Intermetallics 23 (2012) 20–26

Contents lists available at SciVerse ScienceDirect

Intermetallics

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

Deformation twinning feature and its effects on significant enhancement of tensile ductility in columnar-grained Fe–6.5wt.%Si alloy at intermediate temperatures

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A R T I C L E I N F O

Article history:
Received 10 November 2011
Received in revised form
14 December 2011
Accepted 16 December 2011
Available online 3 January 2012

Keywords:
A. Magnetic intermetallics
B. Brittleness and ductility
B. Twinning
B. Plastic deformation mechanisms
D. Microstructure

A B S T R A C T

The tensile deformation behavior of columnar-grained Fe–6.5wt.%Si alloy with <100> fiber texture at intermediate temperatures (300–500 °C) was investigated. Compared with equiaxed-grained Fe–6.5wt.%Si alloy, the enhanced tensile ductility and its mechanism of columnar-grained Fe–6.5wt.%Si alloy were mainly studied by the analysis of tensile twinning Schmid factor value and the deformation microstructure. The results showed that tensile ductility of the Fe–6.5wt.%Si alloy with columnar grains were increased significantly, i.e., the elongation of the columnar-grained specimens were increased to 6.6% (300 °C), 51.1% (400 °C), 51.3% (500 °C), which, respectively, corresponded to an increase of 3.7%, 25.8% and 23.2% compared with that of the equiaxed-grained specimens. The analysis of tensile twinning Schmid factor value and the deformation microstructure both demonstrated that deformation twinning occurred locally in the equiaxed-grained Fe–6.5wt.%Si alloy, while a great number of twins formed homogeneously in the columnar-grained Fe–6.5wt.%Si alloy. The significant enhancement of tensile ductility of the columnar-grained Fe–6.5wt.%Si alloy at intermediate temperatures was mainly ascribed to the formation of a great number of homogeneous deformation twins.

1. Introduction

Fe–6.5wt.%Si alloy, as an excellent soft magnetic material, exhibits high permeability, low coercive force and near-zero magnetostriction. It has wide application prospects in high frequency fields, including transformers, power generators, and electric relay, due to its advantages of reducing the consumption of energy and noise pollution [1–5]. Therefore, the investigations on fabrication and microstructure/property controlling of the Fe–6.5wt.%Si alloy have attracted a lot of attention recently [6–10]. However, the brittleness and hard-to-process problems of the Fe–6.5wt.%Si alloy have not been solved and the fabrication technology based on rolling has no breakthrough so far, which impeded its development and industrial application seriously [11,12]. Fully understanding its brittleness essence and deformation mechanism, developing the effective methods for its plasticization and toughening are the theoretical foundation for the sale-up production and extending application of the Fe–6.5wt.%Si alloy.

Our previous studies proposed the effective methods for plasticization and toughening of the Fe–6.5wt.%Si alloy based on microstructural controlling (grain boundary morphology, precipitate and order degree). The results indicated that the initiation and propagation of cracks in the Fe–6.5wt.%Si alloy could be suppressed during compressive deformation, by controlling grain boundary morphology during directional solidification [13]. The bending mechanical property of the Fe–6.5Si alloy at room temperature could be improved by controlling precipitates and order degree during heat treatment [14]. The Fe–6.5wt.%Si alloy could be strain-softened by pre-deformation methods at intermediate temperature [15]. These results pointed out an important direction for enhancing the cold workability of the Fe–6.5wt.%Si alloy.

Meanwhile, numerous studies reported that mechanical property of the alloy with columnar grains could be improved obviously compared with that of the alloy with equiaxed grains [16–18]. However, different alloys had different mechanisms for the enhanced mechanical property. For Al–Si alloy which formed casting defects easily [16], the mechanical property of this alloy with columnar grains fabricated by directional solidification could be improved because of the less casting defects and the compact microstructure. For Ni_3Al alloy which exhibited grain boundary

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doi:10.1016/j.intermet.2011.12.011

embrittlement [17], the mechanical property of this alloy with columnar grains fabricated by directional solidification could be improved because of the low-energy grain boundary which could resist the intergranular cracks. For Cu–12Al alloy which had strain-induced phase transformation behavior [18], the mechanical property of the alloy with columnar grains fabricated by directional solidification could be improved due to the near-unanimous crystallographic orientation of the columnar grains which can reduce the elastical and phase-transformational incompatibility during deformation. However, the mechanism of enhanced mechanical property in the Fe–6.5wt.%Si alloy with columnar grains is still unclear.

Under the condition that columnar grains were retained without recovery of precipitates and ordered phase, it is of great practical significance to appropriately raise deformation temperature (300–500 °C) for improving the processing efficiency, the rolling yield and reducing the cost. Therefore, it is possible to develop a processing technology of the Fe–6.5wt.%Si alloy based on rolling process.

In this paper, the tensile deformation behavior of the columnar-grained Fe–6.5wt.%Si alloy at intermediate temperatures was investigated compared with that of the alloy with equiaxed grains. The effect and mechanism of the intensive-texture columnar grains fabricated by directional solidification on the tensile ductility of the Fe–6.5wt.%Si alloy were mainly studied, which could provide theoretic foundation for improving the workability of this alloy.

2. Materials and methods

Taking pure iron (99.9wt.%), pure silicon (99.9wt.%) and Fe–B alloy (B: 17.5wt.%, Fe: 82.45wt.%) as raw materials, an Fe–6.5wt.% Si alloy was firstly induction melted and cast in a vacuum furnace. Its chemical composition was shown in Table 1. The as-cast ingot was then forged at a temperature range of 850–1000 °C to both reduce the casting defects and improve the homogenization and compaction of the alloy. The rods with size of Φ7.5 mm × 10 mm were cut from the forged specimen by electric discharge machining. After being polished, cleaned and dried, the rods were solidified to obtain Fe–6.5wt.%Si alloy with columnar grains by directional solidification equipment, herein called as “columnar-grained specimens”. The forged specimen, herein called as “equiaxed-grained specimens”, was used to make comparative tests.

In consideration of the poor heat conductivity, the strict requirements of element and impurity as well as the high melting temperature of the Fe–6.5wt.%Si alloy, the alloy was fabricated by directional solidification through an improved Bridgman zone melting equipment. Detailed processes of the directional solidification referred to the fabrication condition of the Fe–6.5wt.%Si alloy with a directional solidification rate of 1 mm/min in the reference [19].

The specimens were polished and etched with a solution of 3.5% HNO_3 and 96.5% CH_3COOH at room temperature. A LV150 optical microscope was employed to observe the microstructure of the specimens. The crystallographic orientation of specimens was detected by electron backscattered diffraction (EBSD) detector equipped on a scanning electronic microscope. The pole figure set the grain growth direction as *X* and set the direction perpendicular to the *X* direction as *Y* in the measured plane. The specimens were conducted by the heat treatment at 900 °C for 1 h followed by oil quenching according our previous study [14]. Tensile ductility of the Fe–6.5wt.%Si alloy specimens at intermediate temperatures were measured according to China National Standard GB/T 4338-2006. All the tensile tests were carried out along the solidification direction of the specimens at a tensile rate of 0.5 mm/min and at deformation temperature range of 300–500 °C.

Table 1
Chemical composition of Fe–6.5wt.%Si alloy (wt.%).

C	Si	Mn	S	P	Al	B	Fe
0.0032	6.42	0.028	0.0024	0.0081	<0.005	0.048	Balance

3. Results

3.1. Grain morphology and crystallographic orientation of the Fe–6.5wt.%Si alloy

Fig. 1 shows the three-dimensional microstructure of the as-forged Fe–6.5wt.%Si alloy and the columnar-grained Fe–6.5wt.%Si alloy, respectively. Many equiaxed grains with an average size of ~450 μm are observed in the as-forged specimens, as shown in Fig. 1(a). In the columnar-grained specimens fabricated by directional solidification, some columnar grains are distributed homogeneously with a width of ~450 μm which are parallel to each other with straight grain boundaries, as shown in Fig. 1(b). The grain morphology of the specimens fabricated by directional solidification is related to the practical direction of heat dissipation. During directional solidification, the heat dissipation direction of the Fe–6.5wt.%Si alloy is parallel to the drawing without transversal heat dissipation.

Fig. 2 shows the crystallographic orientation of the Fe–6.5wt.%Si alloy. The forged specimen with equiaxed grains exhibits random distribution of crystallographic orientation, as shown in Fig. 2(a). During directional solidification, the grains with the <100> crystallographic orientation grow preferentially and then consumed their neighboring grains with other crystallographic orientation gradually. Therefore, an intensive <100> fiber texture along the solidification direction of the Fe–6.5wt.%Si alloy is obtained, as shown in Fig. 2(b). 34 equiaxed grains (E1–E34) and 4 columnar grains (C1–C4) were selected in order to understand the relationship between the crystallographic orientation and the tensile direction of each grain. The Euler angles of each grain are listed in Table 2.

3.2. Tensile ductility of the Fe–6.5wt.%Si alloy at intermediate temperatures

The equiaxed-grained or columnar-grained specimens were conducted by heat treatment before tensile test at intermediate temperatures. Fig. 3 shows the elongation of the Fe–6.5wt.%Si alloy with equiaxed or columnar grains at different temperatures. The elongation of the equiaxed-grained specimens is 2.9%, 25.3%, 28.1% at 300, 400, 500 °C, respectively. However, the elongation of the columnar-grained specimens is increased to 6.6%, 51.1%, 51.3% which, respectively, corresponded to an increase of 3.7%, 25.8% and 23.2% compared with that of the equiaxed-grained specimens. These results indicate that columnar-grained specimens exhibit higher tensile ductility than that of the equiaxed-grained specimens.

On the other hand, apparent differences in the tensile load–displacement curves between the equiaxed-grained specimens and columnar-grained specimens exist, as shown in Fig. 4. The two curves consist of elastic deformation stage, parabola-like strain-hardening stage and necking stage. The equiaxed-grained specimen exhibits a high work hardening rate and its curve changes smoothly at the parabola-like strain-hardening stage. However, the columnar-grained specimen has a relatively low work hardening rate and its curve exhibits dramatical serration fluctuations (~0.5 kN) which are accompanied by a series of jarring during tensile test.