International Journal of Mechanical Engineering (IJME)
ISSN 2319-2240
Vol. 2, Issue 3, July 2013, 77-84

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

MECHANICAL PROPERTIES OF ALUMINUM JOINTS WELDED BY FRICTION STIR WELDING

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ABSTRACT

The influence of tool rotational speed and welding speed during friction stir welding is studied in the case of aluminum plates with 6 mm thickness. When a tool rotational speed of 1000 rpm is applied with welding speed of 1.5 mm/sec, an optimum tensile strength was obtained in this investigation. Also, it has been found that the microhardness increases with welding speed and decreases as the rotational speed increased.

KEYWORDS: Aluminum Alloys, Friction Stir Welding, Hardness, Tensile Strength

INTRODUCTION

Friction stir welding (FSW) is considered to be the most significant development in metal joining techniques in a decade, it was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys [1-4]. This technique is being applied to the aerospace, automotive, and shipbuilding industries, and it is attracting an increasing amount of research interest. M.L. Santella et. al [5] evaluated the extent to which friction stir processing could improve local mechanical properties of Al castings alloys compared to the base metal. S.R. Ren. et. al. [6] examined the effect of welding speed, rotational speed and heat index on the mechanical properties and fracture behavior of 6061Al–T651 alloy. They reported that the tool welding speed was the dominant factor in determining the thermal exposure, mechanical properties and fracture behavior of FSW 6061Al–T651 joints. Tomotake Hirata. et. al. [7] found that hardness of the stir zone increased, and also formability improved by decreasing the friction heat flow. Shitong Wei. et. al. [8] reported that the heat input for forming the defect-free joints reduced with the increased in welding speed or the decreased in rotational speed.

The hardness values within the Stir Zone (SZ) increased with decreasing heat input. The heat input had a little influence on the transverse tensile strength of the joints. Finally, the maximum ultimate strength of the joints was equivalent to 86% that for the base metal. Arora et. al. [9] found that the weld nugget consisted of very fine equiaxed grains and experienced dissolution of nearly half of metastable precipitates into the matrix during welding. Thermo-mechanically affected zone (TMAZ) also experienced dissolution of precipitates but to a lesser extent whereas coarsening of precipitates was observed in the heat affected zone (HAZ). Singh et al [10] in their study focus on the correlation between dynamic interrogations measures of friction stir welded panels with weld energy, as welded mechanical properties and the microstructure. Cavaliere. et. al. [11] investigated the effect of processing parameters on mechanical and microstructure properties of AA6082 welded joints produced by FSW. They stated that by increasing welding speed the nugget microstructure appeared more fine and uniform. The yield strength increased rapidly from the lowest speed up to

115mm/min, and after that it was decreased by increasing the welding speed. Z. Zhang. et. al. [12] stated that when the welding speed increased, the rotation speed must be increased simultaneously to avoid any possible defects such as voids. Jamshidi et. al. [13] investigated the relationship between the microstructure of the thermomechanically zone and the welding parameters. They found that the asymmetry distribution of the temperature around welding line. Also, they found that the grain size within the TMAZ decreases as the input heat decreased. In this investigation the effect of rotational speed of the welding tool and the welding speed on the mechanical properties of the aluminum alloy has been analysed.

Experimental Step-up

Aluminum alloys with compositions of two main elements: 4.2 wt% Mg, and 0.45 wt% Si used as a base materials in this investigation. Two rectangular aluminum plates of 300 x 150 x 6 mm mm size were butt-welded by friction stir welding process. A conventional vertical milling machine was used for friction stir welding process, by using a fixture. The fixture is tightly fixed on the milling machine table to prevent vibration from occurring as a result of the frictional forces of the welding process. Welding tools with flat shoulder of 24 mm diameter, and 20 mm height, made of high carbon steel, were used. A 6 mm square pin profile was used to carry out the welding process. A spring-loaded unit was used to maintain the applied pressure on the shoulder face of the welding tool against the upper surface of the work piece constant at 3.6 MPa.

The welding process was carried out using five different rotational speeds and five welding (traverse) speed. The rotational speeds were 560, 700, 1000, 1300, and 1600 rpm. The welding (traverse) speeds, were 0.5, 1, 1.5, 2 and 2.5 mm/sec. Single stir pass was applied during the dry welding process. Microstructure examinations were done using optical microscope. The specimens, which were taken from the middle of the stirred zone, were prepared by standard metallographic techniques and etched with Keller’s reagents to reveal the grain structure. Vickers microhardness was measured with 0.5 kgf load and a dwell period of 10s. Several measurements were done for each hardness value. In addition, a tensile test was carried out on a WDW-20 computer controlled universal tensile testing machine. The tensile specimen is loaded at a rate of 0.5/s. The load versus displacement has been recorded by the machine and the yield and ultimate tensile strength were determined. The tensile test specimens had a gauge width of 12 mm and gauge length of 90 mm.

RESULTS AND DISCUSSIONS

In Friction stir welding the amount of heat generated depends on many welding parameters. In this investigation the effect of welding speed and tool rotational speed on the grain size of stir zone has been studied. Figures 1(a) to 2(d) show the recrystallized grain structure with magnification 60X at the stir zone for a tool rotational speed of 560, 700, 1000, 1300 and 1600 rpm at a constant welding speed of 1.5 mm/sec. The shoulder diameter and the welded thickness plate kept constant at 24 mm and 6 mm respectively. It has been shown that as the tool rotational speed increases the grain size has become larger with more particles of Si precipitate. Figure 2 shows the variation of grain size on friction stir process region (FSP) with tool rotational speed.

The welding specimen was cooled freely, so the more heat generated during friction stir welding, the more time is needed to cool it. As the tool rotational speed increased, more heat generated during welding and raising the specimen temperature in the stir zone so that the material is extremely softened and can be subjected to grain growth after deformation. But at low value of rotational speed of 560 rpm, less heat generated during welding process resulted on a fine dendrites growth. Figures 3(a) to 3(d) show the microstructure of the stir zone for different welding speed of 0.5, 1.0, 1.5, and 2.5 mm/sec at a constant tool rotational speed of 1000 rpm. The rate of heat generated per unit length decreases as the welding speed increases. So, at slow welding more heat generated per unit length causes large grain size. While at higher speed of welding a low amount of heat is generated leads to fine dendrites microstructure as shown in Figure 3(d). The effect of welding speed on grain size of FSP zone is shown in Figure 4.

The variation of the micro hardness values in the stir zone is shown in Figures 5 and 6. The micro-hardness distribution in the friction stir welding shows a dependence on the welding parameters, such as welding speed and tool rotational speed. The hardness tends to decreased with increases in heat input in the stir zone. This was mainly due to the different thermal effect with welding conditions. More energy was inputted when the welding speed was slower, or at higher rotational speed. Therefore, the grain size at these welding parameters increases as the heat input decreases as shown previously in Figures.2 and Figure 4. FSW can be considered as a hot-working process in which a large amount of deformation is imparted to the work piece through the rotating pin and the shoulder. Such deformation gives rise to sub-grains with dislocation tangles at the boundaries [14].

When the dynamic recrystallization happens, the original base material grain structure will be completely eliminated and replaced by a very fine-equiaxed recrystallized grain structure in the stir zone. Meanwhile, the dislocation density is decreased. But the dislocation may not be eliminated completely. Some previous studies [14,15] have actually shown that such dynamic recrystallization often leaves some grains with a high density of dislocations in the stir zone. The recrystallized grain size increases with the heat input, and which causes the further decrease of the dislocation density. It is considered that the variation of hardness is related to the microstructural changes in the stir zone induced by welding conditions. As mentioned above, it is clear that the size of recrystallized grain varies with heat input. Therefore, it can be concluded that the generation of additionally refined grains and the higher dislocation density in the stir zone are the main factors that caused the hardness increase associated with decreasing heat input [16]. The hardness profile of the FSW joints is a direct indicator of microstructural evolution during FSW.

The fracture of FSW heat-treatable aluminum alloys usually occurs in the HAZ, i.e. the softest zone in the FSW joints, due to significant coarsening of the precipitates [17]. The hardness distribution of the FSW samples was measured on the welding surface under shoulder face. Figure 7 shows a typical hardness profile of the FSW joints. It has been shown that hardness of the advanced side is lower than that of the retreating side. The variety of mechanisms that alter the strength of materials includes work hardening, solid solution strengthening, precipitation hardening, and grain boundary strengthening. In this study the effect of rotational speed and welding speed on the strength of aluminum welded joints was investigated in order to determine the optimum welding parameters.

It has been found that the strength properties of all the welded joints are lower than that of the base material, irrespective of the welding parameters used to fabricate the joints. Figures 8 and 9 reveal the effect of rotational speed on yield and ultimate tensile strength of the welded joints respectively. At low rotational speed less heat input to the joints leading to increase the yield and ultimate tensile strength. But at higher rotational speed excess heat introduced to the welding joint, leading to decrease on yield and ultimate tensile strength as rotational speed increased to values above 1000 rpm. The optimum yield strength occurred at rotational speed of 1000 rpm. This may be due to the difference in microstructure between the SZ and TMAZ. The SZ is composed of fine-equiaxed recrystallized grains, while the TMAZ consists of coarse deformed grains. Therefore, the interface between the SZ and TMAZ on becomes the poorest location in the tensile test [18].

Figures 10 and 11 show the effect of welding speed on the yield and ultimate tensile strength respectively. As the welding speed increased the strength of welded joints increased. But at higher welding speed less heat input leads to more deformation of materials especially at the interface of SZ and TMAZ zones. So, drop in yield strength occur, when the welding speed exceeds 1.5 mm/sec as shown in Figure10. The reduction in yield and ultimate strength is very little as the welding speed increased from 2 to 2.5 mm/sec, as shown in Figures. 10 and 11 respectively.

CONCLUSIONS

In this study, FSW of aluminum sheets with t thickness of 6 mm was performed. We concluded the following:

- Grain size of SZ related to heat inputted during FSW welding, causes the grain size to increase with respect to rotation speed and to decrease with increasing the welding speed.
- Microhadness of the SZ depends on the grain size. The microhardness is higher with a fine microstructure.
- Tensile strength increases to an optimum value then it starts decreasing. This phenomenon is occurred for both rotational speed and welding speed.

ACKNOWLEDGEMENTS

Authors would like to express their sincere gratitude and thanks to deanship of research in Northern Border University, Kingdom of Saudi Arabia, for their encouragement and kindly supporting this project. Also, Our thanks to Al-Balqa' Applied University (BAU), Jordan. Where this work has been carried out during sabbatical leave granted to the author Salameh A. Sawalha from Al-Balqa' Applied University (BAU) during the academic year 2012-2013

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APPENDICES

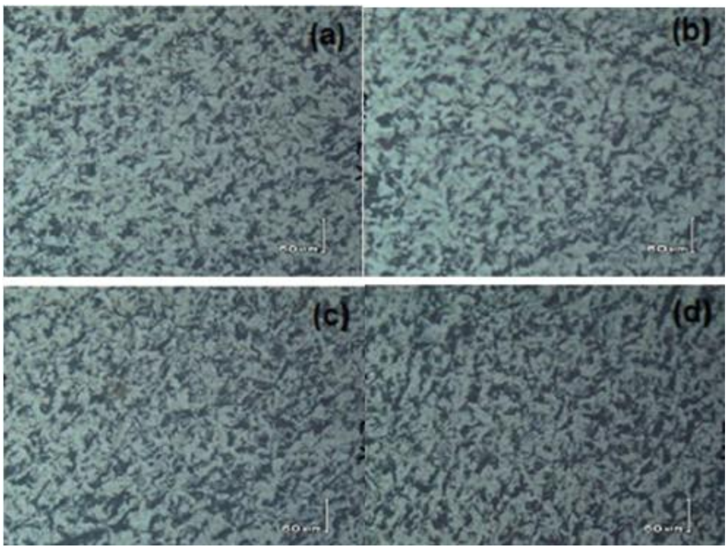

Figure 1: Microstructure of Stir Zone at (a) 1600 rpm (b) 1300 rpm (c) 1000 rpm and (d) 560 rpm

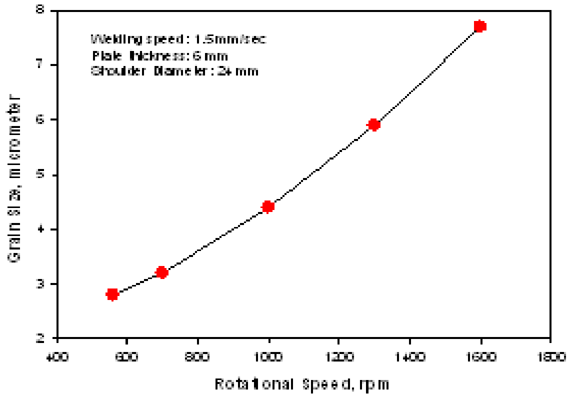

Figure 2: Effect of Tool Rotational Speed on Grain Size of Stir Zone

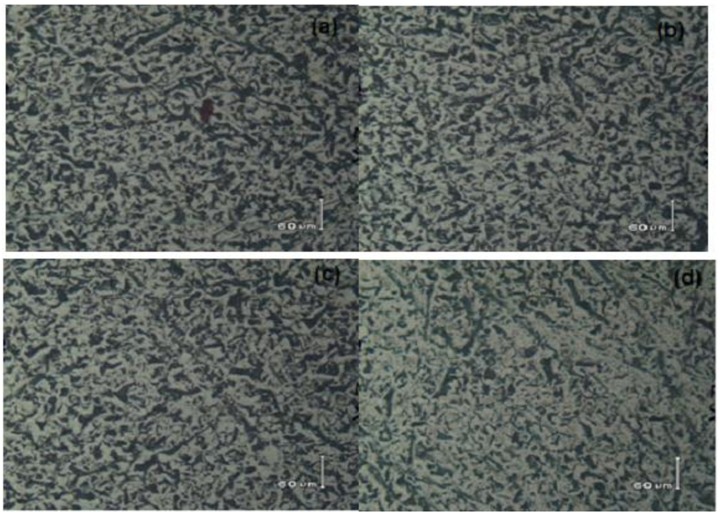

Figure 3: Microstructure of SZ at Welding Speed of (a) 0.5 mm/sec, (b) 1 mm/sec, (c) 1.5 mm/sec and (d) 2.5 mm/sec

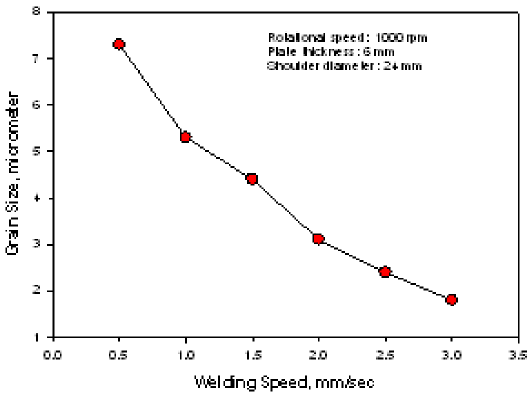

Figure 4: Effect of Welding Speed on Grain Size of Stir Zone

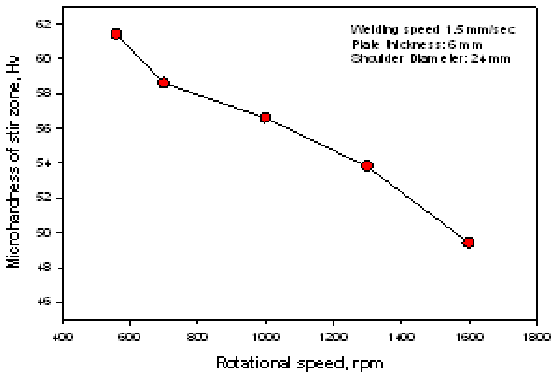

Figure 5: Effect of Rotational Speed on Microhardness of Stir Zone

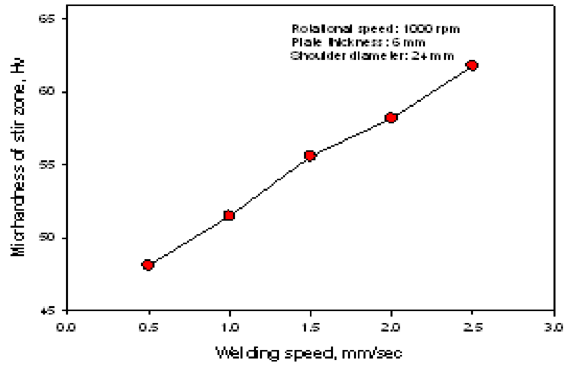

Figure 6: Effect of Welding Speed on Microhardness of Stir Zone

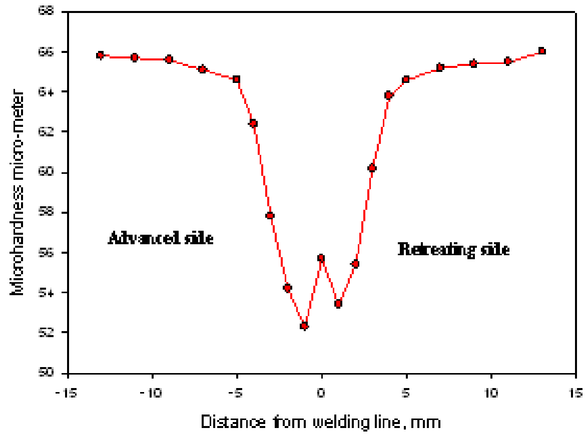

Figure 7: Typical Microhardness Profile

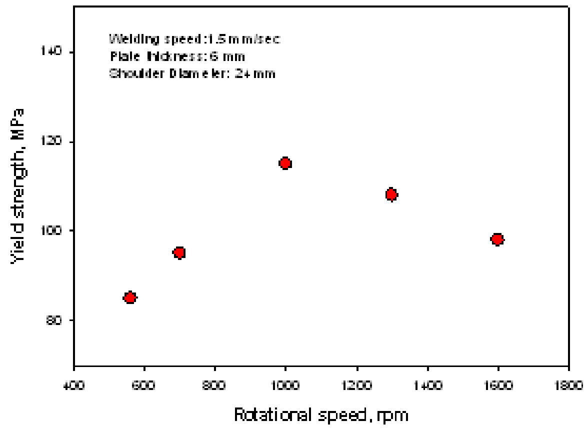

Figure 8: Effect of Rotational Speed on Yield Strength

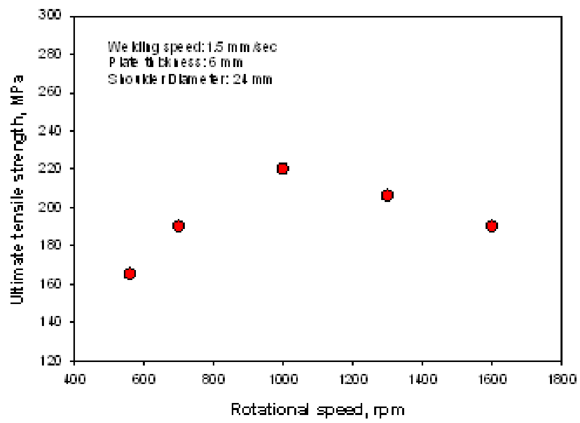

Figure 9: Effect of Rotational Speed on Ultimate Tensile Strength

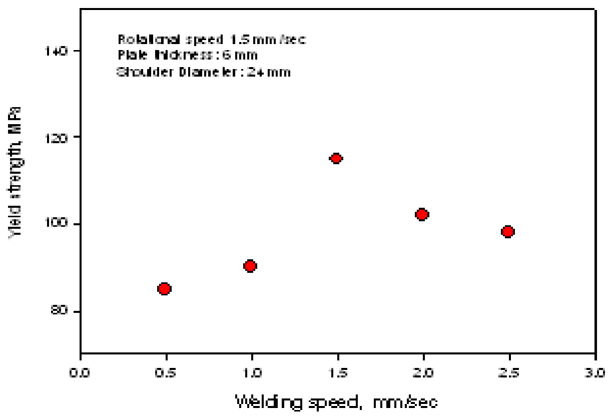

Figure 10: Effect of Welding Speed on the Yield Strength

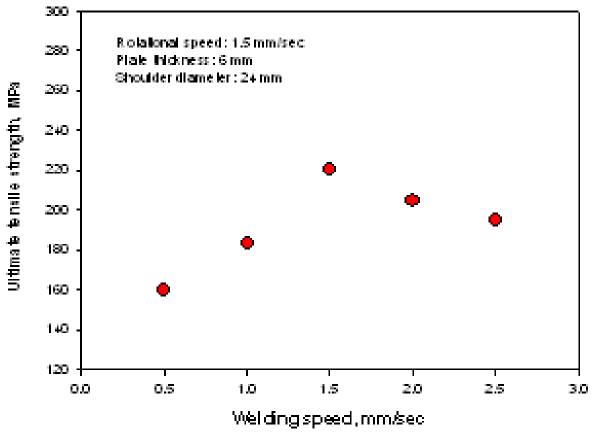

Figure 11: Effect of Welding Speed on Ultimate Tensile Strength