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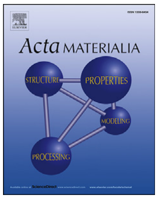

Full length article

Misorientation angle analysis near the growth front of abnormally growing grains in 5052 aluminum alloy

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ABSTRACT

Misorientation measurements at the growth front of abnormally growing grains in 5052 aluminum alloy were made using electron back-scattered diffraction (EBSD). When a three-dimensional morphology of solid-state wetting along a triple junction line is observed on a two-dimensional section, two kinds of morphologies could be observed. One is a morphology of penetrating the grain boundary when the section is parallel to the triple junction line. The other is morphology of a three or four-sided grain with a negative grain boundary curvature when the section is vertical to the triple junction line. Many morphologies of penetrating the grain boundary were observed at the growth front of abnormally growing grains. Grain boundary energies, which were estimated from misorientation measurements of the three grains in the penetrating morphology, satisfied the energetic condition for wetting along the triple junction line. Misorientation measurements showed that some matrix grains away from the growth front of abnormally growing grains had the same crystallographic orientation as that of the abnormally growing grain. Repeated EBSD measurements on each serial section show that these grains were actually identical to the abnormally growing grain, being connected three dimensionally. These results imply that the abnormal grain growth in 5052 aluminum alloy occurs by the mechanism of sub-boundary enhanced solid-state wetting.

1. Introduction

Abnormal grain growth (AGG) refers to the phenomenon that a few grains grow exclusively over other matrix grains whose growth is inhibited normally by precipitates. AGG occurs in many metallic systems. Because of the scientific and technological interests, the mechanism of the AGG has been studied extensively since this phenomenon was reported. But this phenomenon has not been clearly understood yet.

Previously, the AGG mechanism was approached mainly from the viewpoint that the grain boundaries of abnormally growing grains should have the high migration rate compared with those of non-abnormally growing grains. It was suggested that the high migration rate was made by the high mobility or by less pinning of the grain boundary [1–4]. However, these theories have drawbacks and cannot properly explain general features of AGG. For example, Park et al. [5] reported that it is not sufficient to explain the growth advantage of the abnormally growing grain based on specific misorientations of grain boundaries because some other grains in primary matrix grains have more such grain boundaries than abnormally growing grains.

2. Mechanism of sub-boundary enhanced solid-state wetting

Gottstein et al. [6,7] suggested that the triple-junction line mobility plays a more dominant role than the grain boundary mobility in the grain growth. The role of triple-junction line mobility becomes clear if we consider that the growing grain should have negative or inward curvatures, whose geometrical condition is satisfied only when the triple junction line goes ahead of the grain boundary. Considering such a geometrical condition, for a certain grain to grow abnormally, it is necessary that the

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triple-junction line at the growth front should have a high migration rate. Therefore, in order to understand the mechanism of AGG, it is critical to find out the condition under which the triple-junction line should migrate at a high rate. Hwang et al. [8–11] showed by Monte Carlo (MC) and phase field model simulations that the migration rate of the triple-junction line increases abruptly when solid-state wetting occurs. To explain the AGG mechanism, Hwang et al. [9,12–14] suggested based on MC and phase field model simulations that if some grains have sub-boundaries of very low energy, the wetting probability increases so high that these grains can undergo exclusive AGG. Based on these results, Hwang et al. [12,15,16] proposed sub-boundary enhanced solid-state wetting as a mechanism of AGG. According to this mechanism, sub-boundaries with very low misorientation angles should exist exclusively in abnormally-growing grains, which was experimentally confirmed by Park et al. [14], Ushigami et al. [17], Dorner et al. [18] and Shim et al. [19] in Fe-3%Si steel and by Park et al. [20] in Al 5052 alloy.

To examine a wetting morphology evolved when wetting along a triple junction line occurs, we use the three-dimensional MC simulation based on the algorithm reported by Srolovitz et al. [21]. For the simulation, 160 × 160 × 160 sites of a three-dimensional simple cubic lattice are used. In order to focus on the wetting morphology, 4 grains in contact are considered in the simulation using a fixed boundary condition. The condition for a grain A to wet along the triple junction line made by three grains B, C and D is expressed as [22].

$$\gamma_{BC} + \gamma_{CD} + \gamma_{BD} > \sqrt{3}(\gamma_{AB} + \gamma_{AC} + \gamma_{AD}), \tag{1}$$

where γ is the grain boundary energy and the subscript represents the grain boundary. For example, the subscript BC represents the grain boundary between grains B and C. When the grain boundary energies between grain A and grains B, C or D were given as 1 and those between grains B and C, grains C and D and grains B and D were given as 3, the grain A undergoes the triple junction wetting and its morphology evolved by the three-dimensional MC simulation is shown in Fig. 1.

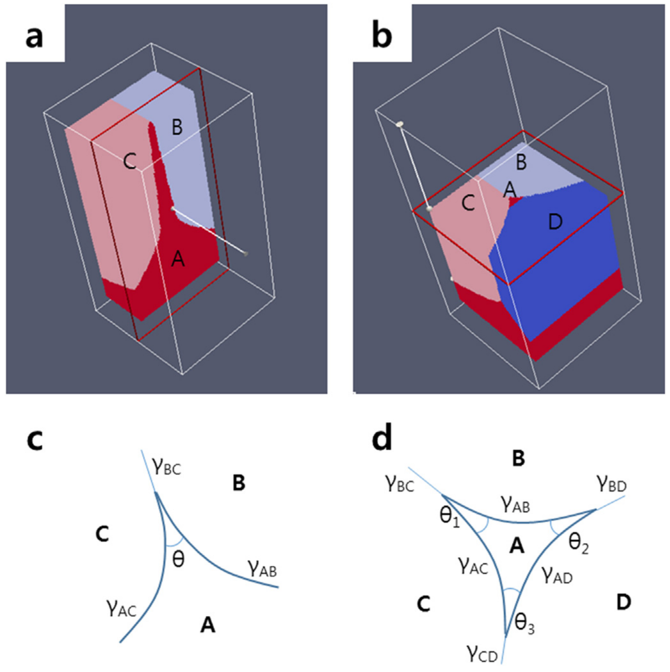

Fig. 1. Two-dimensional microstructure of three-dimensional triple junction wetting morphology made by MC simulation (a), (c) Parallel section to the wetting direction (b), (d) Vertical section to the wetting direction.

Fig. 1a and c shows how the microstructure of triple junction wetting is observed two-dimensionally on a polished surface of real samples when observed on a two-dimensional section parallel to the triple junction line of grains B, C and D. Likewise, Fig. 1b and d shows the microstructure observed on the polished surface vertical to the triple junction line. The penetrating morphology in Fig. 1a and c indicates that the triple junction migrates abruptly ahead of the grain boundary. This means that solid-state wetting increases the migration rate of the triple junction in an abrupt manner. Note that in Fig. 1, the grain boundaries of the penetrating grain A have characteristics of a negative or inward curvature. This negative curvature indicates that the grain A is growing instead of shrinking. Especially the grain A in Fig. 1b and d have three sides on the two-dimensional section. It is highly in contrast with the case of isotropic grain boundary energy where the grain with sides less than 6 in a two dimension has a positive curvature and shrinks. Therefore, a penetrating morphology as shown in Fig. 1a and c and a three-sided grain with negative curvatures as shown in Fig. 1b and d can be a microstructural evidence for solid-state wetting. In Fig. 1b and d, the sum of the inner angles of the three-sided grain A should be less than 180° to satisfy the wetting condition. This condition, which is equivalent to Eq. (1), is known as the criterion of the triple junction wetting [13].

If the grains A and D share a sub-boundary of extremely low angle, the energy of the grain boundary between grains A and D would be negligibly low compared to those of the other 5 grain boundaries in Eq. (1). Therefore, the misorientation angle between grains A and D as well as γ_{AD} can be approximated as zero. This approximation is supported by the previous report that the sub-boundaries observed in the abnormally-growing Goss grains have misorientation angles of ~0.15° and ~0.17° with their energy roughly 20 times less than that of high angle boundaries [10]. If the misorientation angle between grains A and D is approximated as zero, it can be further approximated that

$$\gamma_{AB} \approx \gamma_{BD}, \ \gamma_{AC} \approx \gamma_{CD} \tag{2}$$

Then, the wetting condition of Eq. (1) is simplified as [22].

$$\gamma_{BC} > \left(\sqrt{3} - 1\right)(\gamma_{AB} + \gamma_{AC}) \tag{3}$$

On the other hand, the misorientation angles between grains A and B, grains A and C and grains B and C can be determined experimentally using EBSD from the microstructure of the penetrating morphology on a two dimensional section of real samples as shown in Fig. 1a and c. It should be noted that the sub-boundary angle between grains A and D is not resolved by EBSD. Eq. (3) indicates that if γ_{BC} is 0.732 times higher than the sum of γ_{AB} and γ_{AC}, the triple junction wetting would occur. Therefore, the penetrated grain boundary is expected to have high energy. In agreement with this analysis, all penetrated grain boundaries, which were observed at the growth front of abnormally growing grains in Fe-3%Si steel [23] and Al 5052 alloy [22], had high misorientation angles.

If the measured misorientations are converted to grain boundary energies using such as Read-Shockley equations [13,16,24], it can be checked whether the wetting microstructure such as shown in Fig. 1a and c should satisfy the wetting condition of Eq. (3) or not. In this paper, we examined if the wetting condition of Eq. (3) is satisfied by estimating grain boundary energies from misorientation measurements of the three grains in the penetrating morphology. Some matrix grains away from the growth front of abnormally growing grains turned out to have the same crystallographic orientation as that of the abnormally growing grain.