Grain boundary migration in Fe-3mass%Si alloy bicrystals with twist boundary

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Abstract

The characteristics of grain boundary migration in Fe-3mass%Si alloy bicrystals with $\Sigma$3(011), $\Sigma$5(001) and $\Sigma$9(011) coincidence twist boundaries and random twist boundaries were examined to obtain an information on the development of $\{110\}(001)$ (Goss) texture. The bicrystals were annealed at 1223 K for an appropriate time and the grain boundary migration speed was evaluated.

The $\Sigma$5(001) and $\Sigma$9(011) twist boundaries showed higher migration speed than $\Sigma$3(011) twist boundaries, and the random twist boundaries migrated faster than other boundaries. The migration speed decreased with increasing annealing time due to an increase in the edge components of the lattice misfits in the migrated boundaries. The grain boundary migration was also sensitive to the deviation angle ($\Delta\theta$) from the ideal orientation relationship for a coincidence boundary. The increase of $\Delta\theta$ accelerated the boundary migration. The motion of the grain boundary was influenced by plastic strain. Migration of the $\Sigma$9 twist boundary was more suppressed by plastic strain than that of the random boundary. On the basis of characteristics of the grain boundary migration, the effect of inhibitor on the Goss texture was discussed. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Grain boundary; Fe–Si alloy; Grain-boundary character; Microstructure; Soft magnetic steel; Texture

1. Introduction

Silicon steels are known to be a superior soft magnetic material with good initial permeability and high maximum magnetic flux density [1–3]. The magnetic properties of silicon steels depend strongly on microstructure; the $\{110\}(001)$ oriented (Goss orientation) grains show good soft magnetic properties because magnetic spins can be easily aligned under a cyclically applied magnetic field and the energy loss is low during spin rotation [4]. Many studies have been made dealing with primary and secondary recrystallisation phenomena to obtain the Goss orientation texture [5–9]. The texture is controlled during annealing after cold rolling by several factors: distribution of grain orientations, grain boundary character and grain boundary migration. The effect of impurity atoms and small precipitates segregated at grain boundaries on the recrystallisation texture has been extensively investigated [10–12]. The grain growth is primarily controlled by the grain boundary migration which depends on the grain boundary character. Basic information on migration is necessary to control the texture.

To examine the motion of the grain boundary, the capillary driving force is often used in a variety of bicrystal geometries. Several techniques using bicrystals such as the wedge, reversed-capillary and constant force techniques have been applied [13]. The reversed-capillary technique was first proposed and developed by Sun and Bauer [14,15]. The major advantage of this technique is the relative ease of specimen preparation and the possibility to change the driving force by varying the angle between boundary and specimen edge in a bicrystal.

Nakajima et al. applied this technique to Fe–Si alloy and examined the boundary migration of $(221)$ $\Sigma$9 coincidence and random boundaries in Fe-3mass%Si alloy using bicrystals with a symmetrical tilt boundary [16,17]. The mobility of the grain boundary was about four times larger for the $(221)$ $\Sigma$9 boundary than for the random boundary below 1323 K, while above 1323 K the mobility of the random boundary was larger than that of the coincidence boundary.

Although grain boundaries are composed of tilt and twist boundaries, there is no information about the mobility of the latter in silicon steels. In this paper we report the effect of the grain boundary character on the boundary migration in
Fe-3mass%Si alloy using bicrystals with the twist boundary. Various types of coincidence boundaries were used and the effect of deviation angle from Brandon’s criterion [18] for the coincidence boundary on the migration was determined. The effect of plastic strain on the boundary migration was also examined.

2. Experimental procedure

Master ingots of Fe-3mass%Si alloy were prepared from high purity raw materials by arc melting under high purity argon. Seed crystals with (001) and (011) orientations were cut from a single crystal which was grown from the ingot by the floating-zone method at 5 mm/h. The (001) and (011) oriented single crystals were grown from the seed crystals. After zone-melting a portion of the single crystal, the upper part of the crystal was rotated at an appropriate angle to the lower part. Then, bicrystals were produced by slow solidification of the melting zone. The bicrystals had a coincidence boundary of Σ3, Σ5 or Σ9 with (011), (001) or (011) rotation axis, respectively. The random twin boundary with (011) rotation axis was also prepared. The ideal twist angles (θ) for Σ3(011), Σ5(001) and Σ9(011) boundaries were 70.5, 36.9 and 38.9°, respectively. The twist boundary in bicrystals deviated somewhat from the ideal orientation relationship. Character of the boundary in the bicrystals used is given in Table 1. The bicrystals were put in an evacuated quartz capsule and homogenised at 1279 K for 24 h.

Platelet specimens to examine the grain boundary migration as shown in Fig. 1 were prepared from bicrystals by spark machining. Face A was chosen to be (110). The angle (α) between the grain boundary and specimen edge was chosen to be 24 or 10°. 24° is the same angle used for tilt boundaries by Nakajima et al. [16,17] and 10° is the smallest possible angle in our experiment. The specimen surface was chemically polished in a 1/160 (vol%) fluoric acid/hydrogen peroxide solution after mechanical polishing by fine sandpaper (No. 1500). The specimen was capsulated in an evacuated quartz tube and annealed at 1223 K for various periods to examine the grain boundary migration. The migration was observed by a scanning electron microscope (JSM-840A) and an optical microscope using a Nomarski interference contrast. The migration distance was evaluated from the distance (α) at the specimen edge as shown in Fig. 1(b). To examine the effect of plastic strain on the grain boundary migration, Vickers indentation was applied near the grain boundary under 50 and 100 gf load. The orientation relationship of grains and the grain boundary was examined using X-ray Laue back diffraction and SEM-electron channelling pattern (ECP) techniques.

3. Results

3.1. Change in the migration distance of grain boundary during annealing

The grain boundary structure was characterised by Σ values determined from the ECPs of two adjacent grains. Brandon’s condition was used as the criterion of the exact coincidence orientation relationship. Even if a coincidence boundary satisfies this criterion, the boundary character such as boundary energy and mobility is influenced by the deviation angle (Δθ) from the ideal orientation (θ) relationship.

Fig. 2 shows the change in the migration distance of Σ5(001) coincidence boundaries with different deviation angles during annealing at 1223 K. The migration distance sharply increases at an early stage and the rate of increase is moderated with further annealing time. The migration speed for the boundary with Δθ = 1.7° becomes minimal during
annealing at more than $1 \times 10^3$ s. The grain boundary with a large deviation angle ($\Delta \theta = 4.9^\circ$) migrates faster than that with a smaller one ($\Delta \theta = 1.7^\circ$) at the initial stage.

Fig. 3 shows electron back scattered images of Fe-3mass%Si bicrystals containing $\Sigma 5(001)$ boundaries with $\Delta \theta = 1.7$ and $4.9^\circ$ after annealing at 1223 K for $2 \times 10^3$ s. The original boundary positions can be recognised by a weak straight line. Since the surface energy at the edge of the bicrystal is lower than the boundary energy, the grain boundary migrates accompanied by an increase in $\alpha$ to balance the surface and the grain boundary energies during annealing. Migration distance of the grain boundary with $\Delta \theta = 4.9^\circ$ is greater than that with $\Delta \theta = 1.7^\circ$. At $\Delta \theta = 1.7^\circ$ the major part of the migrated boundary forms a facet, while a facet portion is small and the migrated boundary shows a curved shape at $\Delta \theta = 4.9^\circ$. The specimen surfaces of crystal A and B in Fig. 3(a) were (110) and (710), respectively, and the original grain boundary lay on (001) in crystal A. In crystal A the facet was perpendicular to the (110) surface, while the angle between the facet and the (001) boundary was $54.5^\circ$. Therefore, the facet was indexed to be (111) in crystal A. In crystal B the facet is determined to be (175) from the orientation relationship among the (001) boundary, the (710) surface and the facet.

Fig. 4 shows the time dependence of the migration distance of $\Sigma 3(011)$ boundaries with different $\Delta \theta$ annealed at 1223 K. The error bar represents the migration distance on the top and bottom surfaces of the same specimen. The data contain a large scatter. Although there was a big difference in the migration distance on the top and bottom surfaces of specimens, the boundary rapidly migrated at an early stage of annealing and then the migration speed decreased after 500 s. An increase of deviation angle accelerated the boundary migration but boundaries with both $\Delta \theta = 4.4$ and $7.2^\circ$ lost the mobility and stop after $1 \times 10^3$ s.

Fig. 5 shows the microstructures of $\Sigma 3(011)$ grain boundaries with $\Delta \theta = 4.4$ and $7.2^\circ$ after annealing. The groove of
the migrated grain boundary do not always show a clear contrast as shown in Fig. 5(c). The migrated grain boundary on the bottom surface (Fig. 5(b) where $\alpha$ showed a smaller value than that on the other top surface of the same specimen (Fig. 5(a)) formed three facets tilting by 8, 20 and 58° from the original boundary. When the complicated facets happened to be formed on the bottom surface, the grain boundary migration was strongly disturbed. On the top surface no facet was observed on the migrated grain boundary as shown in Fig. 5(a). The big difference in the migration distance on the top and bottom surfaces is due to the different morphology of the migrated boundaries on two surfaces. Since the migrated boundary showed different morphology on both the surfaces at $\Delta \theta = 4.4^\circ$, the boundary was not perpendicular to the surface and therefore the orientation relation for the facets cannot be analysed. At $\Delta \theta = 7.2^\circ$ as shown in Fig. 5(c), the migrated boundary did not show sharp contrast. On a microscopic scale, the migrated grain boundary may be curved and form a complicated shape in the specimen resulting in a loss of the mobility.

Fig. 6 shows the change in the migration distance of $\Sigma 9(011)$ boundaries with $\Delta \theta = 2.0^\circ$ and $4.0^\circ$ in Fe-3mass%Si bicrystals annealed at 1223 K. The grain boundary migration occurred rapidly at an early stage and then the migration speed decreased with annealing time similar to $\Sigma 5(001)$ boundaries. The increase of deviation angle remarkably accelerated the grain boundary migration.

Fig. 7. Back scattered electron images of Fe-3mass%Si alloy bicrystals annealed at 1223 K for $2 \times 10^3$ s: (a) $\Sigma 9(011)$ twist boundary with $\Delta \theta = 2.0^\circ$ at $\alpha = 24^\circ$; (b) $\Sigma 9(011)$ twist boundary with $\Delta \theta = 4.0^\circ$ at $\alpha = 24^\circ$. 

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**Fig. 4.** Change in the migration distance of the $\Sigma 3(011)$ twist boundary with $\Delta \theta = 4.4$ and $7.2^\circ$ at $\alpha = 24^\circ$ as a function of annealing time at 1223 K.

**Fig. 5.** Back scattered electron images of Fe-3mass%Si alloy bicrystals annealed at 1223 K for $1 \times 10^3$ s: (a) $\Sigma 3(011)$ twist boundary with $\Delta \theta = 4.9^\circ$ at $\alpha = 24^\circ$; (b) image on bottom side of (a); (c) $\Sigma 3(011)$ twist boundary with $\Delta \theta = 7.2^\circ$ at $\alpha = 24^\circ$, same side as (a). 

**Fig. 6.** Change in the migration distance of $\Sigma 9(011)$ twist boundaries with $\Delta \theta = 2.0$ and $4.0^\circ$ at $\alpha = 24^\circ$ as a function of annealing time at 1223 K.
Fig. 7 shows electron back scattering images of Fe-
3mass%Si bicrystals containing $\Sigma 9(011)$ boundaries with $\Delta \theta = 2.0$ and 4.0° after annealing at 1223 K for $2 \times 10^3$ s. The migrated portion of the $\Sigma 9(011)$ boundary showed no significant facet plane and formed a large arc, while the $\Sigma 5(001)$ boundary approached perpendicular to the specimen edge and rapidly decreased the area during annealing. The interfacial energy of the closely packed {110} plane in bcc crystals may be low since the closely packed {111} plane in fcc crystals formed the low interfacial energy [19]. Since the boundary shows a tendency to maintain the (011) low energy plane during migration, a great portion of the boundary moves accompanied by no great change in $\alpha$.

3.2. Effect of $\alpha$ on the grain boundary migration

Since the grain boundary has higher energy than matrix grain, reduction of the grain boundary area provides the primary driving force for the boundary migration in grain growth processes. The driving force depends on the energy balance of grain boundaries and geometrical shape containing the local boundary curvature at the triple junction. In the present study, the driving force for the grain boundary migration is given by the function of $\alpha$: the driving force increases with decreasing $\alpha$. Mullins [20] has analysed the motion of an arbitrary isotropic grain boundary in two dimensions under the condition that the boundary displacement is proportional to the local curvature at each point. Sun and Baver [14,15] assumed that the boundary migrates maintaining the curvature of a hyperbola-like shape, and analysed the motion of the grain boundary in terms of the migration distance ($a$). The displacement of the intersection of the boundary with time along the surfaces is proportional to the radius of a virtual circular boundary given by the following equation:

$$a^2 = 2M \gamma f(\alpha)t$$

where $M$ and $\gamma$ are the mobility and boundary surface tension, respectively. $f(\alpha)$ denotes the slope of the curvature of boundary at the specimen edge.

Fig. 8 shows change in $a^2$ of the grain boundaries annealed at 1223 K for 500 s as a function of $\alpha$. All tested boundaries showed more rapid migration speed at small $\alpha$ than at large $\alpha$. The migration speed is more accelerated at $\Sigma 5$ and $\Sigma 9$ boundaries with a small $\alpha$ value, and as the $\theta$ increases. The $\Sigma 3$ boundaries show different $\alpha$ dependence of the migration from $\Sigma 5$ and $\Sigma 9$ boundaries. The migration of $\Sigma 3$ boundaries shows no significant $\alpha$ dependence at both $\theta = 4.4$ and $7.2°$. At $\alpha = 24°$, $\Sigma 3$ and $\Sigma 5$ boundaries often form facets after initial rapid boundary migration resulting in decreasing migration speed. As shown in Fig. 9, at $\alpha = 10°$, the $\Sigma 5$ boundary easily moves forming no significant facets, while clear facets are observed in the $\Sigma 3$ migrated boundary. Since the boundary energy of the $\Sigma 3$ boundary may be low and formation of facets induces a decrease in mobility, the migration speed must be low even at a small $\alpha$ value.

3.3. Effect of plastic strain on grain boundary migration

Lattice defects such as dislocations and vacancies increase the stored energy in a crystal and provide a driving force for recrystallisation and grain growth. On the other hand, the interaction between the grain boundary and the lattice defects is thought to suppress the mobility of the boundary. To examine the effect of plastic strain on the
boundary migration, a plastic strain was introduced by Vickers hardness indentation. Indentation was applied at intervals of 200 μm parallel to the specimen edge on the (011) specimen surface from the grain boundary under 50 gf load.

Table 2 shows the effect of indentation on the grain boundary migration for a random boundary and the \( \Sigma 9 \) boundary with \( \alpha = 24^\circ \): the migration distance with and without indentation was measured in bicrystals annealed at 1223 K for \( 2 \times 10^3 \) s. Random boundaries show faster migration speed than \( \Sigma 9 \) boundaries with and without plastic strain. The plastic strain interrupts the motion of the grain boundary and the migration distance is decreased, although the decrease in migration distance depends strongly on the grain boundary character. Migration of the \( \Sigma 9 \) boundary is more suppressed by plastic strain than that of the random boundary. When the grain boundary migrates, lattice defects must be absorbed in this boundary. The random boundary can absorb a large number of dislocations, while the coincidence boundary absorbs few lattice defects. Strong interaction between the coincidence boundary and the lattice defects induces a great reduction of mobility of the \( \Sigma 9 \) boundary.

When a large amount of plastic strain is applied under 100 gf load, the \( \Sigma 9 \) boundary is separated into two \( \Sigma 3 \) boundaries during migration as shown in Fig. 10. Since the \( \Sigma 9 \) boundary cannot absorb a large amount of plastic strain, this strain is released by the nucleation of the \( \Sigma 3 \) boundary similar to the formation of annealing twins in fcc metals.

4. Discussion

4.1. Transition in grain boundary migration speed

At an early stage of the grain boundary migration, the boundary moved easily depending on the boundary character, but the migration speed sharply decreased as the period of annealing lengthened. In general, the equilibrium dihedral angles, which are balanced by the individual boundary energies at the triple junction, are given by Herring’s equation as follows:

\[
\frac{\sigma_1}{\sin(\alpha_1)} = \frac{\sigma_2}{\sin(\alpha_2)} = \frac{\sigma_3}{\sin(\alpha_3)}
\]

where \( \alpha_K \) is the dihedral angle and \( \sigma_K \) the boundary energy corresponding to the angle \( \alpha_K \). In present bicrystals \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) correspond to the grain boundary energy, the surface energy in crystal A and the surface energy in crystal B, respectively. \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) indicate the angles of a free specimen surface (\( \equiv \pi \)), \( \alpha \) and (\( \pi - \alpha \)), respectively. Since a surface groove may be formed at the junction of the grain boundary and the specimen surface, \( \alpha_1 \) is actually less than \( \pi \).

Since the boundary energy is believed to be several times larger than the surface energy, the acute angle \( \alpha \) increases approaching to \( \pi/2 \) to maintain the energy balance at the junction, and the grain boundary is forced to move into crystal A. The main driving force for the grain boundary migration depends on the difference of energy between this boundary and the surface and the deviation angle from Herring’s equation. Small \( \alpha \) provides a large driving force for the migration.

Once the boundary migrates, the driving force decreases depending on the curvature of the migrated portion and the
The square of migration distance is represented as a function of mobility, boundary surface tension, coefficient \( f(\alpha) \) and annealing time as shown in Eq. (1). For the present specimens, coefficient \( f(\alpha) \) was about 1.8 for \( \alpha = 24^\circ \). The grain boundary migration is believed to be mainly controlled by mobility and a driving force; the driving force is a function of the grain boundary energy. Therefore, the migration is evaluated by the boundary mobility \( (M) \) and energy \( (\gamma) \).

Fig. 11 shows normalised square of migration distance of various twist boundaries as a function of annealing time together with the results of the \( \Sigma 9(221) \) tilt boundary [16]. There is no great difference in \( a^2 f(\alpha) \) between \( \Sigma 5 \) and \( \Sigma 9 \) twist boundaries with similar deviation angles, while the \( \Sigma 3 \) twist boundary shows a lower \( a^2 f(\alpha) \) value than \( \Sigma 5 \) and \( \Sigma 9 \) twist boundaries. Since energy of the \( \Sigma 3 \) boundary energy is believed to be lower than that of \( \Sigma 5 \) and \( \Sigma 9 \) twist boundaries, the driving force for the grain boundary migration must be low. The \( a^2 f(\alpha) \) value for the \( \Sigma 9 \) tilt boundary is lower than that for the \( \Sigma 9 \) twist boundary although the tested temperature of the former is higher than that of the latter. The coincidence tilt boundary is known to contain some amounts of edge dislocations which may show strong interruption with solute atoms. In fact, when a coincidence twist boundary migrates and the edge component of dislocations increases, the motion of the grain boundary is strongly interrupted by solute atoms resulting in a rapid decrease of the mobility. Mobility of the grain boundary is influenced by the boundary’s character. The driving force is important for the grain boundary migration. The \( M \gamma \) value can be calculated from the slope of the curves in Fig. 11, and the results are given in Table 3 together with

4.2. Effect of grain boundary character on grain boundary migration

The distance of the grain boundary migration was measured. The square of migration distance is represented as a function of mobility, boundary surface tension, coefficient \( f(\alpha) \) and annealing time as shown in Eq. (1). For the present specimens, coefficient \( f(\alpha) \) was about 1.8 for \( \alpha = 24^\circ \). The grain boundary migration is believed to be mainly controlled by mobility and a driving force; the driving force is a function of the grain boundary energy. Therefore, the migration is evaluated by the boundary mobility \( (M) \) and energy \( (\gamma) \).

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Table 3
The driving force \( (M \gamma) \) for various coincidence boundaries. \( M \) and \( \gamma \) represent the mobility and energy of the grain boundary, respectively

| \( \Sigma 5(001) \) \( \Delta \theta = 1.7^\circ \) | \( \Sigma 5(001) \) \( \Delta \theta = 4.9^\circ \) | \( \Sigma 9(011) \) \( \Delta \theta = 2.0^\circ \) | \( \Sigma 9(011) \) \( \Delta \theta = 4.0^\circ \) | \( \Sigma 5(012) \) | \( \Sigma 5(013) \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( M \gamma \times 10^{-11} \text{ m}^2/\text{s} \) | 1.28 | 5.57 | 5.20 | 6.11 | 12.2 | 8.98 |

\( ^a \) The data of the tilt boundaries were reported by Lejeck et al. [21].
the data by Lejcek et al. [21]. There is no significant difference among the $M_g$ values of those boundaries, although $S_5$ with $D_{\hat{1}1}$ shows the lowest value.

4.3. Effect of facets on grain boundary migration

A different shape of migrated portions of $S_5$ and $S_9$ twist boundaries was observed although there was no significant difference in the migration speed of those boundaries. A large portion of the $\Sigma 9$ boundary migrated and gradually deviated from $\alpha$, while a small portion of the $\Sigma 5$ boundary moved and the slope of the curved boundary sharply increased deviating from $\alpha$. The migration and shape change of the grain boundary induce variation in the boundary structure including misfit dislocations so that the boundary energy changes.

To explain the shape change of grain boundaries, variation in the grain boundary energy may be schematically drawn as a function of $b$ as shown in Fig. 12. If the $\Sigma 9$ grain boundary energy sharply increases with $b$, the grain boundary migration is induced maintaining a small increase of $b$ and a large portion of the grain boundary is moved. The initial energy of the $\Sigma 9$ boundary may be low since a large portion can move. The $\Sigma 5$ grain boundary energy also increases with $b$. If the boundary energy does not sharply increase with $b$, a large curvature of the migrated grain boundary can be allowed. The migrated $\Sigma 5$ boundary has a large curvature but the migrated portion is small; this may be due to the high energy of the initial $\Sigma 5$ grain boundary. The $\gamma$ may decrease and reach a local minimum at $54.5^\circ$ forming a facet on $(11\bar{1})$ after an initial increase. At the local minimum, a facet is formed so that the migration of the $\Sigma 5$ grain boundary is suddenly suppressed.

4.4. Grain boundary migration and development of Goss grains

Frequent Goss grains were reported in the recrystallised structure of Goss oriented Fe–Si alloy single crystals [22,23]. Development of Goss grains in Fe–Si alloys is known to be due to the higher mobility of $S_5$ and $S_9$ coincidence boundaries than other boundaries [24]. In this section, the effect of the grain boundary migration on the development of Goss grains in polycrystals is discussed focusing on the $S_9$ coincidence and random boundaries. According to the results of the grain boundary migration using Fe-3mass%Si bicrystals with the tilt boundary [16] and present the twist boundary (Fig. 11 and Table 2), the following relationship on migration speed ($V$) for $S_9$ and random boundaries with main tilt and twist component was reached:

$$V_{\text{random, twist}} > V_{S_9, \text{twist}} > V_{S_9, \text{tilt}} > V_{\text{random, tilt}}$$

However, the grain growth of Goss orientation cannot be expected to occur under the above condition.

In the Fe–Si alloys containing inhibitors such as AlN and MnS [24], coarse Goss grains slightly elongated along the rolling direction although the equiaxed grain structure was formed by primary recrystallisation. Therefore, relation between Goss and $(11\bar{1})(11\bar{2})$ oriented grains in the primary recrystallisation structure is schematically drawn in Fig. 13. Assumed that the grain boundary is perpendicular to the figure, the $\Sigma 9$ boundary parallel to the rolling direction is a twist boundary and the tilt boundary is perpendicular to
the rolling direction. Elongated Goss grain along the rolling direction suggests that the migration speed of the tilt boundary is faster than that of the twist boundary. In the Fe–Si alloys containing inhibitors, the following relation is induced:

\[ V_{9\text{tilt}} > V_{9\text{twist}}, V_{\text{random, twist}} \quad \text{and} \quad V_{\text{random, tilt}} \]  

Inhibitors suppress the migration of grain boundaries but the migration of the \( \Sigma 9 \) tilt boundary may not be influenced by inhibitors. Therefore, inhibitors are necessary for the development of Goss texture due to the control of relative mobility of the \( \Sigma 9 \) tilt boundary to other boundaries. After the formation of a large number of Goss grains, the Goss grains can be coarsened by the dissolution of the inhibitors in matrix.

Migration behaviour of grain boundaries in polycrystalline materials would be more complicated than that observed in bicrystals since each grain boundary is connected with triple junctions and there are many kinds of triple junctions possessing different combinations of the grain boundary energies. In addition, the grain boundary migration should be also analysed in terms of dynamic changes of the grain boundary plane or the grain boundary structure other than the \( \Sigma \) value.

5. Conclusions

The characteristics of the grain boundary migration in Fe-3 mass%Si alloy bicrystals with \( \Sigma 3(011), \Sigma 5(001) \) and \( \Sigma 9(011) \) coincidence twist boundaries were examined during annealing at 1223 K and the following conclusions were reached.

1. The grain boundary migration is very sensitive to the \( \Sigma \) value and the deviation angle (\( \Delta \theta \)) from the ideal orientation relationship for a coincidence boundary. The increase of \( \Delta \theta \) accelerates the grain boundary migration.

2. The \( \Sigma 5(001) \) and \( \Sigma 9(011) \) twist boundaries show higher migration speed at an early stage than \( \Sigma 3(011) \) twist boundaries, but the speed sharply decreases as the boundaries migrate. The edge component of lattice misfits in migrated grain boundaries increases and the dragging solute atmosphere around edge dislocations in grain boundaries is formed resulting in lowering the boundary mobility.

3. Twist and tilt coincidence boundaries mainly contain screw and edge dislocations, respectively. Formation of a different dragging solute atmosphere around these dislocations induces the difference in mobility of these boundaries; migration speed of tilt boundaries is slower than twist boundaries because of strong interaction between edge dislocations and solute atoms.

4. The plastic strain affects the motion of the grain boundary. Migration of the \( \Sigma 9 \) boundary is more suppressed by plastic strain than that of the random boundary since the latter can absorb a large quantity of the lattice defects during migration but the \( \Sigma 9 \) coincidence twist boundary does few.

5. Formation of Goss grains cannot be necessarily explained by the effect of the grain boundary character on the mobility in present bicrystals. Inhibitors are necessary for the development of Goss texture in the Fe–Si alloys.

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