Title	Characteristics of Microstructure and Hardness in Friction Stir Welded 7075 Aluminum alloy Joints(Materials, Metallurgy & Weldability)
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Citation	Transactions of JWRI. 2004, 33(1), p. 17-23
Version Type	VoR
URL	https://doi.org/10.18910/7567
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Characteristics of Microstructure and Hardness in Friction Stir Welded 7075 Aluminum alloy Joints †

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Abstract

The present study focuses on the characteristics of microstructure in the joint region of A7075 aluminum alloy. A7075 aluminum alloy plate with a thickness of 5mm was prepared for the joining. The FSW was performed for butt joints of the alloy with a welding speed and rotating ratio of 300mm/min. and 1500rpm, respectively. Microstructures of the joint region were investigated utilizing the OM, SEM and Electron Back-Scatter Pattern (EBSP) methods. Hardness of the joint was measured by the Vickers micro-indentation system. Grain refinement was achieved in the stirred zone of the joint, but the lowest hardness was obtained in this region. Each grain belonging to the same orientation group tended to form "clusters", and some clusters seemed to be lying along the plastic flow caused by the rotation of the pin. Spatial distributions of microstructure parameters were identical, depending on the area in the joint region observed. In other words, we have obtained an advanced technique for microstructure control that enables us to fabricate peculiar microstructures in limited regions by utilizing FSW or friction stirring in the surface region.

KEY WORDS: (7075 aluminum alloy) (friction stir welding) (electron back-scatter pattern) (hardness) (orientation distribution)

1. Introduction

Friction stir welding (FSW) is one of the solid state bonding techniques for metallic materials, and is now being widely applied to the joining of many kinds of metals such as Al[1], Cu[2], Ti[3], Mg[4], steels[5], and some combinations of dissimilar metals[6].

This unique welding method is realized by metal flow around a rotating tool composed of a shoulder and a pin, and the metal flow is attributed to the high temperature deformation caused by a frictional force between the tool and the metal. Thus the microstructure of joints fabricated by FSW process should be understood in terms of severe deformation and restoration at elevated temperature, although many of them have not been made clear so far.

Since the rotation and movement of the FSW tool yields a complicated metal flow around the tool, the FSW joint can be expected to possess different microstructures from those fabricated by conventional mass production methods such as rolling, extrusion, forging and so on [7]. Thus a novel microstructure control method could be developed based on this joining technique.

The present work focuses on the characteristics of microstructure, especially orientation distributions of a stirred zone in order to obtain fundamental data for microstructure control in a localized region.

2. Experimental Procedure

The starting materials were A7075-T761 Al alloys with a thickness of 5 mm. Chemical composition of the base material is summarized in **Table 1.**

After finishing the side surface of each plate to be contacted and joined, the FSW was performed for butt joints. The welding speed and the rotation rate were 300mm/min. and 1500 rpm, respectively. The tool was inclined by 3 degrees from the vertical axis and was

Table 1 Chemical composition of the base metal.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A7075	0.07	1.50	0.16	0.03	2.50	0.19	5.75	0.03	bal.

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

preheated by plunging into a dummy Al plate before the welding. In the present work the backing plate was SUS304 of 10 mm thickness.

Evaluation of microstructure of the joint was performed on the cross section of the weld called the TD plane, to investigate the grain size and spatial distributions of grain orientations on the ND plane by utilizing optical microscopy, scanning electron microscopy and the SEM-EBSP method [8]. The EBSP was taken at the center position of thickness. Vickers hardness was measured and the results were analyzed in relation to the microstructures.

3. Results and Discussion

3.1 Microstructure of the FSW joint

Figure 1 shows a macroscopic view (a) and three typical mirostructures observed in the present joints such as; stir zone (b), thermo-mechanically affected zone (TMAZ) (c), and heat affected zone (HAZ) (d).

The central region of the stir zone presents a laminated structure called "onion ring", and this region consists of equi-axed fine grains with an average grain size of 5 μm as shown in (b). The upper region of the onion ring is an insufficiently but intricately stirred zone, and an elongated grain structure having a kissing bond exists below the ring. This bottom region has a similar microstructure to that of the base metal. TMAZ has a typical microstructure such as a flow of metal around the stir zone that is clearly observed in Fig.1(c). This metal flow is caused by the friction stirring and high temperature deformation. The HAZ shown in Fig.1(d) is composed of elongated grains structure similar to those in the base metal.

In the upper region of the onion ring where the shoulder is in contact, a large amount of compression stress beneath the shoulder results in a strong constraint force that makes an insufficient flow around the pin. Thus the microstructure does not develop a laminated structure such as the onion ring, but a heterogeneous one.

In the bottom region beneath the onion ring, the microstructure seems not to be affected by the stirring, and particularly this un-mixed region is about 1mm in thickness. This value is quite large since the joining was performed with a 0.1mm gap between the bottom of the pin and the surface of the backing plate. In the present case, no significant change was observed for the shape and size of the pin, so the large amount of the gap could be explained by a change in shape of the pin elastically, such as bending. But this is not a common case for microstructures of FSW joint of metals that are relatively softer than the tool.

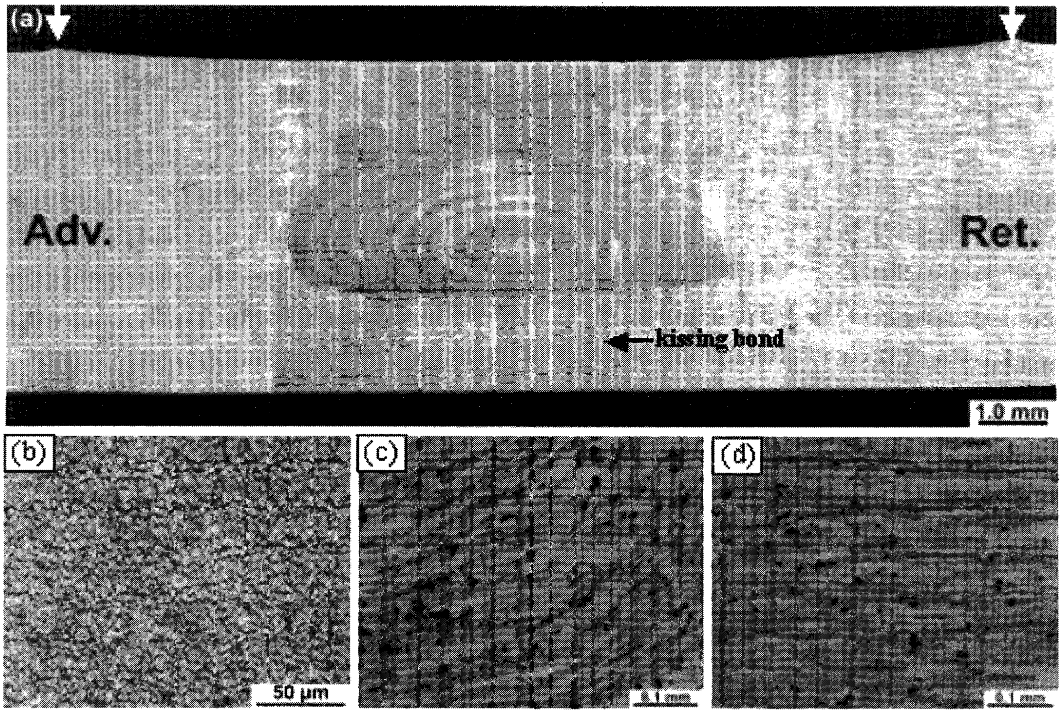

Fig.1 Optical micrographs of 7075Al Alloy FSW joint.
(a)macroscopic view, (b) stir zone, (c)TMAZ, (d)HAZ

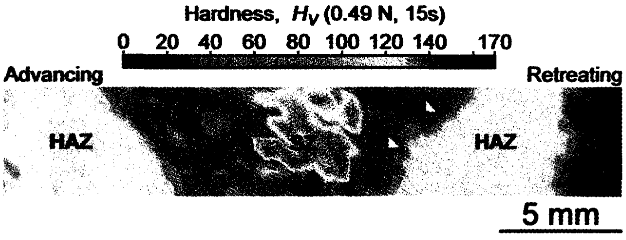

Fig.2 Distribution of hardness in the FSW joint.

3.2 Hardness distribution

Figure 2 shows a hardness distribution across the FSW joint. Hardness decreased in the order of base metal, TMAZ, HAZ and onion ring, although the friction stirred region showed the finest grain size. HAZs with softer regions than the base metal are clearly recognized by red colors in this figure and the softest region are indicated by blue colors appearing in the stir zone.

Friction stirring treatment effectively refines grains as shown in Fig.1(b), but the hardness decreases regardless of the smallest grain size in the present joint. This phenomenon is explained by taking into account the temperature during FSW. In this case, temperature in the stirred zone is reported to be higher than 700K [9], thus there must be a dissolution, or a decrease in the volume fraction of precipitates, during the joining, and in consequence the hardness decreases.

3.3 Orientation distribution

Figure 3 shows an example of orientation distribution in the center region of the onion ring. Fig.3(a) is an orientation distribution as a function of position, i.e., a spatial distribution of grain orientation that is represented by a color corresponding to each orientation represented in a unit stereo triangle. This orientation distribution is on the ND plane of the plate, and a corresponding normal pole figure of {111} orientation is shown in Fig.3 (b). The pole figure shows a weak concentration of {111} orientation about 10 degrees from the ND axis and the maximum value of the pole density is 2.0. Some other {111} orientation is scattered but located near the circle of the pole figure, suggesting that these {111} planes are nearly parallel to the rotation pin.

The spatial distribution in Fig.3 (a) shows some mixtures of orientation groups such as {111}, {110} and {100} as indicated by blue, green and red, respectively. Other orientation groups also exist in this figure. There are some clusters of grains having a similar orientation, but the size of clusters are not large enough to be recognized as a major orientation component in the pole figure. This heterogeneous distribution of orientation is not recognized based on a statistical analysis such as in the pole figure.

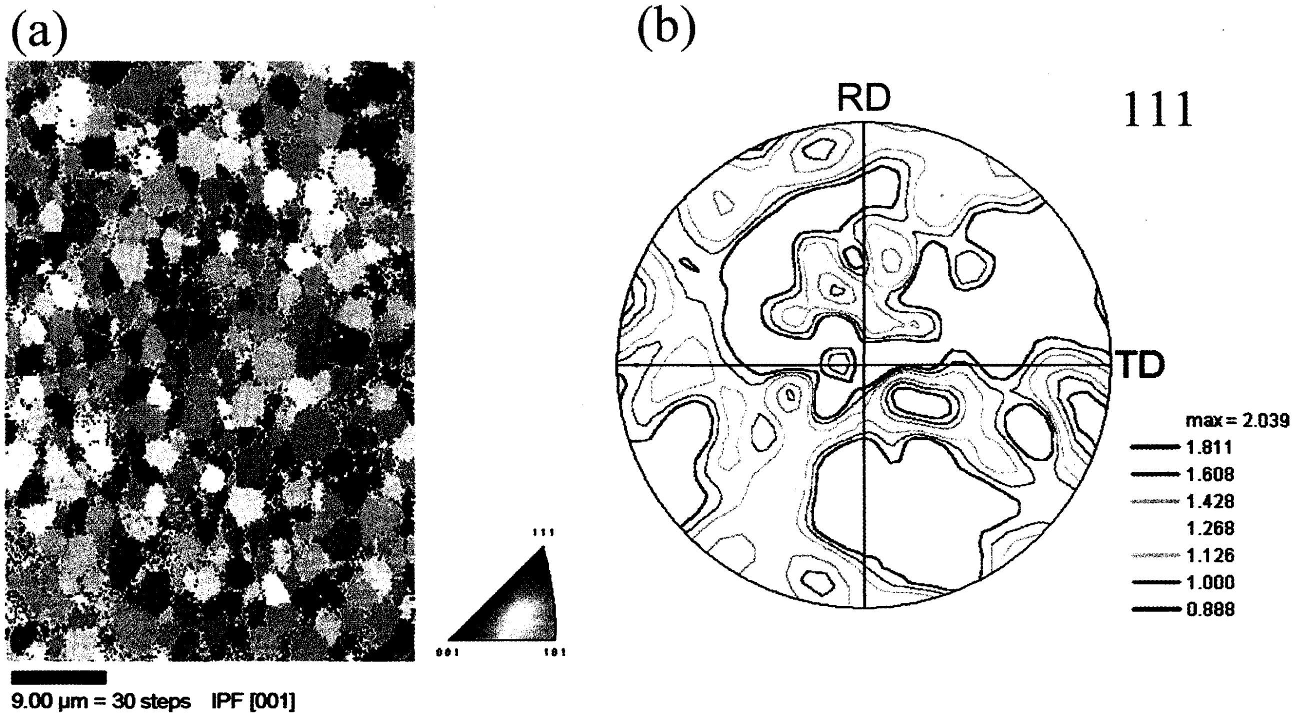

Fig.3 Orientation analyses for the central region in the stir zone of the FSW joint.
(a) a spatial distribution of the orientation on the ND plane, (b) {111} pole figure.

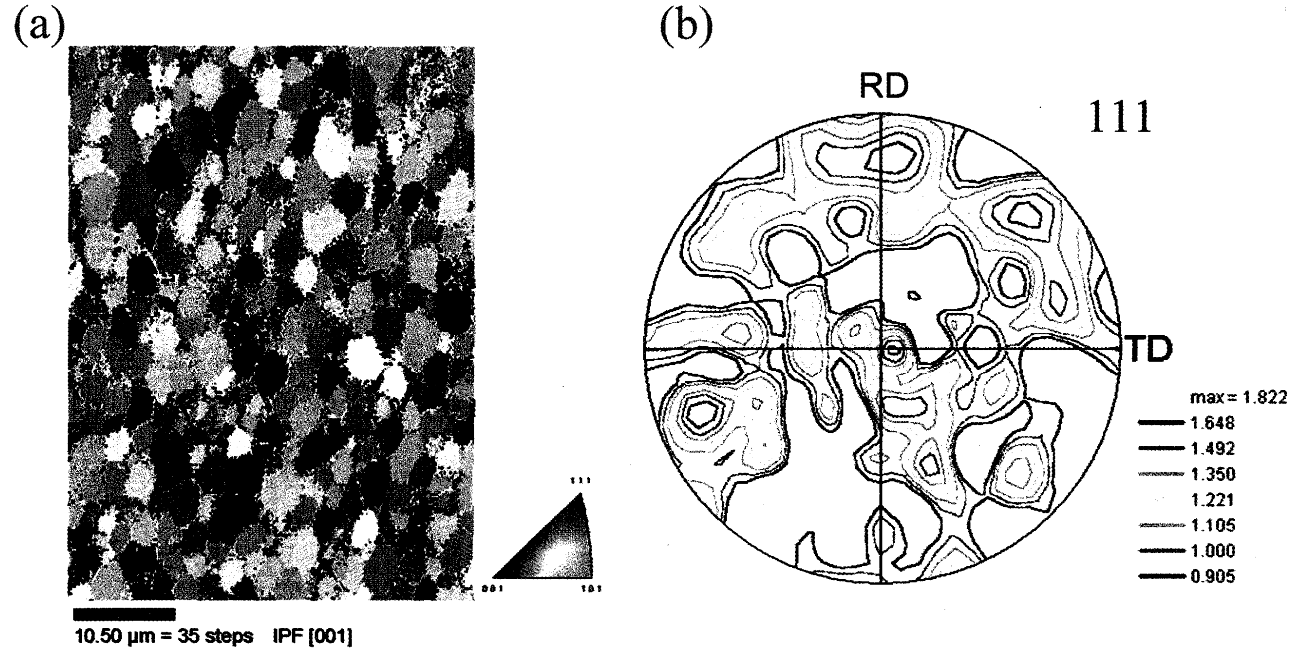

Fig.4 Orientation analyses for the middle region in the stir zone of the FSW joint.
(a) a spatial distribution of the orientation on the ND plane, (b) {111} pole figure.

Since grain boundary migration is affected by local grain boundary character distribution around each triple junction, these heterogeneous distributions of orientation may have a big influence on the evolutions of microstructure such as grain growth and texture development.

Figure 4 shows an orientation distribution map (a) and a pole figure (b) taken from a region between the center and the edge region in the onion ring. Grain size is almost similar to that in the central region shown in Fig.3 (a), but the grains are elongated a little along the direction of the thickness of plate. As compared with Fig.3, both the orientation map and the pole figure are different from those measured in the central region. There are some clusters of grains belonging to the orientation group close to {111} and the frequency of the cluster is larger than that observed in the central region. Meanwhile the {111} poles tend to exist near the circle of the pole figure as shown in Fig4 (b), but their positions are still different from those shown in Fig.3 (b).

Figure 5 shows an orientation distribution map and a pole figure taken from an edge region on the retreating side in the onion ring. In this region, there is a large cluster of blue colored grains, *i.e.* near {111}//ND oriented grains as shown in Fig.5 (a). In addition a {101}//ND cluster represented by the green color exists near to the {111}//ND cluster. Grain size in this region is also similar to those in the central and in the middle regions shown in Figs. 3(a) and 4(a). The pole figure in Fig.5(b) shows a concentration of {111} plane near the ND axis with the maximum pole density of 5.1. Similar to the results in the other two regions explained so far, {111} poles are also located near the circle, suggesting that {111} planes are nearly parallel to the pin.

Depending on the regions observed in the onion ring, different features of microstructure were obtained, such as statistical aspects of orientation distribution as described by pole figures, and spatial distributions of orientation as shown by the color mapping. However, a common characteristic of the orientation distributions is revealed as the tendency that {111} poles exist near the circle of each pole figure.

Figure 6 summarizes results of an extraction of grains having {111}//ND orientation with a tolerance angle of 10 degrees in the three regions of the joint represented in Figs. 4 to 5. Arrows in each pole figures are the {111} poles that were utilized for picking up the grains. Darker grains have {111} planes closer to the ND axis. Most of grains satisfy the pick-up condition, suggesting that {111} planes have a strong tendency to be nearly parallel to the ND direction or the direction of pin.

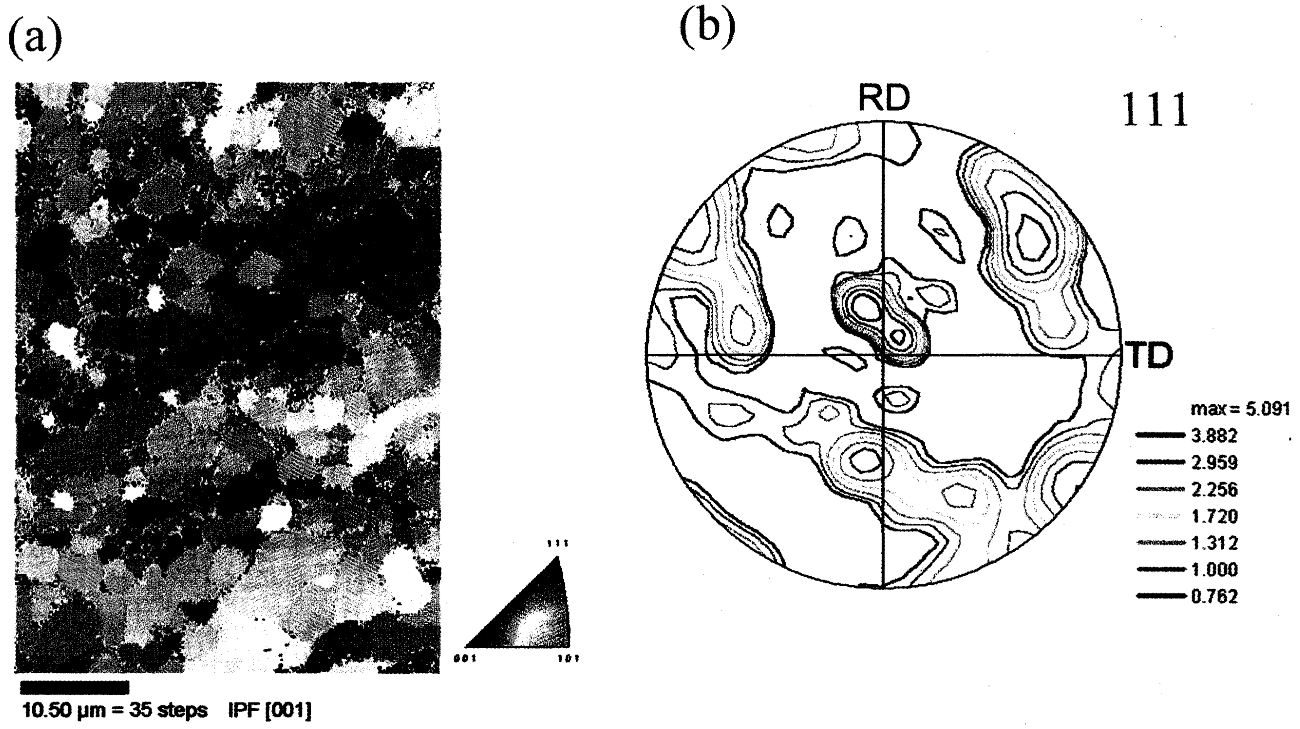

Fig.5 Orientation analyses for the edge region in the stir zone of the FSW joint.
(a) a spatial distribution of the orientation on the ND plane, (b) {111} pole figure.

This result gives us a key to understanding the development of microstructures during FSW. Taking the metal flow around rotating pin into account, the evolution of microstructure will be discussed in the following.

In the FSW process, the rotating and moving pin leaves voids behind it, and these voids are spontaneously embedded by newly compacted metal that is carried from other regions. In this moment microstructure is evolving, and the successive additions in such localized regions at elevated temperatures makes the joint. There should be a strong shear deformation taking place around the rotating pin that yields the stirred zone. Since the shape of pin resembles a screw, an additional metal flow is occurring along the thickness direction. On the other hand, some other deformation modes should be considered since there is a strong constraint force caused by the shoulder that is pressing the metal. But for shear deformation during joining, the shear deformation plane is parallel to the pin in this case. Therefore the shear deformation at elevated temperature is thought to be an essential mode in the development of microstructure in the FSW joint, and we should focus on the relationship between texture formation and the deformation mode.

There are few reports on texture components of severely shear-deformed 7075Al alloys at elevated temperature where a dynamic recrystallization takes place. But it is worthwhile estimating the texture component taken from some reports dealing with orientation analysis on cold rolled Al and Al alloys, where shear deformed regions exist in a surface region.

According to these reports, particular orientation components becomes the main component such as: {111}//P [10] and {100}//P [11,12] for cold rolled sheets of pure Al, {112} for an equal channel angular extruded (ECAE) Al-0.13%Mg alloy [13], where P means a shear deformation plane. In addition, a {111}//ND relationship was observed for a major texture component in some Al alloy sheets that were cold rolled and annealed [14].

Assuming that the relationship of {111}//shear deformation plane holds in the case of FSW, the result shown in Fig.6 can be explained by the shear deformation in the complex flowing of metal around the pin. Moreover, in the present case {111} orientation is a quite an important microstructure factor since many grains have the same tendency of possessing {111}//ND orientation. This orientation analysis would lead to “orientation marking” that enables us to investigate the shear deformation in the flowing metal during FSW.

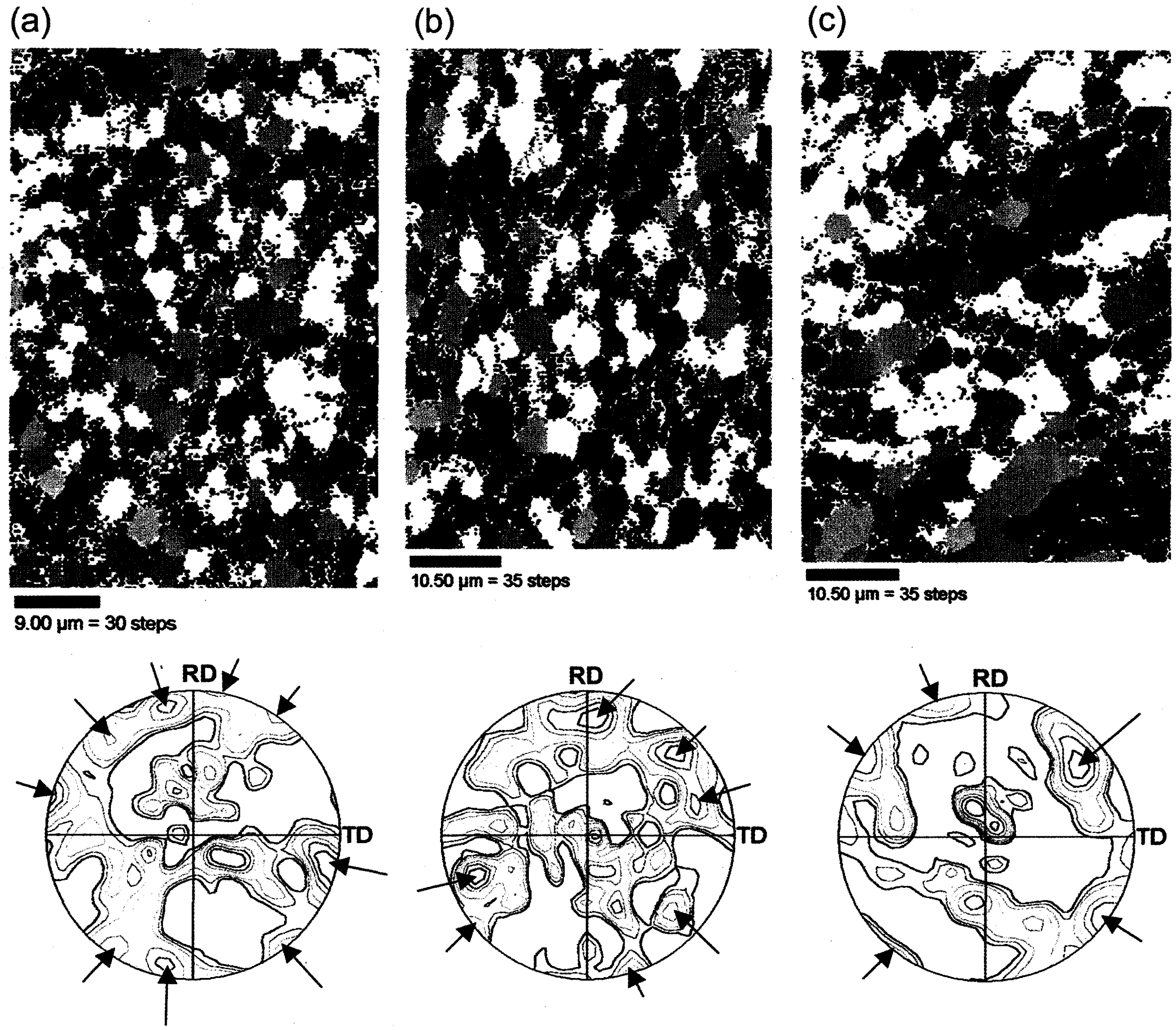

Fig. 6 Spatial distributions of orientation highlighting {111} planes that are parallel to the rotation axis (ND axis on the pole figures). Arrows indicate the poles used for the extraction of the grains.
(a) central region, (b) middle region and (c)edge region.

4. Summary

Microstructures and hardness of a friction stir welded 7075 Al alloy plate were investigated, especially focusing on the orientation distributions in the stirred zone. The following results were obtained.

(1) The stirred zone consisted of three regions along the thickness direction: a heterogeneously stirred region affected by the rotating tool, a grain refined region called onion ring, and an insufficiently stirred region containing a kissing bond. The onion ring has an asymmetric shape having larger size on the advancing side.

(2) Hardness decreased in the order of base metal, TMAZ, HAZ and onion ring, although the friction stirred region showed the finest grain size. The softening behavior in the onion ring region could be caused by dissolution of precipitates during friction stir welding.

(3) A weak texture component as (111)//ND and especially (111)//rotation axis component were observed in each region measured in the onion ring, although these regions showed different pole figures and spatial distributions.

Acknowledgement

This paper was financially supported by Grant-in-Aid for scientific research (B: project No. 13450295) and

Grant-in-Aid for Exploratory Research (project No.15656185). One of the authors (T.S.) is grateful to Prof. T.Sakai and Ms. F.Seki for their helpful discussion and suggestion.

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