Texture and grain morphology dependencies of saturation magnetostriction in rolled polycrystalline Fe83Ga17

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Texture and grain morphology dependencies of saturation magnetostriction in rolled polycrystalline Fe83Ga17

Abstract
Textured polycrystalline Fe-Ga alloys exhibit magnetostrictive strains of 100 ppm or greater and may function as a mechanically robust actuator/sensing material. Current efforts seek to combine the 300+ ppm magnetostrictive strain performance of [100] oriented single crystals with the mechanical properties of polycrystalline forms. One approach to combining these properties is to control the crystallographic texture through deformation processing such as rolling. To determine the relationship between saturation magnetostriction, degree of texturing, and grain morphology we compare the results of three-dimensional finite element simulations with the analytical solution for a random polycrystal and the experimental responses of rolled polycrystalline Fe\textsubscript{83}Ga\textsubscript{17}. Textured specimens were produced through rolling reductions up to 99% of an as-cast ingot and a subsequent 1100 or 590 °C anneal. The high temperature anneal produced a recrystallized grain structure having a wide variation in crystal orientation as determined by orientation imaging microscopy. This recrystallized specimen exhibited a net magnetostriction of ∼170 ppm in the rolling direction and was well correlated with the finite element model result. The low temperature annealed specimen possessed fine elongated grains having dispersed {001}〈110〉 and {111}〈211〉 textures. Net magnetostrictions of 30 and 37 ppm were measured in the rolling direction and 45° off the rolling direction, respectively. The low magnetostriction value in the 45° direction disagrees substantially with the finite element solution of 157 ppm and suggests that unknown factors are dominating the response.

Keywords
iron alloys, gallium alloys, magnetostriction, ferromagnetic materials, recrystallisation texture, hot rolling, finite element analysis, recrystallisation annealing

Disciplines
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Comments
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I. INTRODUCTION

Textured polycrystalline Fe-Ga alloys exhibit magnetostrictive strains of 100 ppm or greater and may function as a mechanically robust actuator/sensing material. Current efforts seek to combine the 300+ ppm magnetostrictive strain performance of [100] oriented single crystals with the mechanical properties of polycrystalline forms. One approach to combining these properties is to control the crystallographic texture through deformation processing such as rolling. To determine the relationship between saturation magnetostriction, degree of texturing, and grain morphology we compare the results of three-dimensional finite element simulations with the analytical solution for a random polycrystal and the experimental responses of rolled polycrystalline Fe$_{83}$Ga$_{17}$. Textured specimens were produced through rolling reductions up to 99% of an as-cast ingot and a subsequent 1100 or 590 °C anneal. The high temperature anneal produced a recrystallized grain structure having a wide variation in crystal orientation as determined by orientation imaging microscopy. This recrystallized specimen exhibited a net magnetostriction of $\sim$170 ppm in the rolling direction and was well correlated with the finite element model result. The low temperature annealed specimen possessed fine elongated grains having dispersed $\{001\}$/$\{110\}$ and $\{111\}$/$\{211\}$ textures. Net magnetostrictions of 30 and 37 ppm were measured in the rolling direction and 45° off the rolling direction, respectively. The low magnetostriction value in the 45° direction disagrees substantially with the finite element solution of 157 ppm and suggests that unknown factors are dominating the response. © 2003 American Institute of Physics. [DOI: 10.1063/1.1540062]
represented by the linear superposition of elastic strains \( \varepsilon_{\text{elas}} \) and saturation magnetostriction \( \lambda \), in the relationship \( \varepsilon_{\text{tot}} = \varepsilon_{\text{elas}} + \lambda \). This superposition relationship is fundamental to the three-dimensional FEM used in this work to model a polycrystal’s total strain response to changes in magnetization from an ideal demagnetized state to one of full saturation in a specified direction. Although the polycrystals in these experiments are not loaded by external forces, elastic strains can arise within grains due to strains imposed by the anisotropic magnetostriction of neighboring grains possessing different crystallographic orientations. The FEM uses constant strain tetrahedrons to subdivide the material volume. Multiple tetrahedrons compose each grain and are assigned rotationally transformed elastic and magnetostrictive properties based on the grain orientation within a global reference frame. Continuity of displacement throughout the material is enforced at the vertices of adjacent tetrahedral elements. The FEM simulates the magnetostrictive strain, going from an ideal demagnetized state to one of full saturation, by introducing a stress-free initial strain for each grain. Accounting for the elastic response of adjoining grains, the overall system is then solved for the lowest energy state to give the equilibrium condition of the system. Introductory texts provide additional details on the FEM.\(^5\)

The magnetostrictive strains used in the FEM are obtained from a theory for the anisotropic magnetostriction of single crystals. The saturation magnetostriction is calculated using two material constants as a first order approximation. Equation (1) provides the engineering strain components for a cubic crystal magnetized to saturation from an ideal demagnetized state.\(^6\) The direction cosines \( \alpha \) define the saturation magnetization direction relative to the crystal axes and the magnetostriction constants \( \lambda_{100} \) and \( \lambda_{111} \) are material properties to be identified experimentally:

\[
\varepsilon_{ij} = \frac{3}{2} \lambda_{100} (\alpha_i^2 - 1/3), \quad \varepsilon_{ij} = 3 \lambda_{111} \alpha_i \alpha_j, \tag{1}
\]

where \( i \neq j, \quad i = 1,2,3, \quad j = 1,2,3 \). The saturation magnetostriction \( \lambda_j \) for an arbitrary direction is given by Eq. (2) where the \( \beta \)'s are the direction cosines of the chosen measurement direction relative to the crystal axes:

\[
\lambda_j = \sum_{i=j} \varepsilon_{ij} \beta_i \beta_j \quad \text{where} \quad i = 1,2,3, j = 1,2,3. \tag{2}
\]

From a practical standpoint it is difficult to achieve an ideal demagnetized state in a crystal with any certainty; however, Eqs. (1) and (2) remain quite useful. The crystal’s net saturation magnetization \( \lambda_j - \lambda_1 \) may be measured by the application of a saturating magnetic field parallel and then perpendicular to the direction of strain measurement.

After the magnetostrictive strains are introduced into the FEM, each grain’s elastic response is modeled using Eq. (3). Elastic tensor strains \( \varepsilon_j \) introduced by neighboring grains result in stresses \( \sigma \) proportional to the single crystal elasticity constants \( c_{ij} \). Cubic materials such as the Fe-Ga alloys require only three independent elastic constants:

\[
\sigma_i = c_{ij} \varepsilon_j \quad \text{where} \quad i = 1,2,\ldots,6, \quad j = 1,2,\ldots,6. \tag{3}
\]

Cubic materials such as the Fe-Ga alloys require only three independent elastic constants:

\[
C_{11} = C_{22} = C_{33}; \quad C_{12} = C_{21} = C_{13} = C_{31} = C_{32} = C_{33}; \quad C_{44} = C_{55} = C_{66}. \quad \text{All other } C_{ij} = 0. \tag{7}
\]

Clark et al. have reported the properties for single crystal specimens of Fe-Ga alloys.\(^1,8\) The magnetostriction constants of \( \lambda_{100} = 200 \times 10^{-6} \) and \( \lambda_{111} = -16 \times 10^{-6} \) for Fe\(_8\)Ga\(_{17}\) and elastic constants \( c_{11} = 196 \text{ GPa}, \quad c_{12} = 156 \text{ GPa}, \quad \text{and } c_{44} = 120 \text{ GPa} \) for Fe\(_{81.3}\)Ga\(_{18.7}\) are used throughout this work.

### III. RESULTS

To provide validation of the FEM approach, a simulation was conducted on a sheet containing 126 identically sized hexagonal shaped grains. Monte Carlo techniques were used to generate a random distribution of crystal orientations throughout multiple simulation runs. The result of interest is the total strain \( \varepsilon_{\text{tot}} = 1 \), which arises from a change in the saturation magnetization direction from perpendicular to one that is parallel with the direction of strain measurement. Ten runs of the FEM simulation gave \( \varepsilon_{\text{tot}, \perp} = \pm 177 \pm 3 \text{ ppm} \) and were accompanied by internal principal stresses ranging between \( \pm 24 \text{ MPa} \). For comparison, noninteracting grains having the same orientation distribution gave \( \lambda_j - \lambda_1 = 104 \pm 3 \text{ ppm} \). These results are in good agreement with the analytical result \( \lambda_j - \lambda_1 = (3/2)(2/3\lambda_{100} + 3\lambda_{111})/5 = 106 \text{ ppm} \). The analytical result assumes no grain interaction and may be derived from the volume integration of Eqs. (1) and (2).\(^9\)

Less regular grain shapes and sizes would likely lead to larger internal stresses and a somewhat lower bulk magnetostriction result than the 23% reduction from 104 to 80 ppm simulated here.

The next portion of the work compares the simulated and actual strain response of a rolled, high temperature annealed Fe\(_8\)Ga\(_{17}\) specimen. The specimen was produced by a 96% hot and warm rolling reduction of an as-cast ingot. A disk specimen, 7.9 mm in diameter, was punched from the rolled material, having a final thickness of 0.38 mm. A subsequent anneal of the disk for 5 h at 1100 °C induced secondary recrystallization and produced through-thickness grains with diameters up to \( \sim 400 \mu \text{m} \). Orientation imaging microscopy (OIM) was used to map each grain and its crystallographic orientation. Figure 1 shows only the mapped central region of the disk with the rolling direction (RD) indicated. The dashed rectangle outlines the strain gauge location used for actual and simulated strain measurements.

The grains of Fig. 1 correspond to the grain misorientations, relative to a \{001\}/(100) sheet texture, plotted in Fig. 2. The numbered grains of Fig. 1 fall within the strain gauge region and are denoted in Fig. 2. To model the specimen with the FEM, a mesh consisting of multiple cubes was fitted to subdivide the grain structure. These cubes compose the volume of the sheet and appear as four-sided polygons at the sheet surface. Each cube is further subdivided into five tetrahedrons.

The actual and simulated strain states of the disk were analyzed for changes in the direction of the saturation magnetization vector from transverse to parallel with the rolling direction. The FEM simulation indicated \( \varepsilon_{\text{tot}, \perp} = 177 \pm 3 \text{ ppm} \) relative to the rolling direction; this value falls between the measurements of 160 and 180 ppm collected in
separate strain gauge installations. Note that the experimental results are sensitive to minor changes in gauge location due to the large grain sizes and their wide range of crystallographic orientation. The FEM was also used to simulate the RD components of stress and strain for a change from a demagnetized state to one of saturation magnetization in the RD. Grains having small angular deviations from the RD (such as 2, 4, and 9) exhibit the largest magnetostrictions with $e_{\text{tot,RD}}$ ranging from 127 to 154 ppm. Variation in $e_{\text{tot,RD}}$ of these grains is influenced by compressive stress levels varying up to 3.6 MPa. These compressive stresses are the result of misoriented neighboring grains having a low $\lambda_1$ in the RD.

A final comparison of a FEM simulation and experimental measurements was conducted on a fine-grained polycrystalline Fe$_{83}$Ga$_{17}$ specimen. An as-cast ingot was reduced by an as-cast ingot was reduced by a fine-grained polycrystalline Fe$_{83}$Ga$_{17}$ specimen. An as-cast ingot was reduced by a fine-grained polycrystalline Fe$_{83}$Ga$_{17}$ specimen. An as-cast ingot was reduced by...