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Material Flow, Stir Zone Growth and Complex Deformation Modes in Friction Stir Welding of Single Crystal Pure Aluminum

Toshiya Shibayanagi[1], Kenzo Mizushima[1], Adrian Gerlich[2], Thomas North[3] and Kenji Ikeuchi[1]

[1]Joining and Welding Research Institute (JWRI),
Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka, Japan.
[2]Department of Chemical and MaterialsEngineering,
University of Alberta, Edmonton, AB, Canada T6G 2V4.
[3]Department of Materials Science and Engineering,
University of Toronto, 184 College St., Toronto, Canada M5S 3E4.

Single crystal pure aluminum sheet was subjected to friction stir spot welding and seam welding in order to clarify the evidence of complex deformation modes proceeding around the welding tool. Friction stir spot welding was performed utilizing a welding tool with a shoulder of 10mm in diameter and a 2.2mm long M4-threaded pin. The welding process was divided into three parts as a function of plunging depth and dwell time such as; (1) 0.9mm of plunging depth where shoulder did not touch the sample surface, (2) 2.4mm in plunging depth where the shoulder just touched the sample surface and no dwelling, (3) dwelling for 2s as the pin was plunged to 2.4mm deep, which is a conventional dwell time for the spot welding. Stir zone grew only when the shoulder touched the sample surface and in accordance with the stir zone growth compression stress field appeared to affect the orientation change from <010>//TD towards <110>//TD which is the stable orientation for FCC metals under compression stress. Thus the metal flow around the rotating pin yields the formation of stir zone and the stir zone does makes the neighboring matrix to deform plastically by compression mode. Besides this compression mode the shear deformation also plays a dominant role in the formation of microstructure of the joints. Friction stir seam welding also showed similar orientation distributions while the asymmetry appeared suggesting some additional material flows affect the growth mode of stir zone together with the deformation modes during welding.

Keywords: *single crystal pure aluminum, friction stir spot welding, friction stir welding, EBSD, texture analysis, compressive stress*

1. Introduction

Friction stir welding (FSW) is well known to be developed to join aluminum alloys[1] and is now expanding its possibility of being applied to fabricate trains, aircrafts, ships, bridges and so on. Together with such progress in industry, scientific approach has been also proceeding in terms of flow visualization[2], material flow models[3], deformation process[4], evolution of microstructure[5], mechanical properties[6]. Metal flow around the welding tool is an essential problem to understand the mechanism of joining as well as the uniqueness of microstructures produced in the stirred zone of the joints.

A concrete flow model is proposed for the case of friction stir spot welding (FSSW) in which the welding tool is just moving up and down along the vertical direction [7]. This model describes two individual flows such as the upper flow coming down from the shoulder contacted region of the material and the second flow coming up along the extremity of stir zone. These two flows come into contact at a position and swallow up into the helical vertical rotational flow around the probe and finally reach the tip of the probe and ejected to the inside of stir zone that is also rotating. The stir zone grows by the successive occurrence of this material transportation process.

Bearing this flow model in mind, it is reasonable to have an image of complex deformation modes in FSSW, and indeed a compressively stressed region has been found besides the well known shear-deformed region in single crystal pure aluminum sheets [8]. However the development process of e compressively stressed region is not made clear regarding the growth of stir zone during FSSW. Additionally FSW may show more complicated mode of deformation yielding asymmetry of orientation distribution.

The present study tries to describe the deformation mode around the probe during FSSW and FSW of single crystal pure aluminum sheets in terms of orientation distribution.

2. Experimental Procedure

2.1 Preparation of single crystals

A single crystal pure aluminum of 99.99 mass% was grown in a Bridgeman-type furnace. After removing oxide film on the grown crystal, the ingot was cut into sheets of 20 by 20 by 4 mm^3 and 57.5 by 17.5 by 4 mm^3 for FSSW and FSW tests, respectively.

The present study adopted two kinds of single crystals with different orientations as shown in Fig.1. One is [001]//ND and [100]//TD oriented, and the other has the orientation of [111]//ND and [112]//TD. The former crystal was subjected to FSSW tests and the latter one was for FSW tests.

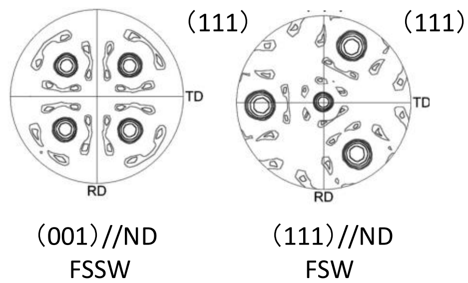

Fig. 1 Initial orientations of single crystal Al.

2.2 Friction stir spot welding

The spot welding tests were performed at a fixed tool rotation speed of 1500RPM utilizing a welding tool comprised of a threaded probe with M4-tapered and three-flat profile of 2.2mm in length and a shoulder of 10mm in diameter. These two parts have the same axis of rotation, i.e. the probe is at the center of the shoulder. The welding tool is made of SKD61 tool steel. The present welding tests adopted following three conditions in order to make clear the effect of stir zone growth on the deformation modes in the region of base crystal adjacent to the periphery of stir zone.

(a) The probe is plunging into the sample but the shoulder is apart from the surface.
(b) The shoulder is retracted immediately just after it touches the sample surface.
(c) The shoulder was inserted into the sample by 0.2mm deep and dwelled for 2s, followed by the retraction.

2.3 Friction stir seam welding

Welding tool utilized for the seam welding tests consists of a probe and a shoulder, which is made of SKD61 tool steel. Probe has a profile of M4-tapered right screw of 2.2mm in length, which is at the center of the shoulder of 10mm in diameter. The welding tests were performed at a fixed tool rotation speed of 1500RPM and a traveling speed of 30mm/min. The tool inclined 3° to the backward along the welding direction.

2.4 Evaluation of microstructures

Each welded sample was cut with an elctro-discharging cutting machine along the line on the center of keyhole caused by the retraction of welding tool. A seriese of Mechanical and electrolytic polishing processes on the cross section of samples yielded surface for microstructural observation as well as the determination of orientation with SEM-EBSD(Electron Back-Scatter Diffraction) method. The electro-polishing was performed at -20°C and DC 20.0V using a mixed solution of perchloric acid and ethanol with the volume ratio of 1 to 9.

3. Results and Discussion

3.1 Orientation distributions in friction stir spot welded samples

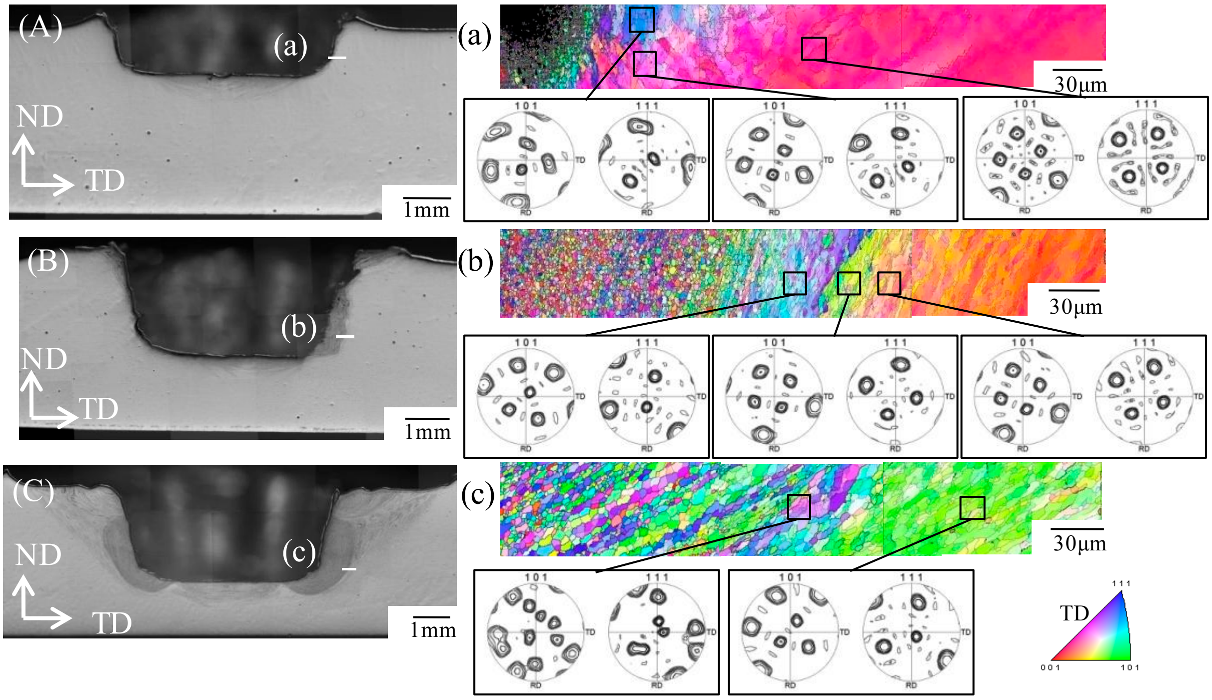

Fig. 2 Cross sections of friction stir spot welded high purity aluminum samples.
(A), (B) and (C): macroscopic image showing stir zone with dark contrast.
(a), (b) and (c): Orientation distributions represented by IPF maps and pole figures.

Figure 2 shows the orientation distributions along the TD direction in the stir zone and its peripheral region of the friction stir spot welded samples. The orientation measurements were carried out along the white line indicated in each cross sectional image such as (A), (B) and (C). The corresponding results are shown in (a), (b) and (c). The color coded image (called inverse pole figure map) represents the orientation distribution in which each color denotes a unique orientation shown in the unit triangle. For example {110} region is represented by green color. Pole figures of {101} and {111} are also imposed on each IPF map, indicating the texture components in the corresponding box.

As the welding process goes on, the orientation showed a remarkable change from [100]//TD to the other components. At the first stage where the shoulder didn't touch the surface, which is shown in Fig.2 (B) and (b), almost all the area has the similar orientation to that of base crystal. Only the peripheral region of stir zone shows [111]//TD which suggests a shear deformation. The second stage is the onset when the shoulder touched the surface. In this case, as shown in Fig.1(B) and (b), stir zone starts to grow and resulting fine grain region appears and also a big variety of the orientation distributions containing [111] as shear deformation and small amount of [110] region where compressive deformation is thought to be dominant. This means stir zone growth affects the appearance of compressive stress, and the last stage of spot welding clearly shows the role of stir zone growth in the development of compressive mode, which is shown in Fig.1(C) and (c). In this image large area of [110]//TD appears, therefore one can conclude that FSSW is a high temperature deformation where different deformation modes takes place depending on the location in the material being welded.

3.2 Orientation distributions in friction stir welded samples

FSW is expected to possess more complicated metal flow than that in FSSW since the welding tool travels in this welding method. However the essential mechanism of metal flow around the probe is thought to be the same no matter what additional flows may occur around the probe or beneath the shoulder. Therefore the compressive stressed region should be observed in the friction stir welded samples.

Figure 3 represents orientation distributions on the cross section perpendicular to the welding direction of friction stir welded single crystal pure aluminum. Fig.3 (A) shows the macroscopic view across the center of keyhole, where dark contrast regions are recrystallized or heavily deformed regions containing low angle boundaries with high density. The boarder between the stir zone and base crystal looks much clearer on the advancing side than on the other side.

Orientation distributions of both sides are represented as IPF maps in (a) and (b), which correspond to the white lines along TD axis indicated in Fig.3 (A). On the advancing side, [112]//TD component appears as a major orientation in the region denoted “1” on the left end side of the map. This is the orientation of base crystal. Starting from this region as moving towards the stir zone the orientation changes gradually in the region “2” followed by an abrupt change into [110]//TD which appeared in the region “3”. The regions “3” and “4” are the compressive loaded region that are already observed in the FSSW tests. The width of these regions is about 250um. Region “5” turns to show near [112]//TD component again and this orientation changes into [111]//TD in the region”6” which suggests shear deformation caused by the rotating stir zone. Stir zone, represented by regions “7” and “8” is composed of fine grains with the average grain size of 5 um. It has a mixture of [100]//TD and [110]//TD orientations, but no concrete explanation for the orientation distribution has been successfully made so far.

The retreating side shows a similar tendency of orientation change as shown in Fig.3(c). The [110]//TD oriented region is observed in the region”6” with the width of about 50um, which is one fifth of that observed in the advancing side. Stir zone shows weak texture of a mixture of two or three components.

The present orientation analyses reveal some important features in FSW and FSSW. The common feature is the compressively stressed region which is represented by the [110]//TD orientation shown as green colored regions in the IPF maps. This means that FSW is a quasi-static welding process of

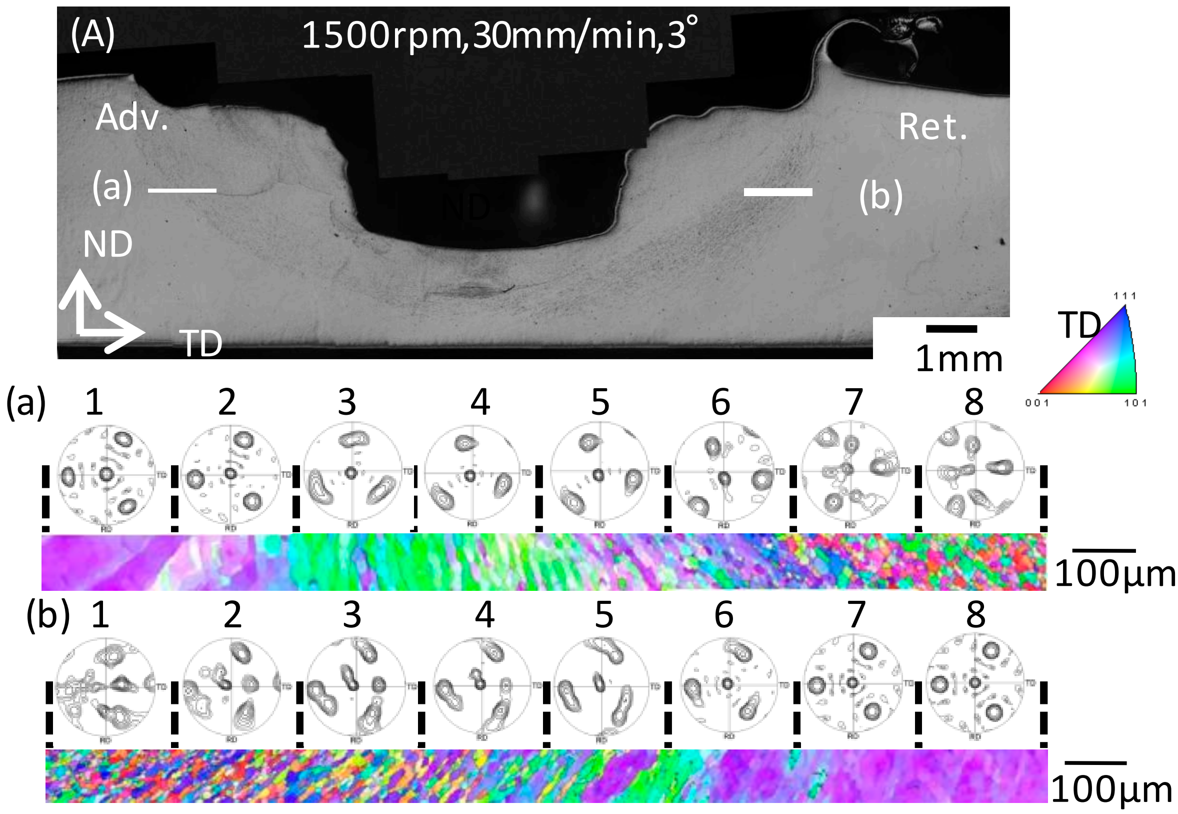

Fig.3 Cross sections of friction stir welded high purity aluminum samples.
(A), (B) and (C): macroscopic image showing stir zone with dark contrast.
(a), (b) and (c): Orientation distributions represented by IPF maps and pole figures.

FSSW when it is described in terms of metal flow around the rotating probe. However the other important feature should be recognized, that is the anisotropy of metal flow and its resulting complex deformation modes.

Regarding some previously proposed flow models of FSW, the advancing side is predicted to experience severer deformation than that on the other side because of the counter flow on this side. But this explanation can only hold only if the velocity of the tangential component of metal flow at the extremity of stir zone is much slower than that around the rotating probe since the welding speed is negligibly slower than that of the ideal tangential speed at the probe surface. Further experiments are required to prove and explain the asymmetric behavior of metal flow and it resulting deformation modes which are detected by orientation change in single crystals.

Summary

Single crystal pure aluminum plates were subjected to friction stir spot welding and friction stir welding. The orientation analyses with SEM-EBSD method revealed that stir zone growth produces compressive loading to its surrounding region in the material being welded in case of FSSW. The compressively stressed regions also appeared even in the friction stir seam welding although the asymmetry of deformation between the opposite sides such as advancing and retreating is newly observed. This feature is a key to understand the mechanism of metal flow which should be well understood and precisely controlled for the sake of producing dependable FSW joints.

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