Friction Stir Welding of a Commercial 7075-T6 Aluminum Alloy: Grain Refinement, Thermal Stability and Tensile Properties

Alexandre Goloborodko¹, Tsutomu Ito¹, Xiaoyong Yun², Yoshinobu Motohashi¹ and Goroh Itoh³

¹Research Center for Superplasticity, Faculty of Engineering, Ibaraki University, Hitachi 316-8511, Japan

²Graduate student, Ibaraki University, Hitachi 316-8511, Japan

³Department of Mechanical Engineering, Faculty of Engineering, Ibaraki University, Hitachi 316-8511, Japan

Commercial 7075-T6 aluminum alloy was subjected to friction stir welding (FSW), resulting in development of a fine-grained structure with average size of about 3 μm in the nugget zone. Static annealing at temperatures ranging from 623 to 773 K for 30 min showed that the fine grain microstructure was stable at temperatures not higher than 723 K. Increase in annealing temperature up to 773 K led to an abnormal grains growth, followed by the development of mm-scale grains. The specimens obtained from the nugget zone demonstrated a superplastic behavior at temperatures ranging from 623 to 723 K and at strain rates ranging from 1×10^{-4} to $1 \times 10^{-2} \text{ s}^{-1}$. Large elongation of about 440% was observed at a temperature of 673 K and at a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$.

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1. Introduction

Friction stir welding (FSW) is a relatively new solid state welding technique for metallic materials, especially for aluminum alloys.¹⁻³⁾ The FSW was first developed at The Welding Institute (TWI) of the UK in 1991.⁴⁾ The basic concept of FSW can be briefly described as follows. A rotating tool with a pin and shoulder is inserted in the materials to be joined and traversed along the line to be joined. Frictional heat is generated by the contact between the rotating tool and the joint workpiece. This localized heating results in a softening and a plasticization of materials. The softened workpiece is severely plastically deformed by the mechanical stirring action of rotating headpin, *i.e.* a complex movement of the constituent metal around the pin arises. In this way, the material is subjected to intense plastic deformation at elevated temperatures. Recent studies have demonstrated that FSW provides the potential for refining the grain size of a joint material down to the submicrometer level in the friction stir welded zone.¹⁻³⁾

The reduction in grain size to the submicrometer level has two significant advantages. First, there will be an increase in the tensile strength with little or no corresponding reduction in the overall ductility at ambient temperature. Second, if the ultra-fine grained microstructure is stable at elevated temperatures where diffusion is reasonably rapid, there will be a possibility of achieving superplasticity: there have been several studies on this effect by using aluminum alloys.⁵⁻⁷⁾

The present investigation was initiated with two objectives. First, to investigate the practicability of significant grain refinement in a commercial 7075 aluminum alloy by using FSW technique and the characteristics of developed microstructure. Second, to examine the tensile properties of this friction stir welded (FSWed) material at room and elevated temperatures and to critically evaluate the thermal stability of the fine-grained microstructure developed.

2. Experimental Procedure

The material tested was a commercially produced 7075 aluminum alloy with the following chemical composition: Zn 5.59, Mg 2.63, Cu 1.52, Cr 0.24, Fe 0.21, Si 0.07, Mn 0.06, Ti 0.02 and balance Al (all in mass%). The alloy was hot-rolled in plate of 3 mm thick and subjected to a normal T6 temper treatment by Kobe Steel Ltd.; this material will be referred in the text as the as-received material. The initial microstructure consisted of large elongated pancake shaped grains typical for a hot-rolled and subsequently T6 tempered structure, as can be seen in Fig. 1. Fine precipitates with sizes smaller than 100 nm were evident in original grain interiors and in (sub)grain boundaries (Fig. 1(b)).

Strips with 50 mm wide were cut from the rolled plate to prepare samples for FSW. One side surface of the strips to be FSWed was polished and then butt-welded together. The FSW was carried out at a tool rotation speed of 1500 rpm and at a traverse speed of 300 mm min⁻¹. For investigation of the thermal stability of the nugget zone microstructure of FSWed samples, they were heat treated in an air furnace for 30 min at temperatures of 623, 673, 723 and 773 K and then quenched in water.

Samples for optical microscopy, electrons back scattering diffraction pattern (EBSP) and transmission electron microscopy (TEM) analyses were cut from FSWed zone. All investigations were carried out for central part of welded zone. Keller's reagent was used to reveal microstructures in as-received and FSWed materials. Metallographic analysis was completed with an Olympus BX60 optical microscope. The EBSP investigation was performed in a Hitachi S-4300SE scanning electron microscope (SEM) with OIM™ software. A Hitachi H-800 TEM operating at an accelerating voltage of 200 kV was used for examination of fine structure. Grain sizes were measured by the linear intercept method.

Tensile properties of the FSWed materials were examined. The dog-bone shaped specimens with a gage length of 6 mm and a width of 3 mm were cut from the materials perpendicular to the welded direction. For the FSWed materials, the

Fig. 1 Typical microstructure of as-received 7075 Al alloy. (a) Optical and (b) TEM micrographs.

nugget region was centered within the gage length. The tension tests were conducted at room temperature and temperatures ranging from 623 to 723 K and at initial strain rates ranging from 1×10^{-4} to $1 \times 10^{-2} \text{ s}^{-1}$. Temperature was controlled with a thermocouple located around the sample. The temperature was controlled within $\pm 5 \text{ K}$. The as-received material was examined under the same conditions mentioned above.

3. Results and Discussion

3.1 Microstructure developed under friction stir welding (FSW)

Typical microstructures of the FSWed 7075 Al alloy are shown in Fig. 2. Fine-grained microstructure is formed in the stirred zone, as shown in Fig. 2(a). It is evident that equiaxed fine grains with average size of about $3 \mu\text{m}$ are developed homogeneously in the whole area within the nugget zone. A typical TEM microstructure developed under FSW and associated selected area electron diffraction (SAED) pattern are presented in Fig. 2(b). No dislocation substructure is observed in the inside of newly formed fine grains. Most part of grain boundaries developed has high angle misorientations, as demonstrated by SAED pattern. It is also seen in Fig. 2(b) that there are many second phase particles along the boundaries and also in grain interiors.

Typical orientation imaging microscopy (OIM) picture

Fig. 2 Typical microstructure developed in 7075 Al alloy during FSW. (a) Optical and (b) TEM micrographs.

and misorientation angle distribution for the FSWed 7075 Al alloy are represented in Fig. 3. In this OIM map, orientation differences, Θ , between neighboring grid points, $\Theta > 2 \text{ deg}$, $\Theta > 5 \text{ deg}$ and $\Theta > 15 \text{ deg}$ are marked by a thin white, narrow and bold black lines, respectively. It is confirmed in Fig. 3(a) that FSW results in the formation of a fine grain microstructure within the nugget zone. The grain structure is homogeneous in whole area and crystal orientations of such grains are rather randomly distributed, as can be seen by different gray scale. The boundary misorientation distribution formed during the FSW shows a bimodal distribution (Fig. 3(b)). About 90% of boundaries have, however, high angle misorientation, *i.e.* $\Theta > 15 \text{ deg}$. These results agreed well with the data reported by Charit and Mishra,⁸⁾ who found that a fraction of high angle boundaries in the friction stirred region of a 2024 Al alloy is about 85%. It is interesting to note that the misorientation distribution developed under FSW except for the low angle misorientations, *i.e.* $\Theta < 5 \text{ deg}$, region approaches a theoretical distribution for random orientations of fully annealed grains in cubic materials derived by Mackenzie,⁹⁾ as shown by dashed line in Fig. 3(b). The average value, Θ_{av} , of 37.7 deg is rather smaller from that for the Mackenzie distribution, *i.e.* 41.2 deg , because of large fraction of low angle misorientations, *i.e.* $\Theta < 5 \text{ deg}$. This should be a characteristic of the grain structure dynamically evolved.^{10,11)}

It can be concluded from Figs. 2 and 3 that the FSW is an

Fig. 3 (a) Typical OIM picture of the microstructure developed and (b) misorientation angle distribution of the FSWed 7075 Al alloy.

effective method for producing of fine-grained microstructure with high angle boundaries. The FSW of the present 7075 Al alloy results in the formation of fine grains with average size of about 3 μm in nugget zone. It seems that the formation of fine grains taking place during FSW process can result from some kind of continuous reaction, which is similar to continuous dynamic recrystallization (CDRX).¹²⁾ Jata and Semiati¹³⁾ showed that CDRX through a dislocation-glide-assisted-subgrain rotation mechanism is responsible for the grain refinement under FSW process.

3.2 Mechanical properties

True stress vs. true strain curves, σ - ϵ , for the as-received, indicated as RM, and the FSWed, FSW, 7075 Al alloys deformed at room temperature are presented in Fig. 4. Strain hardening takes place in all stages of the deformation. It is seen in Fig. 4 that FSW leads to a decrease in the 0.2 pct proof stress by about 150 MPa. At the same time, the FSW process results in an increase in the peak stress and elongation to failure by about 10%. The variations in strength and ductility shown in Fig. 4 suggest the possibility of using FSW to improve the toughness of high strength 7XXX series aluminum alloys.

3.3 Thermal stability

A series of microstructures of the FSWed 7075 Al alloy after static annealing for 30 min at four temperatures, 623,

Fig. 4 True stress-true strain curves for the as-received, RM, and the FSWed 7075 Al alloys deformed at room temperature.

673, 723 and 773 K, is shown in Fig. 5. The change in average size of fine grains with annealing temperature is summarized in Fig. 6. It is evident in Figs. 5 and 6 that the increase in annealing temperature results in grain growth. The static annealing up to 673 K led to little growth of fine grains in the nugget zone. Some structural changes occur, however, during static annealing at 723 and 773 K. The grain boundaries become corrugated under annealing at these temperatures. It may result from local migration of high angle boundaries. The fine-grained structure is coarsened during static annealing at 773 K, resulting in an increase in average grain size from about 3 to 5.5 μm. However, an extremely large, more than 3 mm in size, irregular shaped grain is developed near the root of welded zone at 773 K (Fig. 5(e)). This grain was growing preferentially and consuming the surrounding fine grains.

It can be concluded from Figs. 5 and 6 that the recrystallized fine-grained microstructure developed during FSW coarsened in a discontinuous manner during static annealing at temperatures of above 723 K. This behavior may be attributed to abnormal grain growth, *i.e.* secondary recrystallization.¹²⁾ The abnormal grain growth may be explained by the dissolution of second phase particles during annealing, which often occurs inhomogeneously, allowing a few grains to grow preferentially, thus initiating abnormal grain growth.^{12,14)} It should be noted that the static annealing at temperatures up to 723 K leads to the evolution of uniform fine-grained structure. Such a fine and stable microstructure may be suitable for superplastic deformation and forming at temperatures lower than 723 K. At the same time, the evolution of extremely large grains occurs during annealing at 773 K.

3.4 Superplastic behavior

The series of true stress-true strain, σ - ϵ , curves for FSWed 7075 Al alloy are presented in Fig. 7. Figure 7(a) shows the curves obtained at a fixed temperature of 673 K and at initial strain rates ranging from 1×10^{-4} to $1 \times 10^{-2} \text{ s}^{-1}$. Figure 7(b) shows the σ - ϵ curves obtained at a fixed initial strain rate of $1 \times 10^{-3} \text{ s}^{-1}$ and at temperatures ranging from 623 to 723 K. Strain hardening takes place in a beginning stage of

Fig. 5 A series of microstructures of the FSWed 7075 Al alloy after static annealing for 30 min at the temperatures of (a) 623, (b) 673, (c) 723 and (d), (e) 773 K.

Fig. 6 Change in average size of fine grains developed in the FSWed 7075 Al alloy with annealing temperature.

deformation and then the stress decreases rapidly after reaching a peak stress until fracture. There is a tendency that the increase in strain rate or decrease in temperature results in the increase in strain hardening rate.

The variations in flow stress (at true strain of 0.1) with initial strain rate for the as-received, RM, and the FSWed,

FSW, 7075 Al alloys are plotted in Fig. 8 in double logarithmic scale. Data for as-rolled and friction stir welded materials are presented by solid and open symbols, respectively. It can be seen in Fig. 8 that the FSW leads to a significant decrease in the flow stress. The flow stress of FSWed 7075 Al alloy decreases more rapidly with a decrease in strain rate and an increase in deformation temperature than that of the as-rolled material. A stress exponent of about 2.8 for FSWed alloy was found in strain rate ranging from 1×10^{-4} to $1 \times 10^{-2} \text{ s}^{-1}$ for investigated temperatures. Temperature dependence of the strain rate sensitivity, m , is shown in Fig. 9. The coefficient of strain rate sensitivity slightly increases with the increase in temperature from 623 K to 673 K. Subsequent increase in temperature leads to gradual decrease in the m value. The highest value of the coefficient m of about 0.4 was found at a temperature of 673 K. This may suggest that grain boundary sliding can frequently take place during deformation.

Strain rate and temperature dependencies of the elongation in FSW 7075 Al alloy are represented in Fig. 10. For comparison, data for as-received 7075 Al alloy are also included in this graph. Data for the as-received and the FSWed materials are presented by solid and open symbols, respectively. It can be seen in Fig. 10 that the as-rolled 7075

Fig. 7 Series of true stress-true strain, σ - ϵ , curves for FSWed 7075 Al alloy. The σ - ϵ curves obtained (a) at a fixed temperature of 673 K and at various strain rates and (b) at a fixed initial strain rate of $1 \times 10^{-3}\text{ s}^{-1}$ and at various temperatures.

Fig. 8 The variations in flow stress (at true strain of 0.1) with initial strain rate for the as-received, RM, and the FSWed 7075 Al alloys.

Al alloy did not exhibit superplastic behavior at all investigated strain rates and temperatures. In contrast, the FSWed alloy showed a superplastic behavior with largest elongation of 440% at a temperature of 673 K and an initial strain rate of $1 \times 10^{-3}\text{ s}^{-1}$.

Thus, the results of the present study showed that FSW is

Fig. 9 Temperature dependence of coefficient of strain rate sensitivity, m .

Fig. 10 Strain rate and temperature dependencies of the elongation in the FSWed 7075 Al alloy.

an effective route to produce a fine-grained microstructure with submicron grain size in commercial 7075-T6 aluminum alloy. The FSWed 7075 Al alloy exhibits high ductility of 440% at essentially the same temperature and strain rate range as Supral (Al-6%Cu-0.5%Zr) alloy, which is a classic superplastic material.¹⁵⁾ However, the present results are contradictory to the data previously published by Mishra *et al.*^{16,17)} They reported that the same 7075 aluminum alloy subjected to friction stir processing (FSP)¹⁸⁾ exhibits maximum elongation more than 1250% at a temperature of 753 K and the thermal stability of fine-grained microstructure developed during FSP up to 773 K. The distinction between the present results and data reported by Mishra *et al.*^{16,17)} may be resulted from different techniques used for the development of a fine-grained microstructure and experimental conditions, such as tool sizes, tool rotation and traverse speeds, phase composition, *etc.* These conditions may have a significant influence on fine-grained microstructure developed, mechanical properties and thermal stability of such structure. Effect of conditions mentioned above need further investigations.

4. Conclusions

- (1) Friction stir welding (FSW) of 7075-T6 aluminum alloy plates results in the formation of a homogeneous fine-grained structure with average size of about $3\text{ }\mu\text{m}$. Most parts of developed grain boundaries, about 90%, have

high angle misorientations.

- (2) The fine-grained structure developed under FSW is stable during static annealing at temperatures up to 723 K. Further increase in annealing temperature to 773 K results in an abnormal grain growth, following by the evolution of very large, mm-scale, grains.
- (3) The FSW 7075-T6 aluminum alloy exhibited a superplastic behavior at temperatures from 623 to 723 K. Large elongation of about 440% was observed at a temperature of 673 K and at a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$.

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