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Sharp Goss orientation and large magnetostriction in the rolled columnar-grained Fe–Ga alloys

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ABSTRACT

In this work, the ⟨1 0 0⟩ directional solidified feedstock slabs were used to produce the rolled Fe–Ga sheets, and sharp Goss orientation was developed in the 0.3 mm sheets after annealing processes. The area fraction of Goss grains in the annealed binary Fe–Ga sheets approached to 62.4% without abnormal grain growth, accompanied with a maximum magnetostriction ($\lambda_{//}-\lambda_{\perp}$) of 199 ppm. The addition of only 0.1 at% NbC notably promoted the abnormal Goss grain growth without sulfur annealing, and large single-crystal-like grains, up to several centimeters, were obtained with few island-like grains after sulfur annealing and final Ar/H_2 annealing processes. High magnetostriction ($\lambda_{//}-\lambda_{\perp}$) of 245 ppm with little deviation was achieved in the $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheets, and a large magnetostrictive strain ($\lambda_{//}$) up to 243 ppm under no pre-stress was observed with an applied magnetic field along the rolling direction.

1. Introduction

Magnetostrictive Fe–Ga alloys, also named "Galfenol", have received increasing attention since first reported in 2000 [1]. Along the ⟨1 0 0⟩ orientation in the single-crystal Fe–Ga alloy, the magnetostrictive strain can be as high as ~400 ppm in a low field of ~200 Oe [2]. Besides, Fe–Ga alloys are strong and robust enough to be mechanically machined [3], and can be welded with other ferrous materials, compared with the widely used Terfenol-D alloys, which have giant magnetostriction (> 1000 ppm) but require high applied field (> 1000 Oe). These attributes make Fe–Ga alloy a good candidate for the sensors, actuators and transducers.

It is desirable to obtain the ⟨1 0 0⟩ orientation in the polycrystal Fe–Ga alloys to maximize the magnetostrictive performance. The ⟨1 0 0⟩ orientation in bulk alloys can be produced by a directional solidification (DS) process [4–6]. However, the high conductivity of Fe–Ga alloy requires it to be as thin as possible to avoid eddy current losses in the high frequency field. Efforts have been made to prepare the ⟨1 0 0⟩ orientation along the rolling direction (RD) in the rolled sheets [7–13]. The sharp Goss orientation {0 1 1}⟨1 0 0⟩ by abnormal grain growth (AGG) is widely used in the grain oriented Fe–Si steel, which has the similar α-Fe (BCC) structure with Fe–Ga alloy. The AGG of Goss grains is attributed to the inhibitors of normal grain growth (NGG) by the uniform dispersion of fine precipitates, such AlN and MnS, and the content of inhibitors is often below 0.1 at%. Cubic texture {0 0 1}⟨1 0 0⟩ or Goss texture {0 1 1}⟨1 0 0⟩ was reported in previous work with ternary addition, such as B [8] or NbC [9,10]. The ternary addition was thought to act as inhibitors, resulting in the AGG in the Fe–Ga sheets. In addition, the S-induced surface energy effect was also reported to accelerate the AGG of Goss grains [11–13]. However, binary Fe–Ga alloys exhibit low ductility and poor rollability [8,14], thus, high content up to 1 at% of ternary addition was employed to improve the machinability in the sheets [8–13]. The high contents of ternary addition would result in the large amounts of island-like grains and precipitates [12,13], and some unfavorable effects, such as higher coercivity (Hc), on magnetic properties can be expected. To avoid the unfavorable effect of Nb-rich precipitates, our prior work reduced the content of NbC to 0.16 wt% (~0.09 at%), and H_2 was introduced to eliminate Nb-rich precipitates [15].

In this work, Fe–Ga sheets with a thickness of 0.3 mm were produced by the rolling processes on ⟨1 0 0⟩ oriented columnar-grained slabs. The effect of sulfur annealing on the texture evolution was investigated in binary $Fe_{83}Ga_{17}$ and $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheets. Large Goss grains with few precipitates and island-like grains were found in the final annealed $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheet. High value of average magnetostriction ($\lambda_{//}-\lambda_{\perp}$) of 245 ppm was achieved with deviation below ±10 ppm, and a high $\lambda_{//}$ of 243 ppm was observed in a final annealed sheet.

2. Experimental

The binary $Fe_{83}Ga_{17}$ alloy and $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ alloy were prepared from Fe (99.9%), Ga (99.99%), and master alloys of Nb–Fe

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and Fe–C, and ⟨1 0 0⟩ oriented columnar-grained alloys were grown by the DS process [6] at a growth rate of 720 mm/h. The slabs with a thickness of ~18 mm were obtained from the DS alloys by electrical discharge machining. The slabs were hot rolled along the growth direction of columnar grains at 1150 °C to ~2.1 mm, followed by warm rolling at ~600 °C to ~1.1 mm. After an intermediate annealing at 850 °C for 5 min, further rolling was undertaken to the final thickness of ~0.3 mm. The Fe–Ga sheets, 12 mm × 16 mm cut by electrical discharge machining, were enclosed in quartz ampoules with 0.3 atm. Ar used as protecting gas (Ar-annealed). Additional elemental S (~1 mg/cm^2) were enclosed to investigate the influence of sulfur annealing on texture evolution (S-annealed). The heating rate at 0.25 °C/min was employed from 900 °C to 1080 °C in quartz ampoules without dwell at 1080 °C, and final annealing process was undertaken at 1200 °C for 6 h under flow Ar/H_2 (H_2 vol%=25%) mixed atmosphere [15].

The X-ray diffraction (XRD) was detected on the normal direction (ND) of the sheets. Electron backscatter diffraction (EBSD) patterns were captured and analyzed to obtain area fraction of texture components and inverse pole figure (IPF) images. The magnetostriction was measured at room temperature by resistance strain gauges with gage area of 2.8 mm × 2.0 mm (base area of 6.4 mm × 3.5 mm), and the gages were positioned along the RD. Saturation magnetostriction are calculated by $(3/2)\lambda s=\lambda_{//}-\lambda_{\perp}$, where $\lambda_{//}$ and $\lambda_{\perp}$ are the maximum magnetostriction when magnetic field parallel and perpendicular to the RD are applied, respectively.

3. Results and discussion

The XRD patterns for the final annealed sheets are shown in Fig. 1. After the final annealing process at 1200 °C for 6 h under flow Ar/H_2, all the sheets exhibit single α-Fe (bcc) phase and dominant (1 1 0) peak, suggesting the preferred (1 1 0) grain growth on the final annealed sheets. In addition to the dominant (1 1 0) peak, obvious (2 0 0) and (2 1 1) diffraction peaks can be found in the binary $Fe_{83}Ga_{17}$ sheets. No patterns for the Nb-rich phase in the NbC-doped sheets and the sulfide phase in the S-annealed sheets can be found in Fig. 1, due to the low content of 0.1 at% NbC and final Ar/H_2 annealing process.

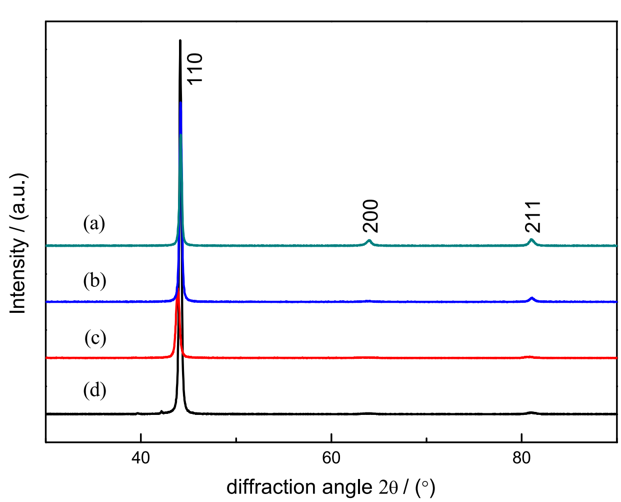

Fig. 1. XRD patterns for the final annealed sheets: (a) S-annealed and (b) Ar-annealed in binary $Fe_{83}Ga_{17}$ sheets; (c) S-annealed and (d) Ar-annealed in $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheets.

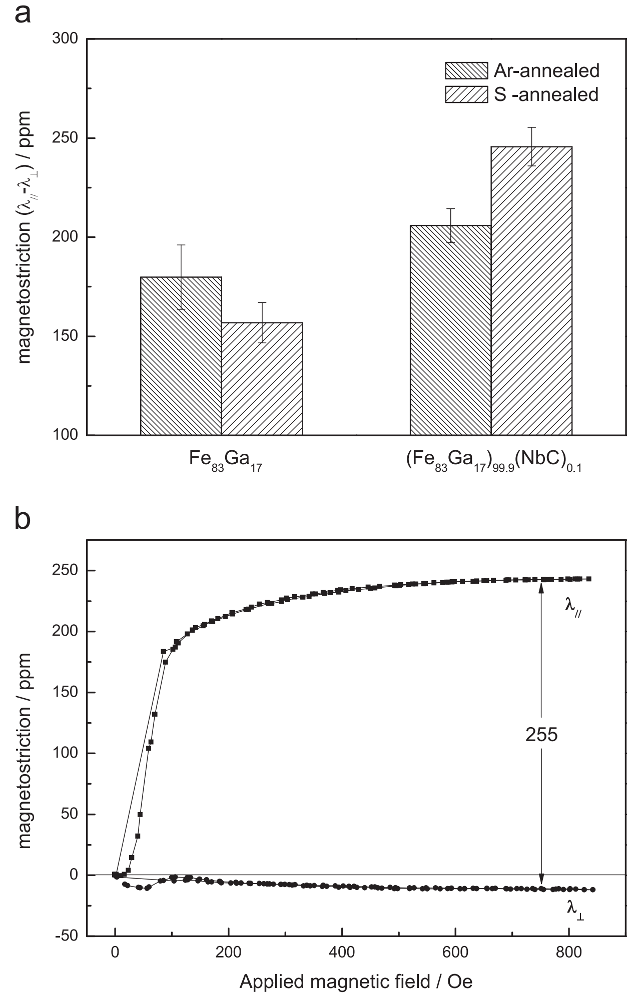

Fig. 2. (a) Average magnetostriction, $(3/2)\lambda s=\lambda_{//}-\lambda_{\perp}$, for final annealed sheets and error bars show the standard deviation in the average values; (b) the magnetostriction versus applied magnetic field for one S-annealed $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheet.

The observed average magnetostriction, $3/2\ \lambda s=\lambda_{//}-\lambda_{\perp}$, for the final Ar/$H_2$ annealed sheets are shown in Fig. 2a. The average values were obtained from five samples with the same annealing protocol, and the error bars show the standard deviation from the average values. For the binary $Fe_{83}Ga_{17}$ alloy, the average value of $3/2\ \lambda s$ was 179 ppm and 156 ppm for the Ar-annealed and S-annealed sheets, respectively. Compared with binary $Fe_{83}Ga_{17}$ sheets, a significant increase in the $3/2\ \lambda s$ was observed in the $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheets, with average values of 205 ppm and 245 ppm the for the Ar-annealed and S-annealed sheets, respectively. The error bars of the deviation in the average values are small for all the samples, compared with our prior work [15]. For the binary $Fe_{83}Ga_{17}$ sheets, a maximum value of 199 ppm was observed in the Ar-annealed sheet, and the deviation was around ±16 ppm and ±10 ppm for the Ar-annealed and S-annealed sheets, respectively. Much smaller deviation below ±10 ppm was observed in the $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheets, for both the S-annealed and Ar-annealed sheets.

In addition to the high average values and little deviation in the $3/2\ \lambda s$, there was a large difference in the observed $\lambda_{//}$ and $\lambda_{\perp}$ for the same annealing protocol. In a S-annealed $(Fe_{83}Ga_{17})_{99.9}(NbC)_{0.1}$ sheet, as shown in Fig. 2b, the $\lambda_{//}$ along the RD was as high as 243 ppm, while the $\lambda_{\perp}$ was only −12 ppm. The magnetostrictive strain of 243 ppm under no pre-stress approaches to the level of Fe–Ga single crystals, and the value is the highest value of $\lambda_{//}$ along