Improvement of Magnetostrictive Properties of Fe-15mol%Ga Alloy by Texture Formation during High Temperature Uniaxial Compression Deformation

Yusuke ONUKI,1)* Shun FUJIEDA,2) Shigeru SUZUKI2) and Hiroshi FUKUTOMI3)
1) Frontier Research Center for Applied Atomic Sciences, Ibaraki University, 162-1 Sirakata, Tokai, Ibaraki, 319-1106 Japan.
2) Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Sendai, Miyagi, 980-8577 Japan.
3) Faculty of Engineering, Yokohama National University, 79-5 Tokiwadai, Yokohama, Kanagawa, 240-8501 Japan.

(Received on September 7, 2016; accepted on November 29, 2016)

The texture control of Fe–Ga solid solution alloy is examined by high temperature deformation, based on the previously suggested mechanism of high temperature deformation texture formation, “preferential dynamic grain growth (PDGG)”. As the result of uniaxial compression deformation of Fe-15 mol% Ga alloy at 1 173 K, sharp alignment of <001> along the compression axis was observed. Microstructural observation by EBSD revealed that the <001> alignment was attributable to the growth of <001> oriented grains. The observed textures and microstructures were similar to those seen in the previous studies of Fe–Si alloys, in which the activation of PDGG was confirmed. Based on these facts, it is concluded that PDGG can be applied as a texture control technique for Fe–Ga alloy. The deformed sample showed larger saturation magnetostriction than the sample without deformation, indicating the effectiveness of the texture control by high temperature deformation.

KEY WORDS: texture; magnetostriction; high temperature deformation; preferential dynamic grain growth.

1. Introduction

Fe–Ga alloys show large magnetostriction, straining along a direction of magnetization.1) Thus, the application of Fe–Ga alloys to actuator devices have actively investigated. In addition, the inverse effect of magnetostriction of Fe–Ga alloys has also attracted much attention for application to energy harvesting technology, which can generate electrical power from ambient vibration. For example, Ueno2) recently suggested the high-output vibration energy harvester module using Fe–Ga alloy. In the module, a coil is wound around a flat bar of Fe–Ga alloy, which receives alternative tension and compression strains during vibration of the module. The ambient vibration can be picked up by a coil around Fe–Ga alloy as electric voltage in accordance with Faraday’s law of induction, because the magnetic flux change in the coil is caused by the inverse magnetostrictive effect.2)

The magnetostrictive and elastic properties of Fe–Ga alloy, which is a BCC random solid solution, strongly depend on crystal orientation. For instance, Fe–Ga alloy exhibits larger magnetostriction constant in <100> in comparison with that in <111>. In addition, the Young’s modulus in <100> of this material is much smaller than that in <111>. Thus, in order to obtain large magnetostrictive and its inverse effects, texture of Fe–Ga alloy should be controlled so that the easy magnetization axis, <100>, is highly aligned along a certain sample direction.3)

Some studies reported high performances of textured Fe–Ga alloy.4,5) Fabrication of a single crystal has also been attempted, which has contributed for understanding the nature of magnetostriction in Fe–Ga alloys.6–8)
The texture formation by thermomechanical processing has also been suggested, which can realize flat-sheet forming and texture/microstructure control, simultaneously. Na and Falatau successfully formed Goss texture ({011} <100>) by applying hot/worm-rolling and annealing.5) This was due to the secondary recrystallization as known as the fabrication technique of the Fe–Si oriented electrical steels. However, annealing in toxic H2S atmosphere was required to form the sharp texture.

In our previous studies, two of the authors reported “Preferential Dynamic Grain Growth (PDGG)”, which is the phenomenon taking place during high temperature deformation of solid solution alloys and resulting in characteristic textures. When PDGG takes place, grains having a specific orientation grow up consuming the grains having the other orientations.

PDGG was firstly found in FCC aluminum-based alloys.9,10) The following studies for BCC iron-based alloys (Fe–Si11,12) and 430 stainless steel13) confirmed that the above mechanism could be applied regardless of crystal structure. The details of the PDGG mechanism can be found in our previous study.11) The mechanism predicts that the
growing orientation should be stable and have low Taylor factor. In case of uniaxial compression deformation of BCC metals, the orientation satisfying these criteria is <100> || compression axis.

Since the texture control using PDGG only requires high temperature deformation, it can be applied for materials with insufficient ductility at room temperature, such as Fe-Ga alloy. In this paper, the activation of PDGG in Fe-15 mol% Ga alloy is reported.

2. Experimental Procedures

An Fe-15 mol% Ga rectangular ingot of 50 mm × 50 mm × 150 mm was casted in vacuum. The longitudinal direction was the cast direction. The ingot was hot-forged perpendicular to the cast direction after preheating at 1273 K, which resulted in the shape of 40 mm × 40 mm × 230 mm. A cylindrical specimen with a height of 18 mm and diameter of 12 mm was cut out from the ingot. The cylindrical axis of the specimen was parallel to the cast direction. The specimen was set on the testing machine and heated up to 1173 K. The temperature of the sample was kept at 1173 K for 1.8 ks followed by uniaxial deformation test. The crosshead speed was controlled so that a constant strain rate was maintained during the deformation. The specimen was immediately quenched after the desired strain was introduced. The sample was fully consisted of α (BCC) phase at 1173 K, as the phase diagram predicted. One specimen was quenched immediately after the annealing process without the deformation sequence. This is referred to as the annealed specimen showing the state before the deformation in the following. After the deformation test, the specimens were served for X-ray texture measurement and EBSD. One can find the details of the deformation test and texture analysis in the previous papers.

The magnetostriction measurements were conducted using strain gauges on the surfaces served for X-ray pole figure measurement and EBSD. Based on the texture measurement, the sample direction having highest <100> axis density in the compression plane was found either in deformed or annealed specimens. A strain gauge with a gauge length of 0.5 mm was attached parallel to this chosen direction on the square specimen with 5 mm × 5 mm × 1 mm cut from each sample. Magnetic field of 4.2 × 10^5 kAm^{-1} was applied parallel and perpendicular to the gauge direction. The magnitude of saturation magnetostriction was determined as the difference of the saturated magnetic fields.

3. Result and Discussion

The distributions of compression axis in the crystal coordinates before and after the high temperature deformation tests are shown in Fig. 1. A weak concentration of the compression axis exists at <001> even before the deformation test, probably due to the casting or hot-forging (Fig. 1(a)). After the deformation up to a strain of −0.93 with a strain rate of 5.0 × 10^{-3} s^{-1}, the axis density at <001> increased but also a peak at <111> appeared (Fig. 1(b)). By increasing strain, however, the peak at <111> disappeared and the axis density at <001> was strengthened as shown in Fig. 1(c). It should be noted that both <001> and <111> are the stable orientations under uniaxial compression deformation. Hence, the axis densities at both orientations should increase with increasing strain if only the geometric effect of the slip deformation on the texture formation is considered. Therefore, the decrease of <111> axis density indicates the shrinkage of <111> oriented grains due to the grain boundary migration. By decreasing strain rate, the <001> alignment becomes higher, as Fig. 1(d) shows. Figure 2 shows the IPF maps based on EBSD measurement, which respectively correspond the samples shown in Fig. 1. It can be confirmed that the increase of <001> axis density corresponds to the increase of the <001> oriented regions. <111> oriented regions are much smaller than <001> oriented regions. The subgrains surrounded by low angle grain boundaries are seen in all the deformed microstructures. In the previous studies of Fe–Si alloys, the authors showed that the density of low angle grain boundary, or the subgrains size, is a function of deformation condition, i.e. temperature and strain rate. This feature can be found also in the current study; the sizes of subgrains in Figs. 2(b) and 2(c) (the same deformation condition but different strain) are similar but those in Fig. 2(d) is larger. The microstructures seen here and the dependency of the texture development on the deformation condition are very similar to those observed in the previous study of Fe-5.8 mol% Si alloy. From the above results, it can be concluded that the PDGG took place in Fe-15 mol% Ga alloy.

With the increase of the grains having <001> parallel to the compression axis, the pole density of the other <100> parallel to the compression plane also increased. As seen in Fig. 3(a), <100> in the compression plane is concentrated into one direction before the deformation. The concentration was strengthened after the hot deformation as shown in Fig. 3(b) as well as the <001> density along the compression axis.

This might be due to the growth of preexisting <001>
The relationship between the applied density in the compression plane, shown by the arrows in Figs. 3(a) and 3(b). The texture after the deformation inherits the {001} < 100 > texture component seen in the initial texture. This is most likely candidates for the growing grains, it is possible to increase the magnetostriction. However, more study is important and actually beneficial in this study because high < 100 > density along a certain in-plain direction is desired to increase the magnetostriction. The rotation tensor expected by Taylor model becomes a unit tensor for the grains having < 001 > oriented grains. The coarsened microstructure and the sharp texture were achieved by high temperature uniaxial compression deformation. These features were most likely resulted from PDGG. The magnetostriction of the deformed sample was as large as that of < 100 > in the single crystal. Hence, it can be concluded that high temperature deformation is one of the promising texture control methods for Fe–Ga alloys.

**4. Summary**

It was examined whether preferential dynamic grain growth (PDGG) could take place in Fe-15 mol% Ga alloy. The coarsened microstructure and the sharp texture were achieved through high temperature uniaxial compression deformation. The latter was compressed up to −1.9 at 1 173 K with 5.0×10^{-4} s^{-1}. The black and gray lines are high and low angle grain boundaries having misorientation higher than 15° and between 2° and 15°, respectively. (Online version in color.)

**Acknowledgements**

This work was performed under the Cooperative Research Program of “Network Joint Research Center for Materials and Devices” and supported by JSPS KAKENHI Grant number JP15K18230.

**REFERENCES**

1) J. Atulasimha and A. B. Flatau: *Smart Mater. Struct.*, 20 (2011), 043001.
2) T. Ueno: *J. Appl. Phys.*, 117 (2015), 17A740.
3) Y. Onuki, S. Fujieda, R. Ukai, S. Sato, M. Sato, K. Kajiwara and S. Suzuki: *J. Alloys Compd.*, 653 (2015), 195.
4) J. H. Li, X. X. Gao, J. Zhu, X. Q. Bao, T. Xia and M. C. Zhan: *Scr. Mater.*, 83 (2014), 246.
5) S.-M. Na and A. B. Flatau: *Scr. Mater.*, 60 (2012), 307.
6) G. D. Liu, X. F. Dai, H. Z. Luo, H. Y. Liu, J. L. Chen and G. H. Wu: *Physica B*, 406 (2011), 440.
7) S. Fujieda, S. Suzuki, A. Minato, T. Fukuda and T. Ueno: *IEEE Trans. Magn.*, 50 (2014), 1.
8) S. Fujieda, R. Ukai, Y. Onuki, S. Suzuki and T. Fukuda: *AIP Conf. Proc.*, 1649 (2015), 27.
9) K. Okayasu, H. Takekoshi and H. Fukutom: *Mater. Trans.*, 48 (2007), 2002.
10) K. Okayasu, S. Takahata and H. Fukutom: *Mater. Sci. Forum*, 702–703 (2012), 336.
11) Y. Onuki, K. Okayasu and H. Fukutom: *ISIJ Int.*, 51 (2011), 1564.
12) Y. Onuki, R. Hongo, K. Okayasu and H. Fukutom: *Acta Mater.*, 61 (2013), 1294.
13) Y. Onuki, K. Okayasu and H. Fukutom: *Mater. Sci. Forum*, 702–703 (2012), 810.
14) E. M. Summers, T. A. Lograsso and M. Wun-Fogle: *J. Mater. Sci.*, 42 (2007), 9582.