has been investigated by Guillaud[7] where it was reported that cobalt ferrite exhibited

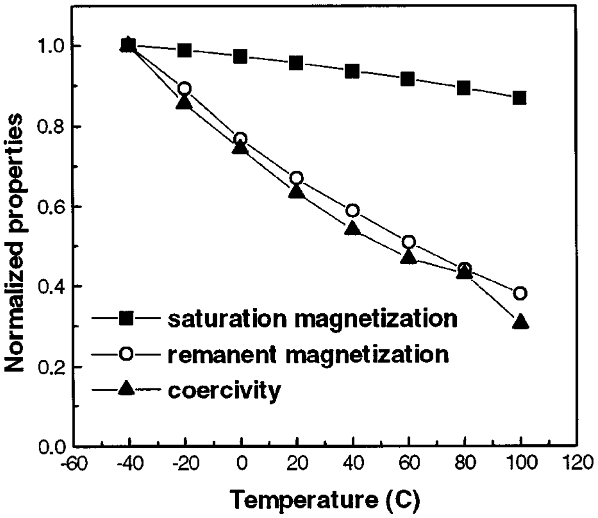

FIG. 3. The temperature dependence of coercivity, remanent magnetization, and saturation magnetization of metal-bonded cobalt ferrite composite. All three properties are normalized by the values at −40 °C.

magnetostrictions of -270×10^{-6}, -190×10^{-6}, and -110×10^{-6} at −196, −80, and 20 °C, respectively. The magnitude of magnetostriction decreased approximately linearly from −196 °C to room temperature with an average decrease of magnetostriction of 0.4% per degree Celsius. The change of magnetostriction plays an important role in the temperature dependence of the magnetomechanical effect. A decrease in magnetostriction with increasing temperature indicates a decreasing magnetomechanical coupling strength, which could cause a decrease in mms with increasing temperature.

Although the Curie temperature of cobalt ferrite is 520 °C, the saturation magnetization decreases significantly as the temperature increases in the temperature range of −40 to 110 °C, from about 490 to 427 kA/m (85 to 75 emu/g).[9] Our experimental results confirmed that the metal-bonded cobalt ferrite composite exhibits the same behavior. This effect caused the remanent magnetization of the ring-shape ferrite composite to decrease with temperature. This change in remanence was reversible when the temperature was restored to ambient conditions.

The temperature had another effect on the remanent magnetization when the temperature was raised: specifically it caused partial thermal demagnetization of the sample through release of domain walls from pinning sites. This effect was irreversible. The component of remanence decrease due to the reversible processes at higher temperatures was regained as the sample was cooled back to 22 °C; the component of remanence due to the irreversible process was not regained. Therefore, the thermal energy has only a reversible effect on the measurements at temperatures lower than ambient temperature while having both reversible and irreversible effects on the measurements at temperatures higher than ambient temperature. Since the magnetomechanical effect depends on M_R, the sensitivity will be dependent on the thermal history from when it was last magnetized.

It is known that torsional stresses on a rod or a ring can be considered as biaxial stresses, in which the two stress axes are perpendicular to each other and at 45° to the axis of torsion.[16] The change of axial field is caused by the magnetization of the cobalt ferrite ring rotating towards the compressive stress direction.[4] Therefore, the mmh mainly comes from the anisotropy of the ferrite composite. From the existing literature,[9] it was found that the anisotropy of pure $CoO\cdot Fe_2O_3$ decreased as the temperature increases. The coefficient K_1 is 90 K J/m^2 at 90 °C, 6.6 K J/m^3 at 200 °C, and is negligible at 280 °C. The coercivity of the metal-bonded cobalt ferrite composite, which depends strongly on anisotropy, was likewise observed to decrease linearly as the temperature increased from −40 to 100 °C. Thus, the temperature dependence of the mmh is caused principally by the temperature dependence of the anisotropy. The metal additives (Ag/Ni) and the bonding treatment of the cobalt ferrite composite could also change the anisotropy and the temperature dependence of anisotropy. The coercivity (~8 kA/m) of the present metal-bonded cobalt ferrite composite is much lower than that reported for cobalt ferrite at 22 °C (~160 kA/m).[7]

It is interesting to note that the mmh effectively disappears above 60 °C while a sufficient sensitivity still exists at that temperature to give a good signal/noise ratio (about 50 A N^{-1} m^{-2}). Therefore, it should be possible to adjust the anisotropy of cobalt ferrite composites by adjusting the levels of metallic additives (Ag/Ni/Co) in order to obtain linear torque response at room temperature.

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[1] R. A. Beth and W. W. Meeks, Rev. Sci. Instrum. **25**, 603 (1954).
[2] W. J. Fleming, Society of Automotive Engineers, Paper No. 900264, 1990.
[3] F. E. Pinkerton, T. W. Capehart, J. F. Herbst, E. G. Brewer, and C. B. Murphy, Appl. Phys. Lett. **70**, 2601 (1997).
[4] Y. Chen, J. E. Snyder, C. R. Schwichtenberg, K. W. Dennis, R. W. McCallum, and D. C. Jiles, IEEE Trans. Magn. **35**, 3652 (1999).
[5] R. M. Bozorth, E. F. Tilden, and A. J. Williams, Phys. Rev. **99**, 1788 (1955).
[6] P. E. Tannenwald, Phys. Rev. **99**, 463 (1955).
[7] C. Guillaud, Rev. Mod. Phys. **25**, 64 (1953).
[8] E. Du T. de Lacheisserie, *Magnetostriction* (CRC, New York, 1993), p. 267.
[9] J. Smit and H. P. J. Wijn, *Ferrites* (Wiley, New York, 1959).
[10] R. Valenzuela, *Magnetic Ceramics* (Cambridge University Press, Cambridge, 1994).
[11] I. J. Garshelis, IEEE Trans. Magn. **28**, 2202 (1992).
[12] I. J. Garshelis and C. R. Conto, J. Appl. Phys. **79**, 4756 (1996).
[13] I. J. Garsheis and C. A. Jones, J. Appl. Phys. **85**, 5468 (1999).
[14] Y. Chen, J. E. Snyder, C. R. Schwichtenberg, K. W. Dennis, R. W. McCallum, and D. C. Jiles, Paper HF-09, 43rd Annual Conference on Magnetism and Magnetic Materials, Miami, November 1998.
[15] D. C. Jiles, J. Phys. D: Appl. Phys. **28**, 1537 (1995).
[16] M. J. Sablik and D. C. Jiles, IEEE Trans. Magn. **35**, 498 (1999).