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# Grain orientation dependence of ΔE effect and magnetomechanical coupling factor in polycrystalline Galfenol alloy

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ABSTRACT

The ΔE effect of Galfenol single crystal is anisotropic and symmetric. The magnetomechanical behavior of polycrystalline Fe-Ga alloy was found to be dependent on the grain distribution. An energy-based model was used to simulate the effect of grain distribution on ΔE effect and coupling factor of the polycrystalline Galfenol alloy. Seven types of textured $Fe_{84}Ga_{16}$ alloys each with 95, 75 and 50 vol% textured grains were designed by the MTEX toolbox. The alloys having the same < uvw > preferred orientation show a similar ΔE effect and coupling factor variation with the stress and magnetic field. Different < uvw > preferred oriented alloys have great difference in the ΔE effect and coupling factor variation. The effect of texture intensity on the ΔE effect and coupling factor depends on the texture types. The ⟨100⟩ oriented alloys with fiber texture, Goss texture and cube texture respectively have a similar large ΔE effect. The texture intensity has a relatively small effect on the ΔE effect and coupling factor *k* of ⟨100⟩ oriented alloys. Compared with ⟨100⟩ oriented alloys, the ⟨110⟩ and ⟨112⟩ oriented alloys have much smaller ΔE effect and coupling factor. The ΔE effect and coupling factor variation with stress and magnetic field of those two kinds of textured alloys is much more complex than that of ⟨100⟩ textured alloys.

## 1. Introduction

Fe-Ga alloys are promising actuation and sensing material because of their moderate magnetostriction under low saturated field and good mechanical property [1]. For magnetic material the strain-stress response under stress appears non-linear. This phenomenon is called ΔE effect [2]. When a magnetic field is applied on material, the Young's modulus appears to be affected not only by the stress but also by the magnetic field [3–5]. The ΔE effect of Galfenol can be utilized in vibration control and stiffness control [6–10]. The Young's modulus response to stress and magnetic field of Fe-Ga is significant for its application. Magnetomechanical coupling factor *k* is a measure of the coupling of magnetic energy into the elastic energy of the material which is usually used as a measure of transduction efficiency of the material.

The ΔE effect of Galfenol has interested many researchers. S. Datta et al. studied the variability in Young's modulus of single crystal Fe-Ga alloys with different composition, which showed more than 60% change in Young's modulus [5]. G. Petculescu et al. measured the elastic moduli of $Fe_{100-x}Ga_x$ (x = 12–33) single crystals with and without a magnetic field within 4–300 K, and found that the moduli show a smooth dependence on temperature [11]. S.U. Jen et al. measured the Young's modulus E and damping capacity of $Fe_{81}Ga_{19}$ under the temperature varied from room temperature to 300 °C, and the results showed that in the E versus T plot when H = 0 there is a downward kink at 232 °C [12]. In previous study, we have studied the magnetomechanical behavior along different crystal directions [13], which clearly showed that the ΔE effect varies with the crystal direction. The ⟨100⟩ directions have the largest magnetostriction and the largest ΔE effect under the same bias magnetic field. It can be expected that the grain distribution has a great effect on the magnetomechanical coupling behavior. The production cost of single crystal Fe-Ga alloy is high, so commercial actuators and sensors are more likely to be made of textured polycrystalline Fe-Ga alloy with little degradation of the actuation and sensing properties. However, there is no work systematically studying the effect of grain orientation distribution on the magnetomechanical behavior of Fe-Ga alloy which is useful for material application and production.

In order to obtain large magnetostriction, it is better to produce polycrystalline alloy with ⟨100⟩ preferred orientation. ⟨100⟩ fiber texture is usually obtained by directional solidification [14]. {110}⟨001⟩ Goss texture and {001}⟨100⟩ cube texture are two kinds of

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texture usually obtained by rolling and secondary recrystallization [15,16]. Na also obtained {110}⟨112⟩ texture when the ($Fe_{81.3}Ga_{18.7}$) +1 at.% B + 0.05 at.% S sheet was annealed at 1200 °C for 2 h [16]. For the BCC Fe-Ga alloys, {001}⟨110⟩ rotated cube texture, {111}⟨110⟩ and {111}⟨112⟩ textures are often obtained after rolling [17]. In this study these seven kinds of texture are simulated to study the effect of grain orientation on the ΔE effect and coupling factor.

Model simulation is widely used in the study of magnetomechanical behavior of magnetostrictive material. L. Daniel and O. Hubert used a semi-analytical model in which magnetization rotation is not considered to simulate the ΔE effect [18,19]. Zhangxian Deng et al. presented a new optimization procedure on the basis of an existing discrete energy-averaged model which incorporated measurement uncertainties to simulate the minor strain-stress loops [20]. S. Datta predicted the variable modulus in Galfenol as a continuous function of stress and magnetic field by using an energy-based non-linear constitutive model which was developed on the basis of Armstrong model [5]. The model prediction showed good correlation with experimental results.

In this work, with the bias magnetic field and compressive stress applied along various crystallographic directions, the magnetomechanical behavior of Fe-Ga single crystal has been studied on the basis of an energy-based model. Then seven kinds of textured alloys each with 95, 75 and 50 vol% textured grains were simulated to compare the influence of grain distribution on the ΔE effect and magnetomechanical coupling factor. The results show that the magnetomechanical behavior depends on the preferred orientation. This study could be very meaningful for the Galfenol production and its application design.

## 2. Model description

In this paper, an extended model based on the Armstrong model is used to simulate the magnetomechanical behavior of single crystal and polycrystalline Galfenol alloys. This probability model was originally proposed by Armstrong to model the magnetization and magnetostriction of TbDyFe [21]. This model was adapted later on by many researchers to model the sensing and actuating behavior of magnetostrictive material. Won-Je Park et al. combined this probability distribution model with the Jile-Theokle model to simulate the domain motion and predict the magnetostriction of TbDyFe [22]. J. Atulasimha et al., using a model based on the Armstrong model, modeled the magnetomechanical behavior of polycrystalline Fe-Ga alloy from its cross-section texture by treating the polycrystal as composed of multiple grains of sing crystals, each with a different orientation to the loading axis [23]. S. Datta developed a model based on the Armstrong model to simulate the figures of merits of Fe-Ga alloys with different composition [24].

When applied magnetic field and stress, the magneto-elastic equilibrium of a magnetostrictive material can be seen as a result of a competition between several energy contributions: the exchange energy $G_{ex}$, magnetocrystalline anisotropy energy $G_K$, magnetostatic energy $G_H$, magnetoelastic energy $G_{me}$, elastic energy $G_{el}$ and mechanical workdone $W_{mech}$. The exchange energy can be ignored because it is very small in a bulk sample. The works of Kittel, Chikazumi and Mudivarthi [25–27] show that the magnetoelastic energy $G_{me}$, elastic energy $G_{el}$ and mechanical workdone $W_{mech}$ can merge into two terms: a stress-induced energy $G_\sigma$ and an anisotropy energy due to the equilibrium magnetostrictive strains. Then the total energy affecting both strain and magnetization in a bulk material is expressed by the sum of magnetocrystalline energy, magnetostatic energy and stress-induced anisotropy energy as shown in Eq. (1). The stress-induced anisotropy energy $G_\sigma$ was also called as strain or stress energy [28], and it has been erroneously called as the magnetoelastic energy [29] or elastic energy [30]. Some researchers even wrongly thought that the elastic energy and the magnetoelastic energy are the same [18].

$$\begin{aligned} G_t &= G_K + G_H + G_\sigma \\ &= K_1 \sum_{i<j}^{3} \alpha_i^2\alpha_j^2 + K_2\alpha_1^2\alpha_2^2\alpha_3^2 \\ &\quad - \mu_0 M_s H \sum_{i=1}^{3} \alpha_i\beta_i \\ &\quad - \tfrac{3}{2}\lambda_{100}\sigma \sum_{i=1}^{3} \alpha_i^2\gamma_i^2 - 3\lambda_{111}\sigma \sum_{i<j}^{3} \alpha_i\alpha_j\gamma_i\gamma_j \end{aligned} \tag{1}$$

where $\alpha_i$, $\beta_i$ and $\gamma_i$ (i = 1, 2, 3) are the direction cosines of the magnetization, applied magnetic field and applied stress, respectively. $K_1$ and $K_2$ are the magnetocrystalline anisotropy coefficients, and the $K_1$ used here is fixed with the magnetostrictive anisotropy constant. $H$ is the magnetic field strength and σ is the magnitude of applied uniaxial stress. $\lambda_{100}$ and $\lambda_{111}$ are saturated magnetostriction coefficients.

In this study for simplicity uniaxial stress is used, but in reality the stress state is complex. So here Eq. (1) is extended to incorporate 3D stresses. For 3D modeling, the stress-induced energy expression in Eq. (1) needs slight modification. Any 3D stress tensor acting on a body can be decomposed into three principle stresses $\sigma_j$ and principle directions ($\gamma_{1j}$, $\gamma_{2j}$, $\gamma_{3j}$). The stress-induced anisotropy energy is sum of the stress-induced anisotropy energies due to each principle stress [27]

$$G_{\sigma 3D} = \sum_{j=1}^{3} \left\{ -\frac{3}{2}\lambda_{100}\sigma_j \left( \sum_{i=1}^{3} \alpha_i^2\gamma_{ij}^2 - \frac{1}{3} \right) - 3\lambda_{111}\sigma_j(\alpha_1\alpha_2\gamma_{1j}\gamma_{2j} + \alpha_2\alpha_3\gamma_{2j}\gamma_{3j} + \alpha_1\alpha_3\gamma_{1j}\gamma_{3j}) \right\} \tag{2}$$

The direction cosines can be expressed in terms of the azimuthal angle $\theta$ and polar angle $\phi$. So the total free energy $G_t$ can be expressed in terms of $\theta$ and $\phi$. It is assumed that the magnetic moment distributes along a spatial direction ($\theta_i$, $\phi_j$) with a certain distribution probability $P_{ij}$ which is determined by the energy along this direction. Armstrong [19] gave the expression of probability $P_{ij}$:

$$P_{ij}(\theta_i, \phi_j) = \frac{\exp[-G_t(\theta_i, \phi_j)/\omega]}{\int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} \exp(-G_t(\theta, \phi)/\omega)\sin(\theta)d\theta d\phi} \tag{3}$$

The magnetostriction along the direction ($\beta_{1R}$, $\beta_{2R}$, $\beta_{3R}$) can be calculated as the sum of all magnetic moments contribution:

$$\lambda = \int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} \left[ \frac{3}{2}\lambda_{100}\left( \sum_{i=1}^{3} \alpha_i^2\beta_{iR}^2 - \frac{1}{3} \right) + 3\lambda_{111} \sum_{i<j}^{3} \alpha_i\alpha_j\beta_{iR}\beta_{jR} \right] P_{ij}\sin\theta d\theta d\phi \tag{4}$$

where $G_t(\theta,\phi)$ is the total energy for the magnetization along the direction ($\theta$, $\phi$). $\omega$ is the energy distribution parameter. The $\beta_{iR}$ (i = 1, 2, 3) is the direction cosine of measurement.

In this model the hysteresis effect is not considered for simplicity. It is assumed that the magnetization process is reversible. However, in reality because of the imperfections and the magnetocrystalline anisotropy of material the magnetization process is irreversible. So if want to improve the simulation accuracy, the hysteresis effect needs to be considered in future study.

For the Fe-Ga single crystal with cubic structure, its Young's modulus is crystallographic direction-dependent. The Young's modulus $E$ at any direction of [$hkl$] can be calculated by the following relationship:

$$\frac{1}{E_{hkl}} = S_{11} - 2(S_{11} - S_{12} - 0.5S_{44}) \times (\alpha_{s1}^2\alpha_{s2}^2 + \alpha_{s1}^2\alpha_{s3}^2 + \alpha_{s2}^2\alpha_{s3}^2) \tag{5}$$

where

$$S_{11} = \frac{C_{11} + C_{12}}{(C_{11} - C_{12})(C_{11} + 2C_{12})} \tag{6}$$

$$S_{12} = \frac{-C_{12}}{(C_{11} - C_{12})(C_{11} + 2C_{12})} \tag{7}$$