Microscopic Observations of Friction Stir Welded 6061 Aluminum Alloy*1

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1. Introduction

Friction stir welding (FSW) is a solid state technique invented at the TWI (Cambridge, U. K) in 1991.1) It is a valid welding technique for joining aluminum alloys that are difficult to weld by a fusion process and can be applied to a large number of aluminum alloys. Recent studies report investigation of textural gradients associated with FSW and dynamic recrystallization in pure Al 1100,2–4) and suggest that the fine grain structure formed within the center of the welded zone is produced by dynamic recrystallization. Aerospace industry material 2024 Al alloy was also investigated in the evolution of the grain structures by EBSD.5) Microstructure of 5182 Al alloy before and after FSW were both examined.6) Murr et al. presented a detailed analysis of precipitation and precipitation-related microstructures in friction stir welded 6061 aluminum utilizing conventional transmission electron microscopy.7,8) Although the FSW process has greatly developed, both in tool design and materials that have been successfully welded, there are still many uncertainties concerning the microstructural evolution that occurs during this process. The area surrounding the welding stir zone in 6061 Al alloy, for example, the thermo-mechanically affected zone (TMAZ) or the boundary between the TMAZ and the welding stir zone, have not yet been fully investigated.

The purpose of this paper was to utilize the new technique of high resolution electron back scattered diffraction (EBSD) to investigate the grain and substructure formed during welding stir of the 6061-T6 Al alloy. This technique enables grain misorientations to be measured over large areas with a resolution of about 20 nm9) and can therefore obtain statistically significant quantitative data on the fine grain structures presented in FSW. We have tried to understand the microstructures and mechanical properties of these regions and to clarify the dynamic flow mechanisms in TAMZ.

2. Experimental Procedure

The material selected for this investigation was 6 mm thick 6061 Al alloy plates treated in the T6 condition. The chemical composition was as follows: Si 0.71, Fe 0.18, Cu 0.30, Mn 0.07, Mg 1.14, Cr 0.14, Zn 0.03, Ti 0.02, balance Al (all in mass%). The plates were held in compression and were rigidly clamped to the milling machine bed during welding. The diameter of larger shoulder and small pin, which is threaded, were 20 mm and 6 mm, respectively. The rotating tool was aligned flush along the contact line and parallel with the surface of the clamped metal plates. This created an integral joint by severe plastic deformation of the material affected by the passage of the stirring tool. In this report, the travel speed was 104 mm/min and the rotating speed was 1100 rpm.

After the welding stir process, specimens were cut into several sections, perpendicular to the welding direction. Specimens were mechanically polished first with 1000 grit and 1500 grit SiC paper and then with 3 μm diamond paste. The final polishing of these specimens was accomplished using colloidal silica. After polishing, specimens were etched in a nitric acid/methanol solution at 273 K. After these treatments, they were prepared for optical microscopic observation and EBSD measurement. EBSD measurement was conducted in a JOEL SEM, selecting the condition of 20 kV and 15 mm work-distance. A Vickers microhardness measurement that extended across the entire weld region was made using a load of 500 grams and a 15 seconds dwell time.

3. Results and Discussion

3.1 Optical microstructures

Figure 1 illustrates an overview of a typical friction stir weld in 6061 aluminum alloy plate. Several features are prominent in the friction stir welded material. The center portion in Fig. 1, as called in a stir weld zone, is dominated by a region deformed as the wedge-shaped microstructure, particularly in the lower branches, not in what is often
referred to as the nugget zone. The stir weld zone widens near the upper surface in contact with the rotating head-pin fixture, which is hereafter called the ‘shoulder region’. Next to the stir weld zone, affected by thermo and mechanical factors, the flow pattern of the microstructure is identified in the optical micrograph and is called the thermo-mechanically affected zone (TMAZ). In the area next to TMAZ, there is a region that is affected only by welding heat and is usually called the heat-affected zone (HAZ).

Figure 2 shows Vickers microhardness profiles of the specimens produced at the same tool rotation speed as used in Fig. 1. The hardness profiles were measured along the lines shown in Fig. 1. The most significant feature of the hardness profiles in Fig. 2 is the apparent width of the transition region influenced by the solid-state flow accommodating the friction stir weld process, which extends well beyond the apparent HAZ illustrated in Fig. 1. This hardness evolution, which merges with the work-piece or base metal hardness, occurs in large part from both the top to the bottom of the welded work piece and across or within the transition region (HAZ) between the weld zone and the work piece. The hardness data illustrates the uniformly general softening throughout the dynamically recrystallized weld zone and shows a very slight variance within the center of weld zone and from the top to the bottom of the weld. The average hardness of areas A and B marked by circles in Fig. 1 was measured and the value was 50 Hv and 66 Hv, respectively, suggesting that the slight variance in weld zone is associated with a microstructure homogeneous like that wedge-shaped microstructure. Figure 2 also illustrates a variation in hardness between the stir weld zone and the base (or HAZ) hardness of roughly 60 Hv. Thus the stir weld zone softening in general accounts for the hardness variance shown in Fig. 2.

3.2 The measurement of EBSD

Some representative regions of FSW are shown in Fig. 1; the orientation maps corresponding to these results are shown in Fig. 3. From these figures, it can be observed that the microstructure in FSW is not homogeneous. The strong dynamic plastic flow in TMAZ was exhibited not only on the advancing side (in 3(a)) but also on the retreating side (in 3(b)), as these flows had not been recrystallized. The recrystallization of grains was shown through the thickness of the stir weld zone.

Figures 4(a)–(c) show the microstructure in the center of the stir weld zone, which is the region just below the tool shoulder, in the center and the bottom respectively. A plastic deformation appears along the shoulder rotating direction in (a) and corresponds to the pole figure where the most intensity is 4.1, and in which the orientation is tilted. In this area average grain size is 9.2 µm. Figure 4(b) exhibits equiaxed grains formed in the center of the stir weld zone with an average size of about 9.6 µm, slightly larger than grains in the shoulder region. The strong orientation is exhibited in the pole figure associated with the greatest intensity increasing to 7.4; this is stronger than that in shoulder region. Equiaxed grains were also formed in Fig. 4(c), in which the average size is 5.3 µm. As shown, the bottom region is clearly the most refined area. In the lower portion in Fig. 4(c), there is a band that has a larger grain size than in the upper portion and this corresponds to the brighter wedge-shaped portion. This suggests that the change in grain size affects the hardness.
3.3 Dynamic flow mechanisms in TMAZ

To investigate the dynamic flow mechanisms, EBSD measurements of small regions were carried out. Figure 5 shows a typical OIM map for the base material area, TMAZ and the boundary between TMAZ and the stir weld zone that are marked in region C, D and E, respectively in Fig. 1. Different colors indicate different crystallographic orientations defined in the inverse pole figure. High angle boundaries with misorientations of more than 15°/C14 are delineated by thick black lines, while low angle boundaries in the range from 4°/C14 to 15°/C14 by thin lines. The base material microstructure is shown in Fig. 5(a) and the rolling microstructure is also shown. There are few low angle grains among the interior grains. The microstructure shown in Fig. 5(b) is distinctly different from that in 5(a). The grains tilt to one direction and are enlarged. It can be seen clearly that a strong flow plastic deformation has occurred in TMAZ, and also that a few fine grains have evolved along corrugated grain boundaries, new boundaries with low angle misorientation have developed in some regions near the corrugated boundaries, as indicated by G1, G2 and G3; these may be the nucleation sites of new grains. In fact, some new grain have already been formed, such as G4 and G5.

The fraction of low angle grains in this region has increased to 0.4 and it is clear that some subgrains and fine new grains have been formed. When the measurement region approaches the weld stir zone, ex. in region E, the large grains become smaller; this suggests that the mechanical effect in region E is stronger than in region D, grains rotate along the axis and are then screw cut into fine grains. Thus, friction heating and plastic flow during friction stir welding create fine recrystallized grains and recovered grains in the TMAZ.

The point-to-point misorientation (θ) was measured along the lines L1 indicated in Fig. 5(a), L2, L3 indicated in Fig. 5(b) and L4 indicated in Fig. 5(c). The θ values give the relative difference of crystal orientation between two adjacent scan points. Figure 6(a) shows the results for θ along line L1 and indicates that in the grain interior the θ region is lower than 1°; this corresponds to the lack of dislocation in the grain interior in 5(a). Scan line L2 indicated in Fig. 5(b) indicates that the θ region is lower than 4°, and a few low angle subgrains have been formed. Scan line 3, which is also in Fig. 5(b) but in different grains, has the θ region from 0° to 15°, but exceeds 15° at two places. Figure 6(c) shows the result from scan line L4 in Fig. 5(c) and discontinuously changes in many places. The fraction of large angle grains has increased remarkably to 0.8, suggesting that many fine new grains have been formed.
4. Conclusions

EBSD analysis has been successfully used to study the microstructure formed during friction stir welding of a 6061 Al alloy.

(1) In TMAZ, severe plastic deformation is appeared for heat and mechanically affecting and subgrains are formed for grains rotating along a axis as for the grain plastic flow.

(2) The equiaxised grains are formed in the center of welded area.

(3) The vikkers hardness is the lowest in welded area and the same result was obtained by EBSD measurement.

REFERENCES


Fig. 6 Point-to-point misorientations $\theta$ measured along the lines (a) L1 marked in Fig. 5(a), (b) L2 marked in Fig. 5(b), (c) L3 marked in Fig. 5(b), (d) L4 marked in Fig. 5(c).