6-1-2004

# Magnetostriction and elasticity of body centered cubic Fe100−xBex alloys

A. E. Clark
*Clark Associates*

M. Wun-Fogle
*United States Navy*

J. B. Restorff
*United States Navy*

Thomas A. Lograsso
*Iowa State University*, lograsso@ameslab.gov

G. Petculescu
*University of Mississippi*

# Magnetostriction and elasticity of body centered cubic Fe100−xBex alloys

**Abstract**
Magnetostriction measurements from 77 K to room temperature on oriented (100) and (110) disk samples of $Fe_{93.9}Be_{6.1}$ and $Fe_{88.7}Be_{11.3}$ reveal substantial increases in $\lambda_{100}$compared to iron. For the 11.3% alloy, $\lambda_{100}$=110 ppm, a sixfold increase above that of α-Fe. For the 6.1% alloy, $\lambda_{100}$=81 ppm, ~40% and ~170% greater than $\lambda_{100}$ of comparable Fe–Ga and Fe–Al alloys, respectively, for $H$=15 kOe. Large differences exist between the values of $\lambda_{100}$ and $\lambda_{111}$ ($\lambda_{100}>0$, $\lambda_{111}<0$) and their temperature dependencies. Elastic constants, $c_{11}$, $c_{12}$, and $c_{44}$, from 4 to 300 K were obtained on the same Fe–Be alloys. From these measurements, the magnetoelastic energy coefficients $b_1$ and $b_2$ were calculated. While the magnitudes of the magnetostrictions $\lambda_{100}$ and $\lambda_{111}$ are widely different, the magnitudes of $b_1$ and $b_2$ are within a factor of 2. The Fe–Be alloys are highly anisotropic magnetostrictively, elastically, and magnetoelastically. For $Fe_{88.7}Be_{11.3}$ at room temperature $\lambda_{100}/\lambda_{111}$, $2c_{44}/(c_{11}-c_{12})$, and $b_1/b_2$ are −6.6, 3.55, and −1.86, respectively.

**Keywords**
iron alloys, beryllium alloys, magnetostriction, magnetoelastic effects, elastic constants, magnetic anisotropy

**Disciplines**
Condensed Matter Physics | Metallurgy

**Comments**
The following article appeared in *Journal of Applied Physics* 95 (2004): 6942 and may be found at http://dx.doi.org/10.1063/1.1688676.

JOURNAL OF APPLIED PHYSICS VOLUME 95, NUMBER 11 1 JUNE 2004

# Magnetostriction and elasticity of body centered cubic $Fe_{100-x}Be_x$ alloys

A. E. Clark
*Clark Associates, Adelphi, Maryland 20783*

M. Wun-Fogle[a] and J. B. Restorff
*Naval Surface Warfare Center, Carderock Division, West Bethesda, Maryland 20817*

T. A. Lograsso
*Ames Laboratory, Ames, Iowa 50011*

G. Petculescu
*University of Mississippi, University, Mississippi 38677-1848*

(Presented on 8 January 2004)

Magnetostriction measurements from 77 K to room temperature on oriented (100) and (110) disk samples of $Fe_{93.9}Be_{6.1}$ and $Fe_{88.7}Be_{11.3}$ reveal substantial increases in $\lambda_{100}$ compared to iron. For the 11.3% alloy, $\lambda_{100}=110$ ppm, a sixfold increase above that of $\alpha$-Fe. For the 6.1% alloy, $\lambda_{100}=81$ ppm, $\sim$40% and $\sim$170% greater than $\lambda_{100}$ of comparable Fe–Ga and Fe–Al alloys, respectively, for $H=15$ kOe. Large differences exist between the values of $\lambda_{100}$ and $\lambda_{111}$ ($\lambda_{100}>0$, $\lambda_{111}<0$) and their temperature dependencies. Elastic constants, $c_{11}$, $c_{12}$, and $c_{44}$, from 4 to 300 K were obtained on the same Fe–Be alloys. From these measurements, the magnetoelastic energy coefficients $b_1$ and $b_2$ were calculated. While the magnitudes of the magnetostrictions $\lambda_{100}$ and $\lambda_{111}$ are widely different, the magnitudes of $b_1$ and $b_2$ are within a factor of 2. The Fe–Be alloys are highly anisotropic magnetostrictively, elastically, and magnetoelastically. For $Fe_{88.7}Be_{11.3}$ at room temperature $\lambda_{100}/\lambda_{111}$, $2c_{44}/(c_{11}-c_{12})$, and $b_1/b_2$ are $-6.6$, 3.55, and $-1.86$, respectively.
 [DOI: 10.1063/1.1688676]

## I. INTRODUCTION

It was recently shown that the substitution of nonmagnetic Ga into common body centered cubic (bcc) Fe enhanced the tetragonal magnetostriction constant $\lambda_{100}$ over tenfold, while at the same time leaving the rhombohedral constant $\lambda_{111}$ nearly unchanged.[1] Initial results in a thesis by Gersdorf decades ago revealed the possibility of a similar large enhancement for Fe–Be alloys.[2] These dependencies are reminiscent of that observed long ago in Fe–Al alloys by Hall.[3] The object of this article is to measure the magnetostriction and elastic constants of $Fe_{93.9}Be_{6.1}$ and $Fe_{88.7}Be_{11.3}$, calculate their magnetoelastic energy coefficients, and compare the results to those of $Fe_{100-x}Ga_x$ and $Fe_{100-x}Al_x$ ($x<17$). For this study, the magnetostrictions, $\lambda_{100}$ and $\lambda_{111}$, and the elastic constants, $c_{11}$, $c_{12}$ and $c_{44}$, were measured from cryogenic temperatures to room temperature.

## II. EXPERIMENTAL PROCEDURE

Single crystals of $Fe_{93.9}Be_{6.1}$ and $Fe_{88.7}Be_{11.3}$ were prepared by Bridgman growth of arc-cast ingots of electrolytic Fe (99.999% pure) and Be (99.9% pure) in alumina crucibles. The ingots were stabilized in the crucible for 1 h at 1600 °C and lowered at a rate of 4 mm/h. Following growth, the ingots were heat treated at 1000 °C for 168 h and cooled at a rate of 10 °C/h. Although the equilibrium condition of these alloys below $\sim$700 °C contains the hexagonal $FeBe_2$ Laves phase, this phase was not present in the x-ray diffraction patterns following heat treatment. While the diffraction patterns confirmed the bcc structures, the local ordering of Be and Fe on the bcc lattice is not known. (100) and (110) oriented single crystal disks ($\sim$0.3 cm$\times$0.6 cm diameter) were cut from the boule by EDM machining for magnetostriction and magnetization measurements. Oriented parallelepipeds (0.1 cm$\times$0.2 cm$\times$0.3 cm) with perpendicular {001} faces were cut for resonant ultrasonic spectroscopy (RUS) elastic constant measurements. Chemistry of the samples was measured by inductively coupled plasma–optical emission spectroscopy on adjacent pieces to the measurements samples.

Magnetostriction measurements of $\lambda_{100}$ and $\lambda_{111}$ were obtained from 77 K to room temperature using nonmagnetostrictive Kyowa KFL-1-120-C1-11 strain gauges. Temperature dependencies of the magnetizations were obtained using $\sim$20 turn No. 36 gauge wire coils. All reported magnetostrictions were taken at a field of 15 kOe. The RUS method was used to obtain elastic constants from 4 K to room temperature. The first 23 free-body resonant frequencies of the single-crystal parallelepipeds with {100} faces were recorded. Using normal mode frequency analysis, density, and sample dimensions, $c_{11}$, $c_{12}$, and $c_{44}$ were calculated.

[a]Author to whom correspondence should be addressed; electronic mail: wunfoglem@nswccd.navy.mil

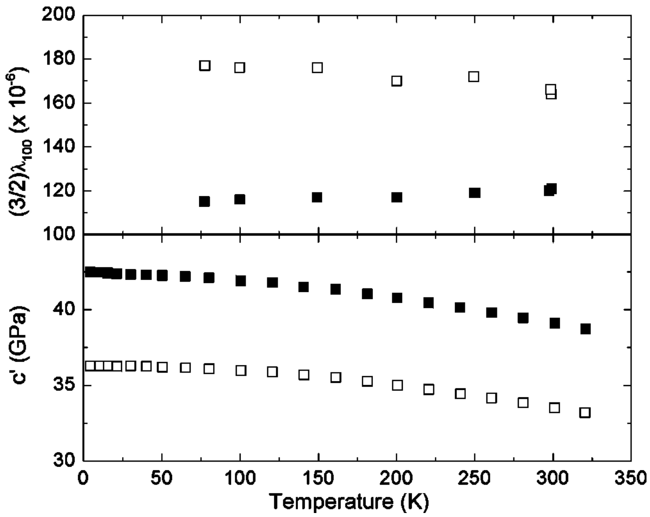


FIG. 1. $(3/2)\lambda_{100}$ and elastic constant $c'$ as a function of temperature for $Fe_{93.9}Be_{6.1}$ (■) and $Fe_{88.7}Be_{11.3}$ (□).

## III. MAGNETOSTRICTION AND ELASTIC CONSTANTS

### A. Tetragonal strains

Common bcc Fe exhibits a small positive $\lambda_{100} \cong 20 \times 10^{-6}$ which changes little from room temperature to cryogenic temperatures.[4] A three- to sixfold larger magnetostriction is found for the $Fe_{93.9}Be_{6.1}$ and $Fe_{88.7}Be_{11.3}$ alloys. However, like Fe, the temperature dependencies are extremely small. Fig. 1 shows the maximum Joule magnetostriction $(3/2)\lambda_{100}$ versus temperature. The lower concentration 6.1% Be sample retains the slight anomalous (positive) temperature dependence of Fe,[4] whereas the 11.3% sample exhibits the normal small decrease of magnetostriction with temperature. A conventional decrease with temperature of the magnetization occurs for *both* alloys over this temperature range.

For Fe, the elastic constant $c'$ $(\equiv 1/2(c_{11}-c_{12}))$ $\cong 48$ GPa.[5] For $Fe_{100-x}Be_x$, at room temperature, $c'$ decreases almost linearly from that of Fe according to $c' = 48 - 1.3x$, where $c'$ is in GPa. Similar decreases have also previously been observed in the $Fe_{100-x}Al_x$[6] and $Fe_{100-x}Ga_x$[1,7] alloys. Figure 1 displays the values of $c'$ for $Fe_{93.9}Be_{6.1}$ and $Fe_{88.7}Be_{11.3}$ from 4 K to room temperature.

TABLE I. Elastic constants of Fe, $Fe_{93.9}Be_{6.1}$, and $Fe_{88.7}Be_{11.3}$.

| | $c_{11}$ (GPa) | $c_{12}$ (GPa) | $c_{44}$ (GPa) | $c'$ (GPa) | $B$ (GPa) |
|---|---|---|---|---|---|
| Fe[5] | 237 | 141 | 116 | 48 | 173 |
| $Fe_{93.9}Be_{6.1}$ | 215 | 138 | 121.10 | 38.83 | 164 |
| $Fe_{88.7}Be_{11.3}$ | 195 | 128 | 118.94 | 33.50 | 150 |

### B. Rhombohedral strains

Figure 2 illustrates the magnetostriction and elastic constants for the rhombohedral distortions. Unlike the tetragonal case, $(3/2)\lambda_{111}$ displays almost no change in either magnetostriction or its temperature dependence with Be concentration. There is a striking similarity between these temperature dependencies and that of Fe itself.[4] For Fe, $Fe_{93.9}Be_{6.1}$, and $Fe_{88.7}Be_{11.3}$, $(3/2)\lambda_{111}$ is negative and increases ~40% from 77 K to room temperature. Like $(3/2)\lambda_{111}$, $c_{44}$ at room temperature changes little with Be concentration. Table I lists the elastic constants at room temperature for Fe and the 6.1% and 11.3% Be alloys.

### C. Angular dependence of the magnetostriction

For $Fe_{88.7}Be_{11.3}$ we examined the dependence of the magnetostriction, $\lambda_{\parallel}-\lambda_{\perp}$, for strain measurement directions in the $(1\bar{1}0)$ plane. (Here $\lambda_{\parallel}-\lambda_{\perp}$ denotes the strain resulting from rotation of a magnetic field $\perp$ to $\parallel$ to the measurement direction.) Whenever the magnetostriction is anisotropic, $\lambda_{\parallel}-\lambda_{\perp}$ depends upon the direction of the strain measurement. For rotation of cubic crystals in {110} planes

$$\lambda_{\parallel}-\lambda_{\perp} = (3/4)\lambda_{100}(1-5\cos^2\theta+6\cos^4\theta) + (3/4)\lambda_{111}(1+5\cos^2\theta-6\cos^4\theta). \quad (1)$$

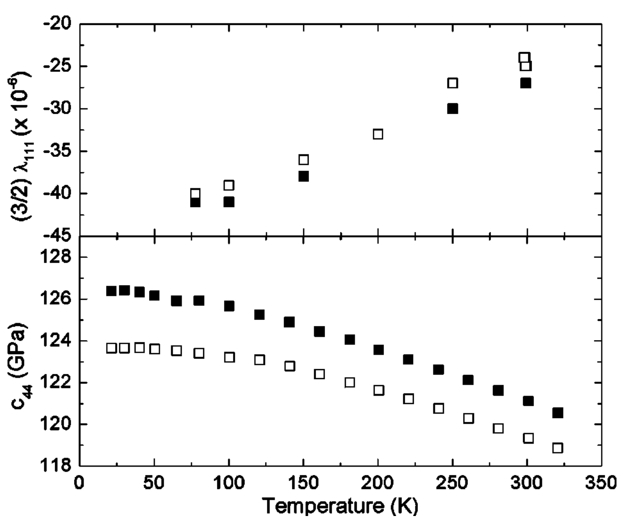


FIG. 2. $(3/2)\lambda_{111}$ and elastic constant $c_{44}$ as a function of temperature for $Fe_{93.9}Be_{6.1}$ (■) and $Fe_{88.7}Be_{11.3}$ (□) (Note the expanded scales).

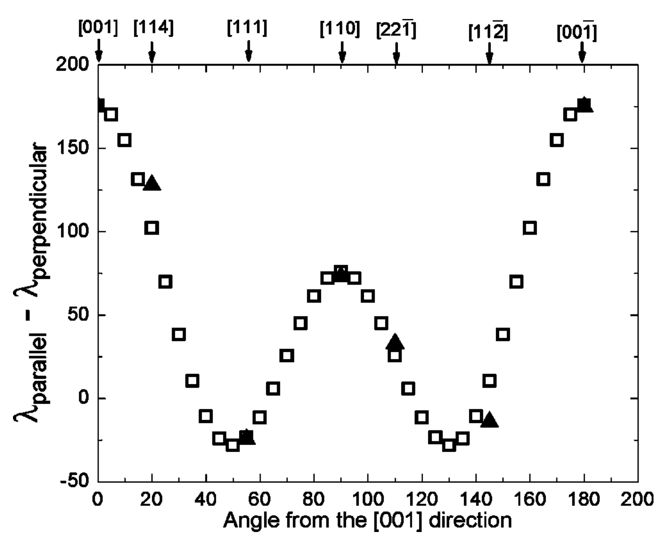


FIG. 3. Angular dependence of $\lambda_{\parallel}-\lambda_{\perp}$ in the $(1\bar{1}0)$ plane for $Fe_{88.7}Be_{11.3}$ calculated from Eq. (1) (□) and experimentally measured (▲).

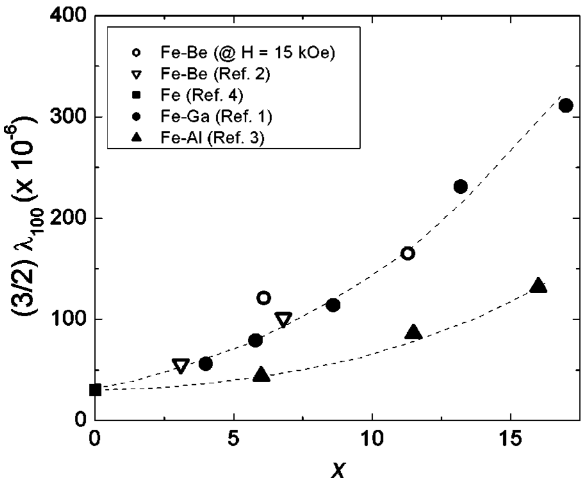


FIG. 4. $(3/2)\lambda_{100}$ for $Fe_{100-x}X_x$ (X=Be,Ga,Al). Note the measured magnetostriction of $Fe_{93.9}Be_{6.1}$ appears noticeably high and may reflect differences in composition between the measured sample and chemistry sample.

Here $\theta$ denotes the angle of the measurement direction with respect to the [001] direction.[8] Substituting into Eq. (1), one finds a value of $(3/2)\lambda_{100}$ at $\theta=0°$, $(3/2)\lambda_{111}$ at $\theta=54.7°$, and $(3/4)(\lambda_{100}+\lambda_{111})$ at $\theta=90°$. Evidence of the applicability of this equation to $Fe_{88.7}Be_{11.3}$ is illustrated by the good agreement in Fig. 3.

## IV. DISCUSSION

Previous studies have shown that the additions of Al, Ga, and small amounts of Be increases the small $(3/2)\lambda_{100}$ value of Fe, although none of these elements are magnetic.[1–3] Figure 4 compares their concentration dependencies up to 17%. (At higher concentrations, the simple bcc structure of Fe is not always retained and the magnetostrictions vary greatly.) Both Fe–Be and Fe–Ga alloys have comparable increases up to ~11% solute, while the Fe–Al increase is much smaller. This is somewhat surprising since Be is a smaller atom than Fe, while both Ga and Al atoms are larger than Fe.

The magnetoelastic energy, which couples the strains with the magnetization directions, can be written

$$E_{\mathrm{me}}=b_1(\alpha_x^2 e_{xx}+\alpha_y^2 e_{yy}+\alpha_z^2 e_{zz})+b_2(\alpha_x\alpha_y e_{xy}+\alpha_y\alpha_z e_{yz}+\alpha_z\alpha_x e_{zx}), \quad (2)$$

where $b_1$ and $b_2$ are magnetoelastic coupling coefficients, $e_{ij}$ are the Cartesian strains, and $\alpha_{ij}$ are the direction cosines of the magnetization with respect to the Cartesian axes.[9] This leads to:

$$-b_1=(3/2)\lambda_{100}(c_{11}-c_{12}),$$

and

$$-b_2=3\lambda_{111}c_{44}. \quad (3)$$

Figure 5 depicts the dependence of the magnetoelastic constants on temperature from 77 to 300 K. Because of the moderating influence of the elastic constants, the temperature dependencies are smaller than those of the magnetostrictions. In fact, although the magnetostriction $(3/2)\lambda_{100}$ of $Fe_{93.9}Be_{6.1}$ exhibits small anomalous positive temperature dependence over this range, the temperature dependence of the magnetoelastic constant $|b_1|$ is negative and normal. Even though the magnitudes of the magnetostrictions $\lambda_{100}$ and $\lambda_{111}$ differ by more than a factor of 6, the magnitudes of the magnetoelastic constants $b_1$ and $b_2$ differ by less than a factor of 2. Clearly, the $Fe_{100-x}Be_x$ alloys are highly anisotropic: (1) magnetostrictively, (2), elastically and (3) magnetoelastically. Table II compares the anisotropies of these alloys with those of Fe.

TABLE II. Magnetostrictive, elastic, and magnetoelastic anisotropies for $Fe_{100-x}Be_x$ alloys at room temperature.

| | $\lambda_{100}/\lambda_{111}$ | $2c_{44}/(c_{11}-c_{12})$ | $b_1/b_2$ |
|---|---|---|---|
| Fe | $-1.0^4$ | $2.42^5$ | −0.41 |
| $Fe_{93.9}Be_{6.1}$ | −4.65 | 3.12 | −1.49 |
| $Fe_{88.7}Be_{11.3}$ | −6.60 | 3.55 | −1.86 |

## ACKNOWLEDGMENTS

This work was supported by the U.S. Office of Naval Research, the Carderock Division of the Naval Surface Warfare Center, and the Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy. The authors also thank Jenny Lichter of MIT, Boston, MA.

[1] A. E. Clark, K. B. Hathaway, M. Wun-Fogle, J. B. Restorff, T. A. Lograsso, V. M. Keppins, G. Petculescu, and R. A. Taylor, J. Appl. Phys. **93**, 8621 (2003).
[2] R. Gersdorf, Ph.D. thesis, Univ. of Amsterdam, The Netherlands, 1961.
[3] R. C. Hall, J. Appl. Phys. **30**, 816 (1960).
[4] E. Tatsumoto and T. Okamoto, J. Phys. Soc. Jpn. **14**, 1588 (1959).
[5] See W. P. Mason, *Physical Acoustics and the Properties of Solids* (Van Nostrand, Princeton, N.J., 1958), p. 358.
[6] H. J. Leamy, E. D. Gibson, and F. X. Kayser, Acta Metall. **18**, 1827 (1967).
[7] M. Wuttig, L. Dai, and J. Cullen, Appl. Phys. Lett. **80**, 1135 (2002).
[8] J. P. Teter, A. E. Clark, and O. D. McMasters, J. Appl. Phys. **61**, 3787 (1987).
[9] See, for example, C. Kittel, Rev. Mod. Phys. **21**, 541 (1949).

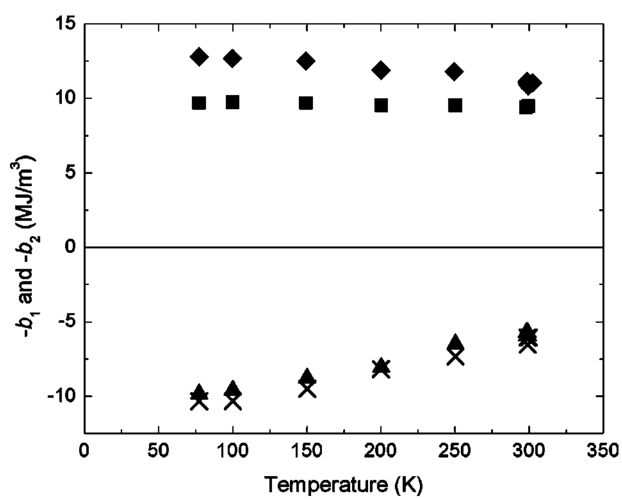


FIG. 5. $-b_1$ for (◆) $Fe_{88.7}Be_{11.3}$ and (■) $Fe_{93.9}Be_{6.1}$ and $-b_2$ for (▲) for $Fe_{88.7}Be_{11.3}$ and (×) $Fe_{93.9}Be_{6.1}$.