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A study on microstructure and strain-hardening rate of friction stir welded Al-Mg-Si alloys using a weak beam technique

E. Sukedai and T. Yokoyama
Okayama University of Science, Okayama 700-0005, Japan
E-mail: sukedai@mech.ous.ac.jp

Abstract. Mechanical properties of a friction stir welded Al-Mg-Si (6061-T6Al) alloy are evaluated by a tensile test. It is found that the strain-hardening rate is higher than that of a base material. In order to investigate the origin, TEM observations have been performed about 4 kinds of materials; base- and friction stir welded-materials, and both materials deformed to 5 % strain by tension. There are not so large differences about dislocation density, size and density of precipitates and crystal defects between the base material and the friction stir welded-materials, but a significant decrease of grain-size in the friction stir welded-materials is recognized. These results suggest a dynamic recovery occurs during FSW process, and it is speculated that the recovery leads to the differences of yield stress and strain-hardening rate between both materials.

1. Introduction
Friction Stir Welding (FSW) method is relatively a simple method, and it has been widely applied to weld light metals such as Al, Mg and Ti alloys. Therefore, this method has been widely used in many industrial fields such as automobile, railway carriage and air-plane companies. In order to redound the reliability of this method, many kinds of mechanical properties of friction stir welded materials (FS welds) have been studied 1-3). It is reported on tensile properties of FS welded Al-Mg-Si (6061-T6Al) alloys that strain-hardening rates of their stress-strain curves are higher than those of the base materials 4, 5). Instinctively, the difference of dislocation density between FS welds and base materials is visualized. Therefore, the dislocation density of a FS welded 6061-T6Al alloy has been measured by X-ray peak profile analysis method 4). However, before FSW process, the 6061-T6Al alloy sheets were thermal refined, i.e. solution treating and aging. Therefore, changes of not only dislocation density, but also microstructure due to the FSW process are considered as important factors to decide mechanical properties, including the phenomenon of strain-hardening rates.

In the present study, to elucidate the origin of the increase in strain-hardening rate of a FS welded 6061-T6Al alloy, microstructures of (1) the base-material and a FS welds, and (2) both materials deformed to 5 % strain by tension have been investigated using a transmission electron microscope (TEM) observation method, especially a weak beam technique, which is probably the best technique to observe dislocations and crystal-lattice defects 6).

2. Experimental procedures
A material used in the present study is a 6061-T6Al alloy sheet and the chemical composition was 0.4-0.8 % Si, 0.8-1.2 % Mg, Fe, Cu, Mn etc, and balance of Al (mass%). The sheet was thermal refined by a solution-treating at 788-823 K, followed by aging at 428-438 K for 18 hrs. FSW conditions were as follows; the rotation speed of the rotating tool was 2000 rpm and welding speeds of specimens A, B and C were 600, 900 and 1200 mm/min, respectively 5). The FSW process was carried out along the rolling direction. Hardness testing on a cross-section perpendicular to the FSW direction was performed. Tensile testing was carried out at a strain rate of 6.2 x 10^{-4}/s. Tensile tests of FS welds were performed to obtain data from FS welds part (weld nugget = WN) as follows; as the width of WN is approximately 25 mm 5), an extensometer with a gauge length of 25 mm was used. Stress-strain...
curves obtained prove almost tensile properties of WN parts. For TEM observations, thin-foil specimens of the base material, a WN part of FS welds A, and both of them deformed to 5% strain were prepared. A JEM 2010F electron microscope operated at 200 kV was used for the observations.

3. Results and discussion

3.1. Stress-strain curves and grain sizes of base material and FS welds

Figure 1 indicates tensile stress-strain curves for the base material and the three FS welds. The tensile strength and ductility of the base material are greatly reduced by FSW process. It is obvious that the yield and tensile strengths of the FS welds A, B and C remain almost unchanged, and they are lower than those of the base material. The elongation of a FS weld A decreases compared with that of the base material. In Fig. 1, it is also clear that strain-hardening rates of FS welds are higher than that of the base material; that is approximately 2 times higher at 3% and 5% strains. In order to elucidate the origin on this phenomenon, the TEM observation was carried out and the results will be discussed in the following section.

It is also known that grain sizes affect the yield and tensile strengths of many kinds of materials. So, grain sizes of a base material and a FS weld A were measured. While the average grain size of the base material, measured by an optical micrograph is approximately 150 µm, the size of a FS weld A is 3-7 µm, estimated by a TEM figure shown in Fig. 2. A significant decrease in grain-size due to FSW process was recognized. The decrease of grain-size in Al alloys due to a FSW process has been reported.

3.2. TEM observation results of base material and FS weld A

Figure 3 (a) and (b) show results of the base material and the FS weld A, respectively. In Fig. 3(a), dislocation segments (see an arrow d), a large number of small defects in 20-40 nm length and bright dots are visible. The small defects are parallel to two directions, and as their visibility depends on reflection conditions, they might be dislocation segments. High resolution EM images indicate many stacking faults parallel to {111} slip planes. Since two directions of small defects are not consistent with the traces of {111} planes, small defects are not stacking faults. In addition, it seems that metastable phases are not observed because of the thermal refining. Bright field images indicate rod- and round-shape precipitates in 100-150 nm in length and 30-50 nm in diameter. The microstructure shown above results from a rolling, followed by the thermal refining. In Fig. 3(b), a few dislocation segments are visible. A large numbers of small defects in 20-80 nm in length also appear parallel to two directions, which are not consistent with slip-plane traces. It is found that the density of small defects is lower than that of the base material. The decrease in the density is considered as a result
from heating due to the FSW process. An arrow indicates a round shape precipitate in 150 nm in diameter.

Figure 4(a) and (b) indicate results of a 5% strained base material and a 5% strained FS weld A, respectively. In Fig. 4(a), it is recognized that dislocation density increases and small defect density decreases compared with the base material (Fig. 3(a)). In Fig. 4(b), dislocation lines can be seen clearer than those of the 5% strained base material, and in the matrix, few defects are visible. It seems considered that many dislocations swept out them due to their interactions.

Figure 5 shows an image of dislocation-lines on a slip plane \{111\} of a 5% strained FS weld A. Long and uniformly distributed dislocation lines are visible, and small defects and bright dots are hardly observed. A comparison of Fig. 5 and Fig. 4(a) makes us speculate that dislocation motions in FS weld A are easier than those in the base material.

Figure 5 shows an image of dislocation-lines on a slip plane \{111\} of a 5% strained FS weld A. Long and uniformly distributed dislocation lines are visible, and small defects and bright dots are hardly observed. A comparison of Fig. 5 and Fig. 4(a) makes us speculate that dislocation motions in FS weld A are easier than those in the base material.

From the results mentioned above, it is found that a significant decrease in grain-size, and also a few decrease in densities of dislocations and small defect occurred due to FSW process. The decrease in grain-size suggests that a dynamical recovery occurred and consequently, a relaxation of internal stress and a softening in the base material occurred. Therefore, it is considered that one of the origins for the
decrease in yield stress of FS weld A is the dynamic recovery. About the increase in strain-hardening rate of FS weld A, two possibilities are speculated on a prediction that strain hardening results from interactions between dislocations and obstacles such as dislocations, precipitates and grain boundaries: 1) Figures 4(b) and 5 suggest the moving distance of dislocations in 5 % strained FS welds is longer than that of 5 % strained base materials. As the result, it is considered that the probability of the interactions in FS welds is higher than that in base materials. This leads to increase the strain-hardening rate of FS welds. 2) The flow stress of base materials is higher than that of FS welds. This higher flow stress might help to enhance for dislocations to surmount the obstacles due to the interaction. This leads to decrease the strain-hardening rate of the base materials. In addition, the problem about elongation of FS welds will be a future one because of lack of TEM observation results.

4. Summary
1) A significant difference of microstructure between the base material and a FS weld A due to FSW process is a decrease in grain size. The decrease was caused by a dynamic recovery during the process. 2) The dynamic recovery occurs a softening of FS weld A and a decrease in the yield stress. 3) Dislocation density in the 5 % strained base material is much higher than that of a 5 % strained FS weld A. This result suggests that a strain-hardening rate of base material is saturated. Observed long and isolated dislocations in the 5 % strained FS weld A suggest that these dislocations lead to increase the strain-hardening rate.

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