Magnetostriction of $Fe_{81}Ga_{19}$ oriented crystals*

Wang Zhi-Bin(王智彬), Liu Jing-Hua(刘敬华), and Jiang Cheng-Bao(蒋成保)†

School of Materials Science and Engineering, Beihang University, Beijing 100191, *China*

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The effect of the orientation on the magnetostriction in $Fe_{81}Ga_{19}$ alloy has been investigated experimentally and theoretically. The $Fe_{81}Ga_{19}$ [001] and [110] oriented crystals were prepared and the magnetostriction was measured under different pre-stress. The saturation magnetostriction of the [001] oriented crystal increases from 170×10^{-6} to 330×10^{-6} under the pre-stress from 0 to 50 MPa. The [110] oriented crystal has a saturation magnetostriction from 20×10^{-6} to 140×10^{-6} with the compressive pre-stress from 0 to 40 MPa. The magnetostriction of [001] and [110] oriented crystals has been simulated based on the phenomenological theory. The domain rotation path has been determined and the resultant magnetostriction calculated under different pre-stress. The experimental and simulated results both show that the [001] oriented crystal exhibits better magnetostriction than [110] oriented crystal. The enhancement of the saturation magnetostriction by the compressive pre-stress in the [110] oriented crystal is higher than that in the [001] oriented crystal.

Keywords: magnetostriction, orientation, $Fe_{81}Ga_{19}$ alloy, simulation

PACC: 7580, 7530G, 7540M, 6150J

1. Introduction

As a kind of smart material, the giant magnetostrictive TbDyFe alloys have been investigated intensively and used widely.[1−7] However, its drawbacks such as the brittleness, high cost, and low corrosion resistance, have restricted its application to some extent. In recent years, FeGa alloys have drawn a lot of interest due to their good magnetostrictive performance in the low field and much better ductility as compared with the well-developed giant magnetostrictive TbDyFe alloys.[8−19] The magnetostriction anisotropy results in the strong dependence of the magnetostriction on the orientations of the TbDyFe magnetostrictive crystals, where [110] and [112] oriented crystals exhibit excellent magnetostriction with the value several decades higher than that in [001] oriented crystals. To explain the magnetostriction under pre-stress in the TbDyFe crystals with different orientations, simulations of the magnetostriction were extensively performed in TbDyFe alloys.[20−23] As for FeGa alloys, two typical preferred orientations are obtained in the oriented crystals, including [001] and [110] orientations.[9,24] However, systematic investigation about the influence of the orientation on the magnetostriction properties in FeGa magnetostrictive alloys was rarely reported. In this paper, the magnetostriction of [001] and [110] oriented crystals in $Fe_{81}Ga_{19}$ alloy are studied experimentally and simulated based on a single domain rotation model. The experimental and simulated results both show that [001] oriented crystal possesses better magnetostriction than [110] oriented crystal in FeGa alloys. The enhancement of the saturation magnetostriction by the pre-stress in the [110] oriented crystal is much higher than that in the [001] oriented crystal.

2. Experimental

The starting elements iron and gallium with a high purity of 99.9% were melted four times by arc melting to prepare $Fe_{81}Ga_{19}$ ingots. Then the ingots were remelted and drop cast in the arc melting furnace to obtain rods with a diameter of 7.0 mm. The oriented crystals were prepared by directional solidification using induction heating zone melting crystal growth method at the growth rate of 20 mm/h, and the optical floating zone melting crystal growth method at the growth rate of 10 mm/h. The preferred orientation along the axis was checked by x-ray pole

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†Corresponding author. E-mail: jiangcb@buaa.edu.cn

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figures obtained using Regaku D/Max 2200 PC x-ray diffractometer. The magnetostriction was measured by the standard strain gauge method. The compressive pre-stress was applied by a gas pressure cell along the axis of the rod during magnetostriction test. The simulation was carried out by a self-written program using Matlab software.

3. Results

In the induction heating zone melting crystal growth furnace, the master rod of $Fe_{81}Ga_{19}$ alloy was put into an alumina crucible, and heated by the high frequency induction coil wound around the crucible with the melting zone length of about 10 mm. During the growth, the molten part was pulled into the liquid metal which is used as the cooling medium. Combining the induction-heated molten zone and liquid metal cooling medium, a super high temperature gradient of around 1000°C/cm was produced. The growth rate was 20 mm/h. The grown crystal with a total length of 100 mm was cut for x-ray diffraction measurement and magnetostriction test. Figures 1(a) and 1(b) are the pole figures of (001) and (110) planes, addressed on the cross section of the grown crystal. There is only one strong peak in the centre of (001) pole figure. There are four symmetrical peaks about 45° away from the centre of the (110) pole figure. Therefore, the grown crystal produced by the induction heating zone-melting crystal growth method possesses [001] preferred orientation.

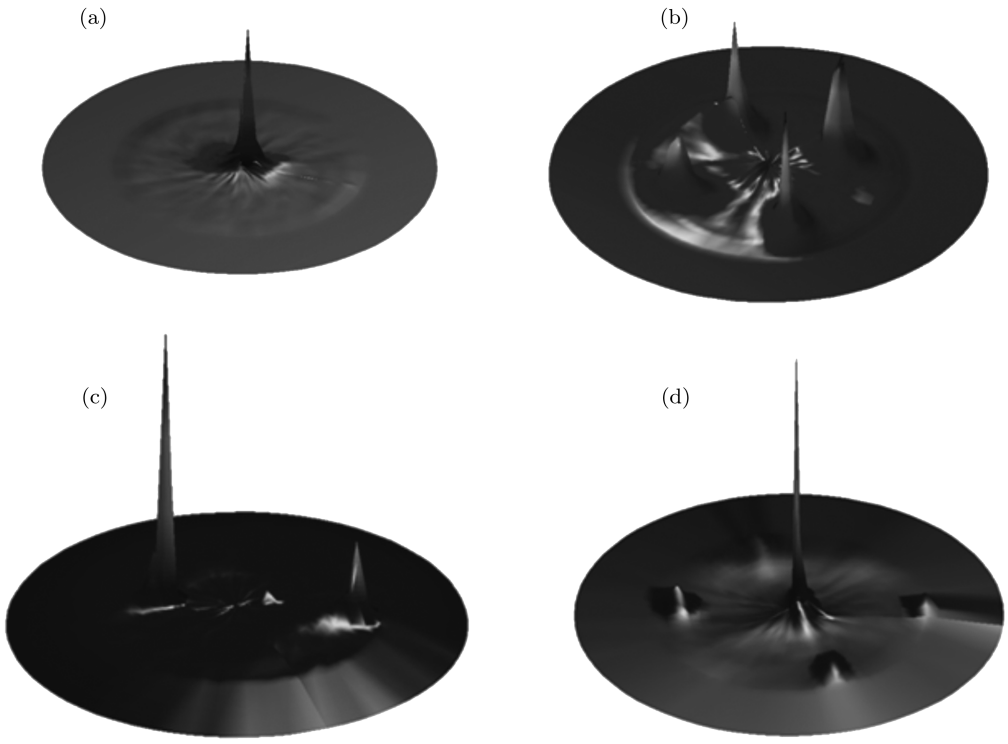


Fig. 1. The pole figures of $Fe_{81}Ga_{19}$ oriented crystals with different orientations. (a) (001) and (b) (110) pole figures of [001] oriented crystal, (c) (001) and (d) (110) pole figures of [110] oriented crystal.

In the optical floating zone furnace, the rod was appended and heated by four lamps around the sample, with the melting zone length of about 6 mm. The melting zone moved upward with the movement of the four lamps to realise the crystal directional growth. The applied growth rate here was 10 mm/h. Compared with the induction heating zone melting crystal growth method, the optical floating zone furnace provided a much lower temperature gradient due to the absence of cooling medium. The total length of the crystal grown by the optical floating zone furnace was about 80 mm. The x-ray pole figures confirmed [110] preferred orientation in the crystal grown by the optical floating zone furnace, as shown in Figs. 1(c) and

1(d).

The tested structure shows only the A2 phase in the grown [001] and [110] oriented $Fe_{81}Ga_{19}$ crystal, which is similar to that in the as-cast sample reported previously.[25] No drastic difference of the structure is detected for the [001] and [110] oriented crystals.

Figure 2 shows the magnetostriction of both [001] and [110] oriented crystals. In the [001] oriented crystal, the saturation magnetostriction increases from 170×10^{-6} with no pre-stress to 330×10^{-6} under 50 MPa. While in the [110] oriented crystal, the saturation magnetostriction increases from about 20×10^{-6} to about 140×10^{-6} with the compressive pre-stress increasing from 0 MPa to 40 MPa. The magnetostriction curve under larger compressive pre-stress is also measured in the experiment, and it is found that the saturation magnetostriction remains nearly unchanged when the compressive pre-stress is larger than 50 MPa in [001] oriented crystal and 40 MPa in [110] oriented crystal. It is apparent that the magnetostriction of [001] oriented crystal is much better than that of [110] oriented crystal. The maximum saturation magnetostriction of [001] oriented crystal is more than two times as that of [110] oriented crystal. It is also observed that the pre-stress enhances the saturation magnetostriction of both [110] and [001] oriented crystals to different extents. The maximum saturation magnetostriction 330×10^{-6} is about two times of that without pre-stress, about 170×10^{-6}, in the [001] oriented crystal. However, the saturation magnetostriction is enhanced from 20×10^{-6} without pre-stress applied, to 140×10^{-6} under a stress of 40 MPa in the [110] oriented crystal, being enhanced about 7 times by the pre-stress.

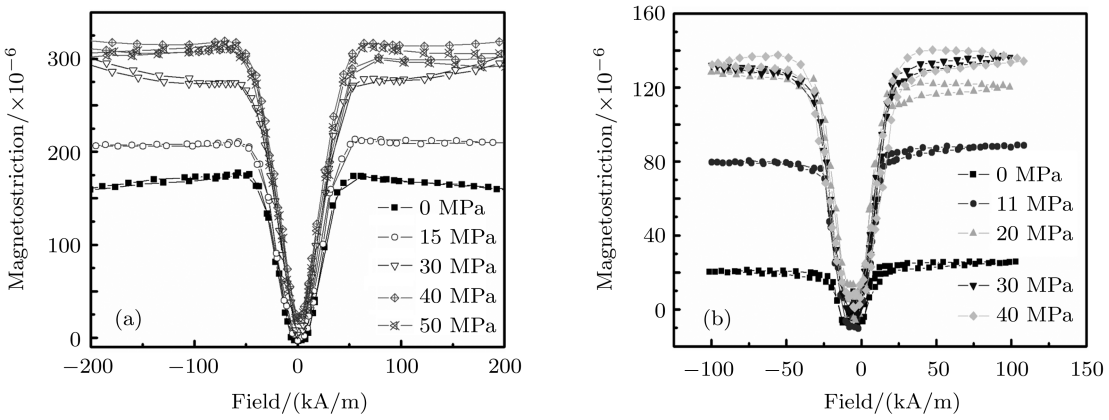


Fig. 2. The tested magnetostriction in $Fe_{81}Ga_{19}$ (a) [001] and (b) [110] oriented crystal.

4. Simulation

To explain the tested magnetostriction of the [001] and [110] oriented $Fe_{81}Ga_{19}$ crystals under different pre-stress, a simulation based on the single domain rotation model has been carried out by using the phenomenological theory. The effect of the pre-stress on the enhancement of the saturation magnetostriction is also clarified by the simulation.

The domain rotation path is determined by the energy minimum principle with increasing magnetic field, and the magnetostriction is accordingly calculated. The free energy determining the domain rotation path is composed of three kinds of energies, including magnetocrystalline anisotropy energy E_k, magnetoelastic energy E_σ and static magnetic energy E_H, as shown in the detailed expressions below. In the single domain rotation model, a whole sphere divided into meshes is used to demonstrate the orientation of the magnetic domain, and every cross point on the sphere denotes a possible magnetisation orientation in the magnetisation process. One neighbouring energetic favourable point is picked up every time till the domain is magnetised to saturation in the applied magnetic field. In the single domain rotation model, the domain wall movement is ignored and the crystal is assumed to be perfect without defects and internal stress.

The expression used for the simulation is listed below.[22]

The total energy E is expressed as

$$E = E_k + E_\sigma + E_H, \tag{1}$$

where the detailed expressions are as follows:

$$E_k = K_1(\alpha_x^2\alpha_y^2 + \alpha_y^2\alpha_z^2 + \alpha_z^2\alpha_x^2) + K_2\alpha_x^2\alpha_y^2\alpha_z^2, \tag{2}$$

$$\begin{aligned} E_\sigma = & -3\lambda_{100}\sigma(\alpha_x^2\gamma_x^2 + \alpha_y^2\gamma_y^2 + \alpha_z^2\gamma_z^2)/2 \\ & -3\lambda_{111}\sigma(\alpha_x\alpha_y\gamma_x\gamma_y + \alpha_y\alpha_z\gamma_y\gamma_z + \alpha_z\alpha_x\gamma_z\gamma_x) \\ & +\lambda_{100}\sigma/2, \end{aligned} \tag{3}$$

$$E_H = -\mu M_\mathrm{s} H\cos\theta. \tag{4}$$

Here α_i denotes the direction cosine of the magnetisation with respect to the coordinate axes [100], [010], and [001], K_1 and K_2 are the magnetocrystalline anisotropy constants; γ_i is the direction cosine of the pre-stress with respect to coordinates, λ_{100} and λ_{111} are the magnetostriction coefficient along [100] and [111] orientations, respectively; θ is the angle between magnetisation and applied magnetic field direction, $\mu_0 M_\mathrm{s}$ is the saturation magnetisation.

The coefficient of magnetostriction λ is denoted as

$$\lambda = \lambda_\mathrm{f} - \lambda_\mathrm{i}, \tag{5}$$

where subscripts f and i refer to the final and initial states, respectively.

For a cubic crystal, the magnetostriction λ can be expressed as follows:

$$\begin{aligned} & \lambda \\ = & \ 3\lambda_{100}(\alpha_x^2\beta_x^2 + \alpha_y^2\beta_y^2 + \alpha_z^2\beta_z^2 - 1/3)/2 \\ & + 3\lambda_{111}(\alpha_x\alpha_y\beta_x\beta_y + \alpha_y\alpha_z\beta_y\beta_z + \alpha_z\alpha_x\beta_z\beta_x), \end{aligned} \tag{6}$$

where β_i is the direction cosine of the measurement direction with respect to the coordinate axis.

When the magnetic field and pre-stress are not applied to the material, only the magnetocrystalline anisotropy energy determines the initial domain positions. FeGa alloy has the easy axes along $\langle 100\rangle$ crystal directions, so the moment of every magnetic domain stays in anyone of the six $\langle 100\rangle$ orientations with equal distribution in its initial thermal demagnetised state. In the simulation, the magnetostriction is calculated along a specific orientation. For the specific orientation considered, the different domains have different angles with the orientation in the thermal demagnetised state. For the convenience of description, the angle between the considered orientation and the domain moment direction is used to mark the different magnetic domains. For the [001] orientation, the angles between the magnetic moments and the orientation are 0°, 90° and 180°, so the domains are defined as 0° domains, 90° domains and 180° domains respectively. Similarly, if we calculate the magnetostriction along the [110] orientation, the domains can be defined as 45° domains, 90° domains and 135° domains, respectively. The relationship between the magnetic domains and the considered orientation is shown in Table 1.

Table 1. Domain configuration of FeGa oriented crystals with different orientations.

crystal axis	domain configuration					
	[100]	[$\bar{1}$00]	[010]	[0$\bar{1}$0]	[001]	[00$\bar{1}$]
[001]	90°	90°	90°	90°	0°	180°
[110]	45°	135°	45°	135°	90°	90°

The simulation adopts the following intrinsic parameters. The magnetocrystalline anisotropy constants for $Fe_{81}Ga_{19}$ alloy are estimated to be $K_1 = 1.96\times10^4$ J·m^{-3} and $K_2 = -4.78\times10^4$ J·m^{-3}, by fitting the experimental data given in Ref. [26]. The saturation magnetisation M_s is 1.5 T,[27] the magnetostriction $3/2\lambda_{100}$ is 400×10^{-6},[12] and the fitted value of λ_{111} for $Fe_{81}Ga_{19}$ alloy is 5×10^{-6}.[12]

Figure 3 shows the domain rotation path and the corresponding magnetostriction curve for the [001] orientation. When the magnetic field is applied along the [001] orientation, only the 90° domains contribute to the magnetostriction, while the 0° domains exhibit no magnetostriction. The 180° domains can be reoriented to become 0° domains by domain wall movement in the applied field. Therefore the bulk magnetostriction along the [001] orientation is calculated by multiplying the magnetostriction of 90° domains and their volume fraction. As shown in Fig. 3(b), the saturation magnetostriction of 90° domains is 400×10^{-6}. It is shown in Table 1 that the ratio for the number of the different magnetic domains is $N_{90°}$:$N_{0°}$:$N_{180°}$ = 4 : 1 : 1, where $N_{90°}$, $N_{0°}$ and $N_{180°}$ represent the number of 90° domains, 0° domains and 180° domains respectively. Therefore the volume fraction of 90° domains is 2/3. The simulated saturation bulk magnetostriction along the [001] orientation is 267×10^{-6} as shown in Fig. 3(c).

The effect of pre-stress on the magnetostriction is also simulated by considering the magnetoelastic energy. With increasing compressive pre-stress, the initial orientations of the magnetic domains will change

due to the change of the magnetoelastic energy. For the [001] orientation, four 90° domains stay in the perpendicular plane for the situation of no pre-stress. However, it is found in the simulation that the 0° and 180° domains nearly do not rotate until the pre-stress is increased up to a critical magnitude of 49 MPa. And when the applied pre-stress is higher than the critical value, the 0° and 180° domains will rotate strongly to the perpendicular plane, and become 90° domains. In this case, the volume fraction of 90° domains is 100%, and the saturation bulk magnetostriction along [001] orientation is enhanced to 400×10^{-6} as shown in Fig. 3(c). The magnetostriction jump effect occurs at higher magnetic field, as compared with the situation of no pre-stress, due to the hindrance of additional magnetoelastic energy resulting from the pre-stress. When the pre-stress is increased continually to even higher values, the saturation magnetostriction remains unchanged, but the magnetostriction jump effect occurs at even higher magnetic field.

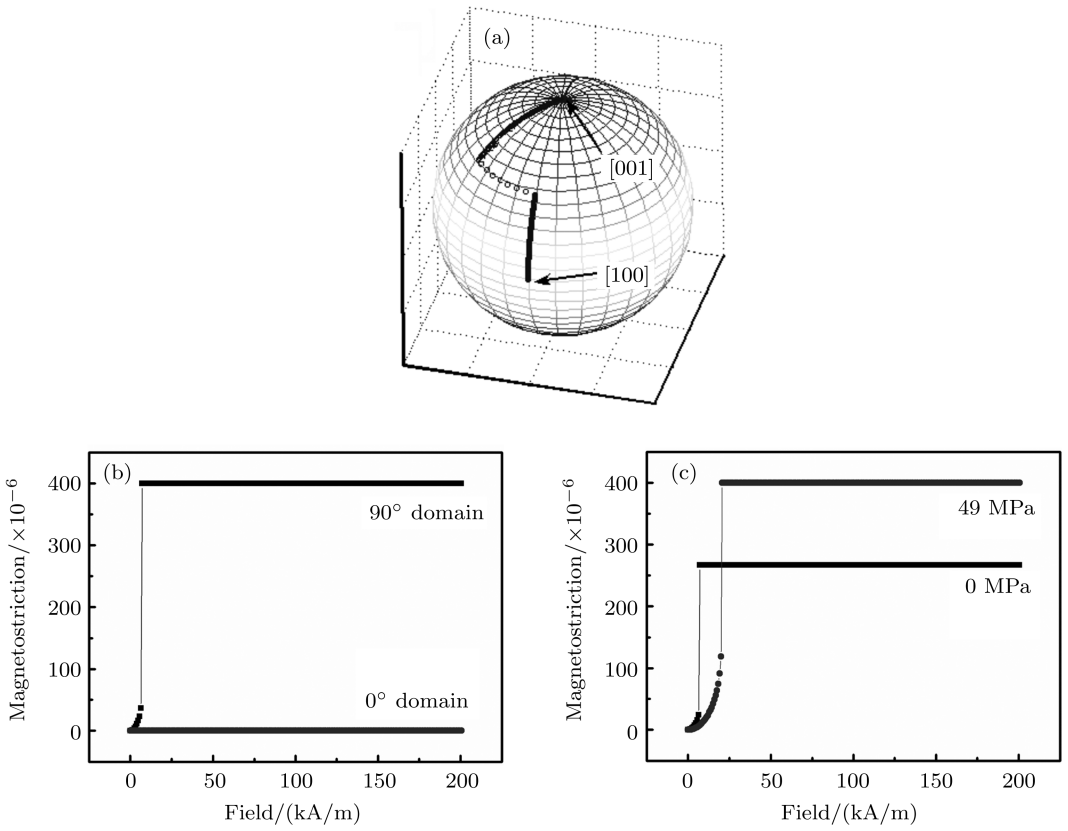


Fig. 3. (a) Domain rotation path and (b) corresponding calculated magnetostriction curve of different single domains, (c) calculated bulk magnetostriction curve in $Fe_{81}Ga_{19}$ [001] oriented crystal.

For the [110] orientation, the magnetostriction and the pre-stress effect are also simulated. As shown in Fig. 4, the 90° domains rotate to the direction of the applied field with a jump process, exhibiting the saturation magnetostriction of 204×10^{-6}. The 45° domain turns to the direction of the applied field gradually and its saturation magnetostriction is 4×10^{-6}, while the 135° domains reorient to become the 45° domains by domain wall movement in the applied field. By summing up the contributions of all the domains, the simulated saturation bulk magnetostriction for the [110] orientation is about 70×10^{-6}. When the pre-stress is applied along the [110] orientation, it is found by the simulation that nearly no rotation occurs of the 45° domains until the pre-stress is increased to a magnitude of 98 MPa. And when the pre-stress is higher than the critical value, the 45° domains rotate strongly to the perpendicular plane to become 90° domains. In this case, the maximum saturation magnetostriction up to 204×10^{-6} is exhibited for the [110] orientation.

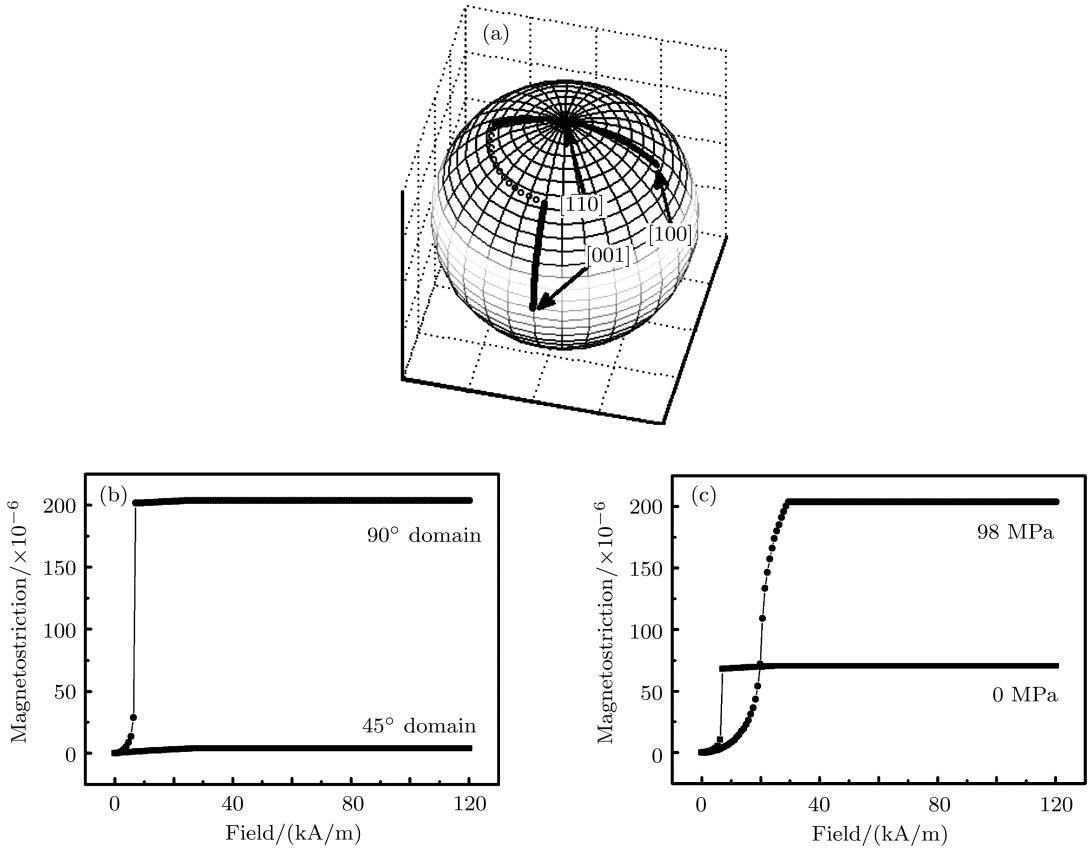


Fig. 4. (a) Domain rotation path and (b) corresponding calculated magnetostriction curve of different single domains, (c) calculated bulk magnetostriction curve in $Fe_{81}Ga_{19}$ [110] oriented crystal.

5. Discussion

In the simulation of the magnetostriction, only the axis orientation is needed to consider, which means that the magnetostriction is calculated along a specific orientation. And the tested magnetostriction of the oriented crystal is also determined along the specific preferred orientation. Therefore it is reasonable to use the simulated results to describe the variation tendency of the magnetostriction of the oriented crystals with different orientations under different pre-stress. It can be found that the tendencies of the simulated and tested magnetostrictions are consistent in the above [001] and [110] oriented crystals. The difference of detailed values can be attributed to the crystal defects and internal stress existing in the real crystal, which is neglected in the simulation.

The experimental and simulated results both demonstrate the magnetostriction anisotropy indeed exists in the FeGa crystal. The [001] oriented crystal has a much higher saturation magnetostriction than the [110] oriented crystal. Comparing the situations in the measurement and simulation with and without pre-stress, it can be also found that the enhancing extent of the saturation magnetostriction by the pre-stress for the [110] orientation is much higher than that for the [001] orientation.

6. Conclusion

1) The tested saturation magnetostriction of the [001] oriented crystal increases from 170×10^{-6} to 330×10^{-6} as the pre-stress changes 0 to 50 MPa. The [110] oriented crystal has a saturation magnetostriction from 20×10^{-6} to 140×10^{-6} as the applied compressive pre-stress changes from 0 to 40 MPa.

2) The magnetostriction of [001] and [110] oriented crystals is simulated based on the phenomenological theory by determining the domain rotation paths under the applied magnetic field and the pre-stress.

3) The magnetostriction anisotropy is confirmed by test and simulation for the FeGa oriented crystals. The [001] oriented crystal possesses a higher saturation magnetostriction than the [110] oriented crystal.

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