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Exploring structural origin of the enhanced magnetostriction in Tb-doped $Fe_{83}Ga_{17}$ ribbons: Tuning Tb solubility

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ABSTRACT

Minor rare earth Tb addition greatly enhances the magnetostriction of $Fe_{83}Ga_{17}$ alloy. However, the structural origin of the enhanced magnetostriction remains unclear, since it is quite difficult to detect Tb element directly. Here, high temperature annealing is designed to tune the Tb solubility for exploring its structure origin in the Tb doped $Fe_{83}Ga_{17}$ ribbons. It is found during annealing a Tb-rich phase precipitates, leading to the decrease of the tetragonal distortion of the matrix, and the dramatic decrease of the magnetostriction accordingly. These results inversely consolidate that the enhanced magnetostriction is induced by solid soluted Tb element in Fe-Ga alloy.

Magnetostrictive materials that can change their dimensions in an applied magnetic field, have been investigated extensively due to their applications in actuators, sensors and transducers [1–3]. Recently, $Fe_{100-x}Ga_x$ alloys, named Galfenol, with a high magnetostriction up to 400 ppm and excellent mechanical properties is reported and exhibits wide application potential [4–7]. The high magnetostriction can be attributed to the asymmetric modified-$D0_3$ nanoinclusions induced tetragonal distortion of the matrix [8–10]. In order to further improve the magnetostriction, lots of efforts have been made by adding 3d and 4d transition elements such as V, Cr, Ni, Mo, Co, Mn, Rh, Zn, Nb [11–16] or main group elements such as Be, C, B, Al, Ge, Sn [17–21]. But rare enhancement has been observed until the doping of minor rare earth elements such as Tb [22,23].

However, Tb element has little solid solubility in Fe-Ga alloy. By improving the cooling rate with melt-spun method, the forced solid solubility of Tb can reach 0.2 at.%. It is regarded that these Tb atoms are solid soluted in Fe-Ga alloy, inducing a larger tetragonal distortion of the matrix, and thus a giant longitudinal magnetostriction up to 2000 ppm [10,24,25]. Nevertheless, the existence of doped Tb element is quite difficult to be detected directly due to the minor addition of only 0.2 at.%. Therefore the structural origin remains a puzzle why so minor Tb addition can induce such a giant magentostriction variation. Here, high temperature annealing is designed to tune Tb solubility in the Tb-doped Fe-Ga ribbons. By investigating the correlation between the magnetostriction and microstructure evolution, the structural origin of enhanced magnetostriction in minor Tb-doped Fe-Ga ribbons can be revealed.

In this letter, we demonstrate that solid soluted Tb in Fe-Ga ribbons starts to precipitate from the matrix in the form of 2:17 rombohedral phase with high temperature annealing. At the same time, the tetragonality of the matrix decreases actually, the magnetostriction decreases accordingly, and the calculated magnetostriction matches well with the measured one. Our results consolidate that the enhanced magnetostriction of Fe-Ga ribbon originates from the minor rare earth element solid soluted in the matrix. These findings may stimulate the development of new magnetostrictive alloys [22].

The ingots of $Fe_{83}Ga_{17}$ and $Fe_{83}Ga_{17}Tb_{0.2}$ alloy were prepared by arc-melting high purity (99.99%) Fe, Ga and Tb four times, and then homogenized at 1273 K for 10 h under argon atmosphere. Ribbons with a thickness of ~50 μm were prepared by single roller melt spun method. The subsequent heat treatment was carried out in vacuum at 1223 K for 10 min, 30 min or 4 h respectively, and the samples were then brine quenched to room temperature. The microstructure was characterized by Apollo 3000 scanning electron microscope (SEM) and JEM-2100F transmission electron microscope (TEM). Geometric phase analysis (GPA) method was used to visualize atomic level strain. High-resolution synchrotron X-ray diffraction (XRD) measurements were performed on the BL14B1 beamline of the Shanghai Synchrotron Radiation Facility (SSRF), where the 18 KeV photon beam was focused to a $150 \times 150\ (\mu m)^2$ spot. The magnetostriction of the ribbons was measured in the direction of the ribbon length by the conventional strain gauge method with the magnetic field applied perpendicular to the ribbon plane.

According to the metastable phase diagram [26], for the nominal composition of $Fe_{83}Ga_{17}$, $D0_3$ phase starts to precipitate from the A2 matrix at around 723 K. Later this $D0_3$ phase is proved to be asymmetric modified-$D0_3$ structure with Ga-Ga pairs using transmission electron microscopy [10]. Therefore, modified-$D0_3$ nanoheterogeneities occur in the ribbons during rapid cooling when entering the A2/$D0_3$ coexistence region. It is reported that the magnetostriction arises from the

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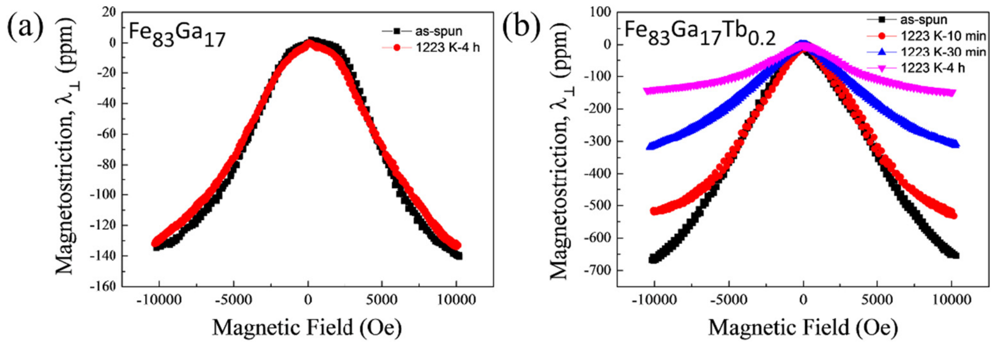

Fig. 1. The transverse magnetostriction $\lambda_{\perp}$ of (a) $Fe_{83}Ga_{17}$ melt-spun ribbons (b) $Fe_{83}Ga_{17}Tb_{0.2}$ melt-spun ribbons before and after heat treatment at 1223 K for different time and brine quenched. For $Fe_{83}Ga_{17}Tb_{0.2}$ ribbon, the magnetostriction decreases gradually with the heat treatment.

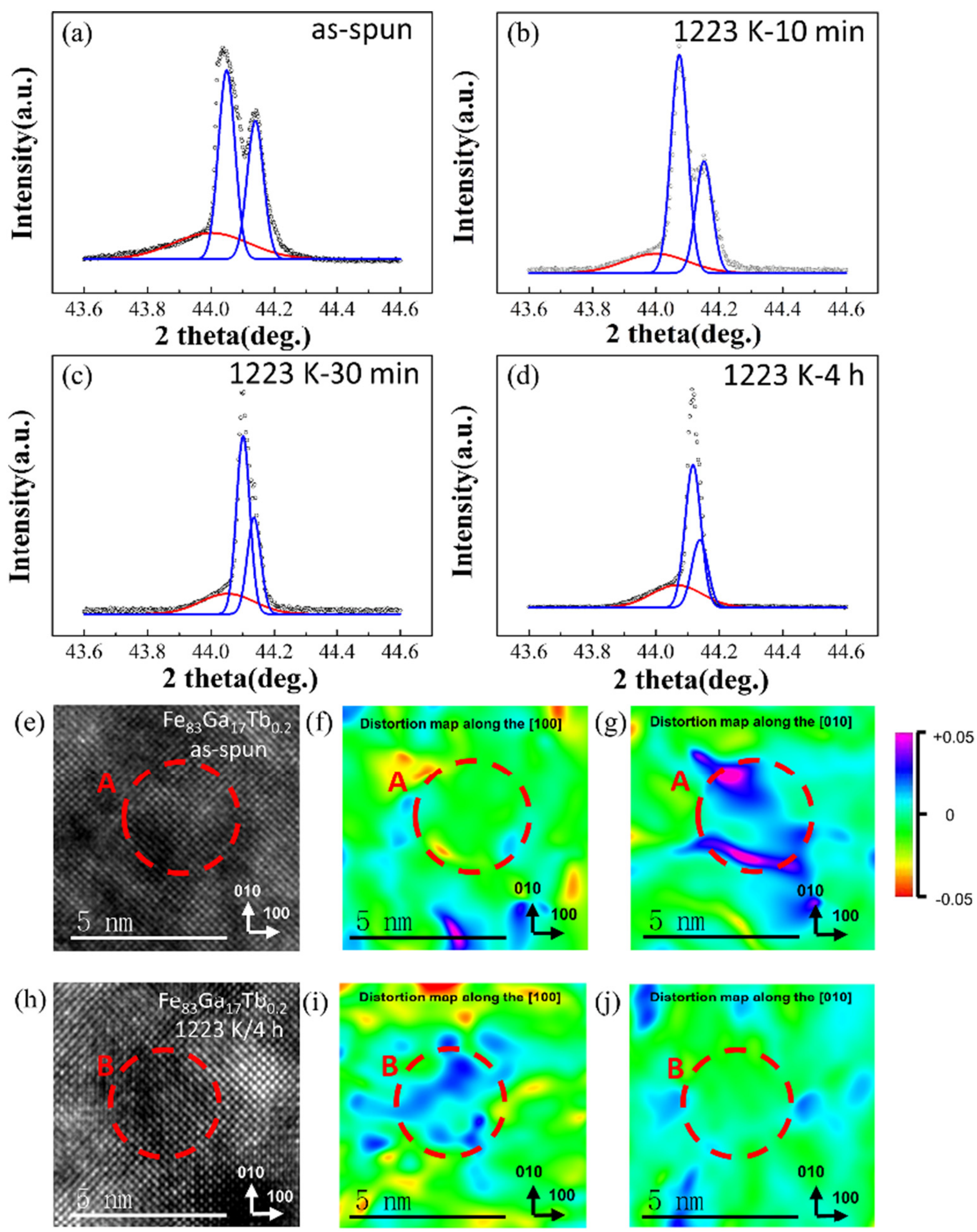

Fig. 2. (a)–(d) {301} synchrotron XRD reflections of the $Fe_{83}Ga_{17}Tb_{0.2}$ melt-spun ribbons before and after heat treatment at 1223 K for different time and brine quenched. The tetragonal distortion gradually decreases with the heat treatment. (e)–(j) Geometric phase analysis of the HREM images of $Fe_{83}Ga_{17}Tb_{0.2}$ ribbons before (e, f and g) and after 1123 K heat treatment for 4 h (h, i and j). (e) HREM image of $Fe_{83}Ga_{17}Tb_{0.2}$ ribbons where a modified-$D0_3$ nanoinclusion is marked by dashed red circle. (f) and (g) Distortion maps along the [100] and [010] directions showing that the distortion of heterogeneity A is along [010]. (h), (i) and (j) indicates a much less distortion along [100] in the matrix after heat treated.