Journal of Magnetism and Magnetic Materials 417 (2016) 321–326

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Sharp Goss texture and magnetostriction in binary $Fe_{81}Ga_{19}$ sheets

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ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form
19 April 2016
Accepted 22 May 2016
Available online 24 May 2016

Keywords:
Fe–Ga alloy
Secondary recrystallization
Goss texture
Magnetostriction

ABSTRACT

Goss ({110}⟨001⟩) texture development and magnetostriction in binary $Fe_{81}Ga_{19}$ sheet were investigated. Millimeters-sized Goss grains, covering 80% area of the annealed sheet surface, are produced by secondary recrystallization without effects of inhibitor and surface energy. The micro-texture analysis demonstrates that primarily recrystallized Goss grains have an evident advantage in size and number to be potential secondary nuclei. The grain size distribution of primary Goss grains can induce the continuable abnormal growth until the completion of secondary recrystallization. The obtained magnetostriction coefficient is close to those with the help of inhibitor or surface energy.

1. Introduction

Fe–Ga alloy has the excellent comprehensive properties, including large magnetostriction along ⟨100⟩ direction at low saturated applied magnetic field, high mechanical strength, high permeability, high Curie temperature and weak temperature dependence [1–5]. In last decade, Fe–Ga alloy has attracted much attention in terms of a prospective candidate of smart materials in actuation, sensing and energy harvesting applications. Due to the significant magnetocrystalline anisotropy and high electrical conductivity, highly textured Fe–Ga sheets produced by efficient rolling methods are more expected compared with single crystal and directionally solidified polycrystalline. Therefore, lots of efforts have been made to prepare thin sheets with the preferred texture of ⟨100⟩//RD (rolling direction) [6–8].

Sharp Goss ({110}⟨001⟩) and Cube ({100}⟨001⟩) textures were produced by abnormal grain growth in the case of using NbC particles as inhibitors and surface energy modification [9–12]. The centimeters-sized Goss grains and magnetostriction coefficients close to 300 ppm were obtained in Fe–Ga-based alloy sheets containing 1 mol% NbC particles when annealing under H_2S+Ar atmosphere [13–15]. Yuan et al. [16,17] reported the centimeters of Goss grains and magnetostriction coefficients of 233–245 ppm by 0.1 mol% NbC addition and H_2+Ar or sulfur annealing atmosphere. However, the purification annealing at high temperature necessary to eliminate inhibitor constituents after complete secondary recrystallization can degrade the mechanical property. Therefore, the production of strong η-fiber (⟨100⟩//RD) texture in Fe–Ga alloy without using inhibitors has been a challenging question. A few studies were undertaken in binary Fe–Ga alloy, but the magnetostriction coefficients are evidently lower because of the ill-developed secondary recrystallization without effects of inhibitor and surface energy [18,19].

In this paper, sharp Goss texture was realized by secondary recrystallization in rolled binary $Fe_{81}Ga_{19}$ sheets without inhibitor elements and surface energy effect, and the mechanism of Goss texture development was explored based on micro-texture analysis.

2. Experimental

$Fe_{81}Ga_{19}$ alloy ingots were prepared from pure Fe (99.99%) and Ga (99.99%) by arc melting. The ingots of Φ 30 mm × 13 mm were hot forged to 9.0 mm at 1200 °C and then hot rolled to 1.7 mm with finishing temperature of 800 °C. Hot rolled bands were normalized at 1000 °C for 10 min and further cold rolled to a final thickness of 0.50 mm at 200 °C by 70% reduction. The cold rolled sheets were first annealed at 800 °C for primary recrystallization, and then heated from 800 °C to 1100 °C at 20 °C/h. All the annealing processes were carried out under flowing argon and quenched in water after annealing.

Orientation distribution functions (ODFs) of rolled and annealed sheets were measured by X-ray diffraction method. Electron back-scattered diffraction (EBSD) analysis was performed to investigate the secondary recrystallization mechanism for Goss grains. Moreover, magnetostriction coefficients under the applied fields from 0 to ±2000 Oe were measured at room temperature by strain gauges positioned along the rolling direction. The magnetostriction coefficient was calculated according to $(3/2)\lambda=\lambda_{//}-\lambda_{\perp}$,

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http://dx.doi.org/10.1016/j.jmmm.2016.05.075
0304-8853/

where $\lambda_{//}$ and $\lambda_{\perp}$ are the magnetostriction coefficients under the applied magnetic fields parallel and perpendicular to RD, respectively [16,17]. In order to characterize the variation of microstructure and magnetostriction coefficient, the samples were taken out of furnace at different temperatures of 850 °C, 900 °C, 950 °C, 1000 °C and 1100 °C. The adopted magnetostriction values were taken as the average over four samples for each annealing temperature in order to increase the statistical reliability.

3. Results and discussion

3.1. Microstructure and texture during deformation and primary recrystallization

Fig. 1 shows the microstructures and textures of hot forged and hot rolled $Fe_{81}Ga_{19}$ bands. The forging microstructure reveals millimeter-sized equiaxed and columnar grains, and the forging texture is characteristic of relatively strong cube texture in a random background. The microstructure and texture in hot rolled bands exhibit a marked through-thickness gradient. Fragmented grains with strong Goss texture appear at subsurface, while coarse grains with strong α-fiber (⟨110⟩//RD) and weak γ-fiber (⟨111⟩//ND, normal direction) form at center layer. This gradient is attributed to the strain distribution gradient through thickness from the intense friction between rolls and plate during hot rolling. The hot rolling Goss texture at quarter layer is generally considered to be the origin of secondary recrystallization Goss texture [20]. After normalizing treatment, hot rolled bands are completely recrystallized with an average grain size of 100 ± 20 μm, and the texture is somewhat weakened at both quarter and center layers compared with hot rolling texture.

Fig. 2 presents the microstructures and textures of cold rolled and primarily recrystallized $Fe_{81}Ga_{19}$ sheets. The cold rolling microstructure is characterized by elongated grains with widely formed in-grain shear bands inclined by 32–35° to RD. The similar morphology of shear bands has also been found in low-carbon steels, IF steels and silicon steels [21–23]. The cold rolling texture is featured by strong γ fiber with peaks at {111}⟨112⟩ and {111}⟨110⟩ through sheet thickness. Primarily recrystallized grains have a nearly uniform size with an average value of 25 ± 5 μm. The primary recrystallization texture is mainly composed of dominant Goss and weak γ fiber. It is noteworthy that Goss grains are widely distributed through thickness and exhibit an advantage in quantity with area fraction of 20.5%.

The development of strong Goss texture in primary recrystallization needs abundant preferred nucleation sites and efficient grain growth. Coarse-grained normalized microstructure, strong cold rolling γ texture as well as 70% reduction can contribute a high density of shear bands as nucleation sites for Goss grains. Moreover, Goss grains can gain a size advantage from the proper intensity of shear bands determined by cold rolling reduction and temperature. Therefore, the obtained advantage of primary Goss grains in number and size can be attributed to the applied rolling and annealing parameters, as shown in our previous work [24].

3.2. Texture and magnetostriction during high temperature annealing

Fig. 3 shows the microstructure evolution of $Fe_{81}Ga_{19}$ sheets during heating process from 800 °C to 1100 °C. The relatively uniform grains are observed at 850 °C with an average grain size of 30 ± 10 μm. As the temperature rises to 900 °C, a small portion of grains grow to 200–300 μm while matrix grains are only 50 ± 10 μm. At 950 °C and 1000 °C, abnormal grain growth occurs where the largest grains reach up to a millimeter level and the average size of matrix grains is restricted around 100 μm and

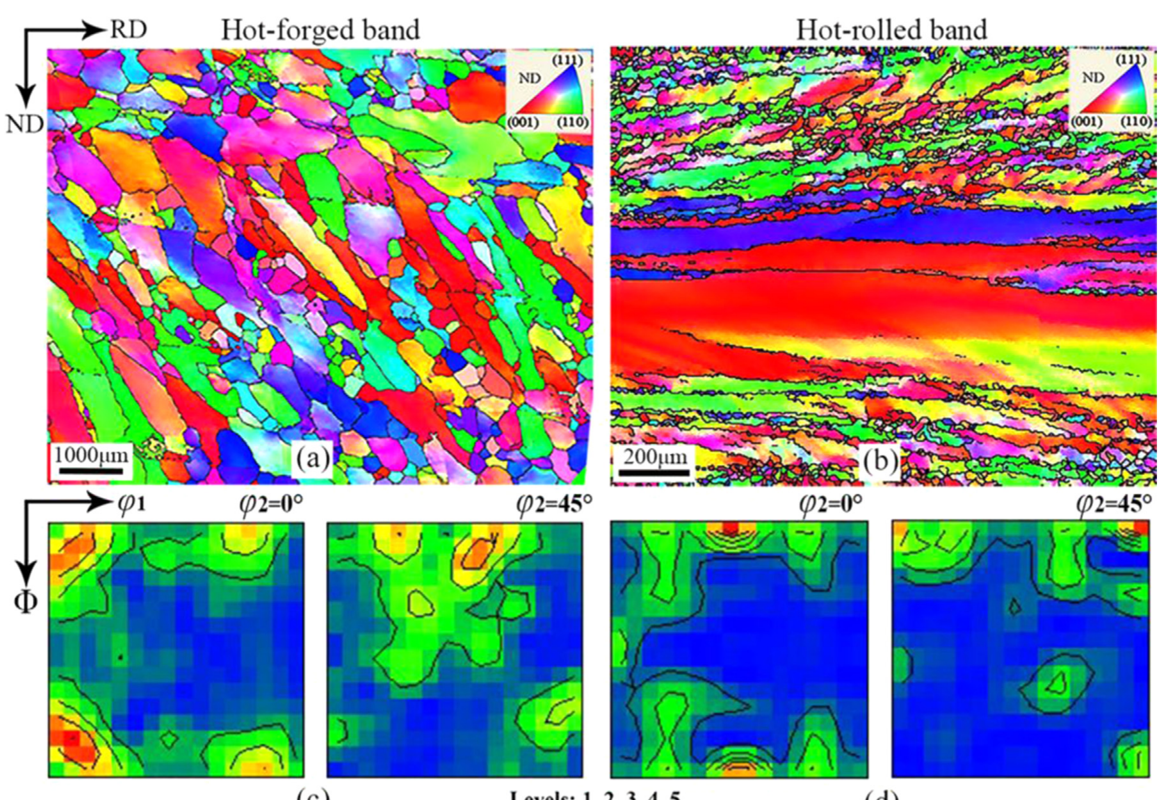

Fig. 1. Microstructures (a, b) as well as constant $\varphi_2=0°$ and $\varphi_2=45°$ sections of ODFs (c, d) of hot-forged and hot-rolled $Fe_{81}Ga_{19}$ bands.