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Stress dependence of ΔE in amorphous ribbon

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The Young's modulus with magnetic field (ΔE effect) has been investigated by the single domain model in $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous ribbon for as-received state. The stress dependence of Young's modulus was analyzed in terms of the volume fraction of transverse domains, the average internal stress, and transverse anisotropy constant as a function of applied stress, and yielded a good agreement with the experimental results.
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I. INTRODUCTION

The field dependent Young's modulus (ΔE effect) has been extensively studied in amorphous ribbons, because the combination of large magnetostriction and low anisotropy produces very large effects.[1] Magnetostriction and associated magnetoelastic effects are originated from the rotation of the transverse magnetic moments in the ribbon direction under the influence of the applied magnetic field and applied stresses.[2,3] The applied stress causes changes in the associated transverse anisotropy, the volume fraction of transverse domains, and the average moment angle in the ribbon. These changes influence the magnetic and magnetoelastic behavior in a complicated way.

The purpose of this paper is to present the stress dependence of Young's modulus $E(H)$ in as-received $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous ribbon, and to relate them with the existing single domain model for the amorphous materials.

II. EXPERIMENT

A block diagram for the Young's modulus measurement by impedance resonance method[4] is shown in Fig. 1. The sample was the commercially available 2605SC amorphous ribbon supplied by Nipon Metallic Amorphous Ltd. with the dimensions of 2.5 cm×11 cm×25 μm in as-received state.

A stressing device consisted of a spring having the spring constant 1.45×10^3 N/m used to apply tensile stress in the elastic range from 0 to 70 MPa to the sample inside the detecting coil in order to measure simultaneously the referred impedance with frequency. The applied stress was large enough to produce significant changes in the magnetic properties. The resonance of the samples was excited using a small alternating magnetic field in the frequency range from 30 to 60 kHz by a LF impedance analyzer (hp 4192A). The Young's modulus E was calculated from the resonance frequency f_r in the following way:

$$E = 4l^2 f_r^2 \rho, \tag{1}$$

where the density of the sample ρ was 7.32×10^3 kg/m^3 for this sample[5] and the sample length l was 11 cm.

III. ANALYSIS OF ΔE UNDER STRESS

The change of elastic modulus in the ferromagnetic materials (ΔE effect) originates from the rotation of the magnetization under the influence of applied field and stress,[1] which is related to the transverse domains. The quenched-in stress gives rise to the complex pattern of fine and curved domains on the specimen surface which provides two regions of domains inside the amorphous ribbons; the domain oriented parallel and transverse to the longitudinal ribbon direction, whose volume fractions are designated as $v_\parallel$ and $v_\perp$, respectively.[6]

When the magnetization moment is subjected to the external field and stress, the direction of magnetization is given as a function of total energy. Suppose that the field is applied along the ribbon axis, the average internal stress σ_i makes an angle β with the ribbon axis, as shown in the coordinate system in Fig. 2. The magnetization inside $v_\perp$ domains rotates to the direction of applied magnetic field with equilibrium angle ϕ. The total energy is composed of the anisotropy energy E_K, Zeeman energy E_H, internal stress energy E_{σ_i}, stress induced energy E_σ, and is written as

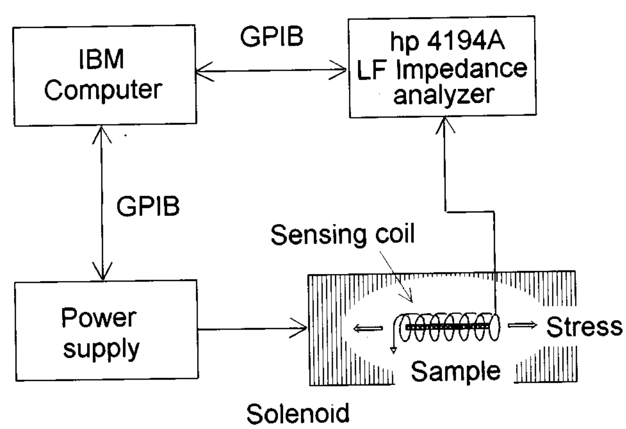

FIG. 1. The block diagram for the measurement of Young's modulus by impedance change.

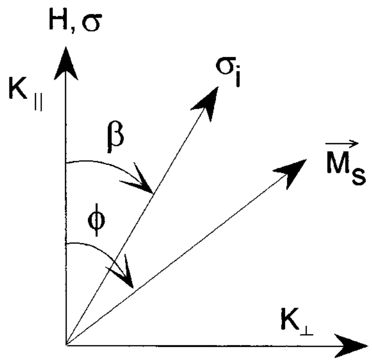

FIG. 2. Definition of the angle ϕ and β.

$$
\begin{aligned}
E_T &= E_K + E_H + E_{\sigma_i} + E_\sigma \\
&= v_\perp [K_\perp \sin^2 \phi - HM_s \cos \phi \\
&\quad + \tfrac{3}{2}\lambda_s \sigma_i \sin^2(\phi - \beta) + \tfrac{3}{2}\lambda_s \sigma \sin^2 \phi],
\end{aligned}
\tag{2}
$$

where λ_s is the saturation magnetostriction, M_s is the saturation magnetization, σ_i is the average internal stress, $K_\perp$ is transverse anisotropy constant, β and ϕ are the angles between ribbon axis and average internal stress, magnetization, respectively. The angle ϕ determines the orientation of the magnetization, whose value in the equilibrium state is calculated from the condition for the minimum of total energy as follows

$$
\begin{aligned}
\frac{\partial E_T}{\partial \phi} &= -K_\perp \sin 2\phi + HM_s \sin \phi \\
&\quad + \tfrac{3}{2}\lambda_s [\sigma_i \sin 2(\phi - \beta) + \sigma \sin 2\phi] \\
&= 0.
\end{aligned}
\tag{3}
$$

The above equation gives the relationship between the magnetization angle ϕ and external stress σ. Here let us consider where a uniaxial tension σ is applied to ribbon axis, then the longitudinal strain $\epsilon_\parallel (= \epsilon_{33})$ is given by a sum of elastic strain and induced strain by field as[7]

$$
\epsilon_\parallel = \frac{\sigma}{E_s} + \epsilon_{\parallel H}, \tag{4}
$$

with

$$
\epsilon_{\parallel H} = \tfrac{3}{2}\lambda_s (\cos^2 \phi - \tfrac{1}{3}) v_\perp, \tag{5}
$$

where σ / E_s is the saturation strain of longitudinal direction, and E_s is the Young's modulus at saturation which is purely elastic value. The $\epsilon_{\parallel H}$ is the longitudinal strain changed with applied magnetic field, which is given as a function of ϕ, as in Eq. (5).[8] The Young's modulus is related with the longitudinal strain $\epsilon_\parallel$ and stress σ, and is given by using Eq. (4) as

$$
\begin{aligned}
\frac{1}{E(H)} &\equiv \frac{d\epsilon_\parallel}{d\sigma} = \frac{1}{E_s} + \frac{d\epsilon_{\parallel H}}{d\sigma} \\
&= \frac{1}{E_s} + \frac{\partial \phi}{\partial \sigma}\frac{\partial \epsilon_{\parallel H}}{\partial \phi} = \frac{1}{E_s} + f(\phi, \sigma, H),
\end{aligned}
\tag{6}
$$

where the chain rule in the derivative is applied for the variables σ and ϕ. After a little algebra substituting Eqs. (3) and (5) into Eq. (6), we can derive the stress and field dependence of Young's modulus and $f(\phi, \sigma, H)$ as follows

$$
E(H) = \frac{E_s}{1 + f(\phi, \sigma, H) E_s}, \tag{7}
$$

$$
\begin{aligned}
&f(\phi, \sigma, H) \\
&\quad = \frac{\tfrac{9}{4}\lambda_s^2 \sin 2\phi v_\perp(\sigma)}{HM_s \cos \phi + 3\lambda_s \sigma_i \cos 2(\phi - \beta) - K_\perp \cos 2\phi}.
\end{aligned}
\tag{8}
$$

The function $f(\phi, \sigma, H)$ embraces all the information of the ΔE effect originating from the rotation of the transverse moments in the ribbon, related to the internal stress and volume fraction of transverse domain.

The volume fraction of transverse domain $v_\perp$ decreases as applied tensile stress increases,[9] but whose value is dominated by the sum of external and internal stresses. The internal compressive stress distribution $N(\sigma)$ is a function of the external stress,[10] and the integral of $N(\sigma)$ gives the amount of magnetization reorientation by external stress. Hence, the stress dependence of volume fraction of transverse domain is written as

$$
\begin{aligned}
v_\perp(\sigma) &= v_\perp(0)\left(1 - \int_0^\sigma N(\sigma) d\sigma\right) \\
&= v_\perp(0)\left(1 + \frac{2\sigma}{\sigma_i}\right) e^{-2\sigma/\sigma_i},
\end{aligned}
\tag{9}
$$

where σ_i is the average compressive internal stress.

By substituting the Eq. (9) into Eq. (7) with the help of Eq. (8), we have the stress and field dependence of Young's modulus, used for the fitting with suitable values of parameters. In calculation of Young's modulus using the resonance frequency obtained by impedance measurement, we take into account the clamping effect that the compressive stress causes the saturated domains at both ends of the sample to be the effective Young's modulus as in the following equation

$$
E(H)_{\mathrm{eff}} = \frac{l^2}{(\Delta/\sqrt{E_s}) + [(l - \Delta)/\sqrt{E(H)}]}, \tag{10}
$$

where Δ is the clamping length of 3.7 cm, $E(H)$ is Young's modulus of the no clamping state.

IV. RESULTS AND DISCUSSION

Fig. 3 shows the experimental results and calculated value of Young's modulus with magnetic field under 0, 2.35, 7.1, 10 MPa tensile stresses for the as-recieved 2605SC Metglas, using Eq. (7) with the help of Eqs. (8) and (9). The fitting parameters[5] were $E_s = 168.5$ GPa, $K_\perp = 100$ J/m^3, $\lambda_s = 30 \times 10^{-6}$, $v_\perp = 0.42$, and $\sigma_i = 3.3$ MPa, and the four curves represent the change of ΔE effect with the different stresses for $\beta = \pi/7$. Here the magnetic field dependence of Young's modulus under 0 MPa represents the values of the

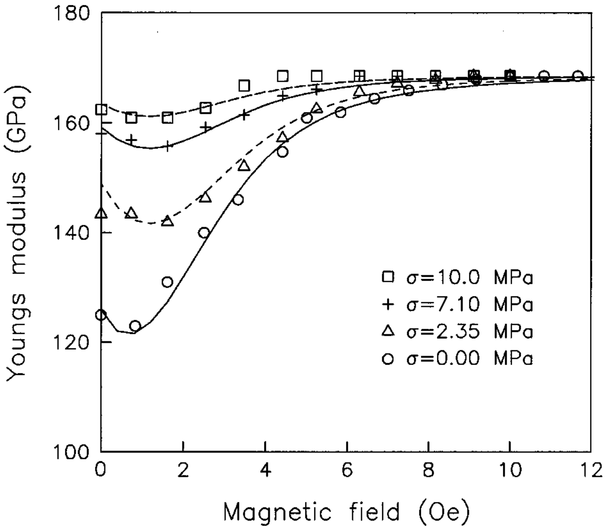

FIG. 3. The Young's modulus with magnetic field under 0, 2.23, 7.1, and 10 MPa applied tensile stresses. The lines are obtained by calculation of the single domain model.

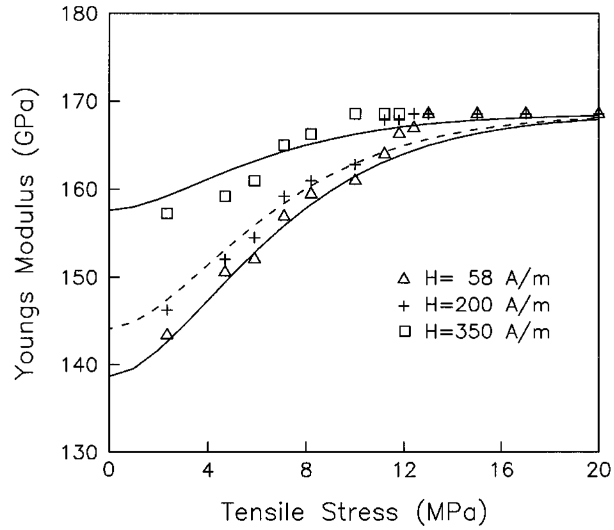

FIG. 4. The Young's modulus with applied tensile stresses under 58, 200, and 350 A/m applied magnetic field. The lines are obtained by calculation of the single domain model.

no clamping state. The decrease of the ratio of Young's modulus $E_s/E_{\min}(\sigma)$ with applied tensile stresses is caused by the decrease in $v_\perp(\sigma)$. The variation of $E(H)$ with magnetic field is shifted toward low field as the tensile increases. Thus, the ΔE effect is well fitted with the single domain model. The effect of the applied tensile stress on the Young's modulus in Fig. 4 is quantitatively similar to that of the applied magnetic field. However, the theoretical calculation using this model is not valid for the applied stress exceeding 10 MPa in the sample.

In this paper the stress dependence of ΔE effect have been investigated by single domain model in $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous ribbon in the as-received state. The stress dependence of the ΔE effect was analyzed in terms of volume fraction of transverse domains $v_\perp(\sigma)$, the direction of internal stress β and transverse anisotropy constant $K_\perp$ as a function of applied tensile stress, and yielded a good agreement with the model for the applied stress not exceeding 10 MPa. This analysis indicated that the stress dependence of the Young's modulus was dominanted by the change of volume fraction of transverse domains $v_\perp(\sigma)$ with applied tensile stress.

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