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Effect of Tool Rotational Speed and Dwell Time on the Joint Strength of Friction Stir Spot Welded AA6061-T6 Sheets [†].

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Abstract: Friction stir spot welding (FSSW) is a technique employed to join materials in solid state. It was first employed by Mazda and Kawasaki companies as a novel sub-technique of the friction stir welding to alternate the spot resistance welding. FSSW successively joined metals both similar and dissimilar. Tool rotational speed and dwell time are the most effective FSSW process parameters. This study investigated the role of the rotational speed of the tool and the dwell time in determining the FSSW joints strength using AA6061-T6 aluminum alloy sheets with a thickness of 1.8 mm as a workpiece material. A classic milling machine was employed to carry out the welding process. Four different values of tools rotational speed with two dwell time values were taken to fabricate the FSSW joints. Four joints were made for each FSSW process condition. Three jointss were averaged to determine the tensile-shear fracture load. The other specimen was employed to examine the micro-Vickers hardness and the microstructure. The investigation reported an increase in the joint strength within a certain range of tool rotational speed and dwell time values corresponding to grain refinement in the weld zone. The variation in mechanical properties was attributed to the corresponding frictional heat generation and material flow during the welding process. Strain hardening and dynamic recrystallization determined the weld nugget hardness. Lower mechanical properties were observed with the excessive heat generation and flow of material with too high speeds and dwell time values.

Keywords: FSSW; rotational speed; dwell time

1. Introduction

Recently, there has been a growing need for the use of lightweight metal alternatives in transportation industries, aircraft, aerospace, various structural components and many other industrial applications due to the high costs of fossil hydrocarbon fuels as well as to reduce the environmental impact. Friction stir spot welding (FSSW) is a solid state welding technique that has been successfully employed to join lightweight metals, such as aluminum, magnesium, titanium, zinc, etc. [1]. **Error! Reference source not found.** represents the process of the FSSW and shows its procedures; (1) plunging, (2) stirring and (3) retracting. Plunging includes inserting a rotating welding tool that has a pin and shoulder into the work piece to a specific depth. During the stirring procedure, the joint is formed under the effect of a frictional heat generation, material flow induced and the forging force applied during the FSSW process. The tool then is retracted leaving a feature called "Keyhole". The joint is formed depending on the frictional heat generation and material flow under the forging force of the welding tool [1]. Several process parameters mainly affect the FSSW joint characteristics, such as tool rotational speed, dwell time, plunge rate and plunge depth [2]. These parameters play a dominant role in determining the weld quality and failure modes. Rotational speed of tool is a dominant welding parameter that controls the weld strength followed by dwell time. Dwell time

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must be within a specified range to prevent making week joints [3]. Heat generation into the weld is proportional to the dwell time because it allows more friction between the tool pin and shoulder with the work pieces being friction stir welded. Shen et al. [4] studied the effect of the tool rotation speed and the dwell time on the mechanical properties of the FSSW weld joints and concluded that the tensile shear load increased with the tool rotation speed and dwell time, and the tool rotation speed played a very important role in determining the strength [4,5]. Sathyaseelan et al. [6] investigated how dwell time influences the fracture load of dissimilar metals. They reported that the optimal frictional heat input could improve the FSSW joint strength and the recrystallization of grains and the distribution of intermetallic compound control the weld quality. Rojikin et al. [7] observed a decrease in the tensile strength with increasing tool rotational speed more than 1600 rpm and this result is related to an increase in the thickness of the intermetallic compounds. Ugla et al. [8] reported that the tensile strength is linearly related to the tool rotational speed and decreased over a certain range of dwell time because of the excessive heat input in the weld region. The FSSW weld microstructure consists of four distinct neighboring zones symmetric with respect to the keyhole called stir zone (SZ), thermomechanically affected zone (TMAZ), heat affected zone (HAZ) and base metal (BM). These zones differ in morphology Depending on their influence by the frictional heat and the material flow during the welding process which are mainly affected by the tool rotational speed and dwell time [4], [6–8].

The heat treatable AA6061-T6 aluminum alloy is one of the most commonly used alloys in different industrial applications in truck frames, motorboats, ship building and aerospace applications. It has a good weldability and a good strength/weight value [1].

Previous studies have investigated the FSSW with specific conditions, parameters and materials and came out with the corresponding findings. Therefore, more research is required with the inclusion of various combinations of welding process parameters for many metals and alloys of industrial and research importance.

This study will focus on investigating two of the most influential parameters on the FSSW process of AA6061-T6 alloy and the results will contribute to raising the economic and design feasibility in its various industrial applications.

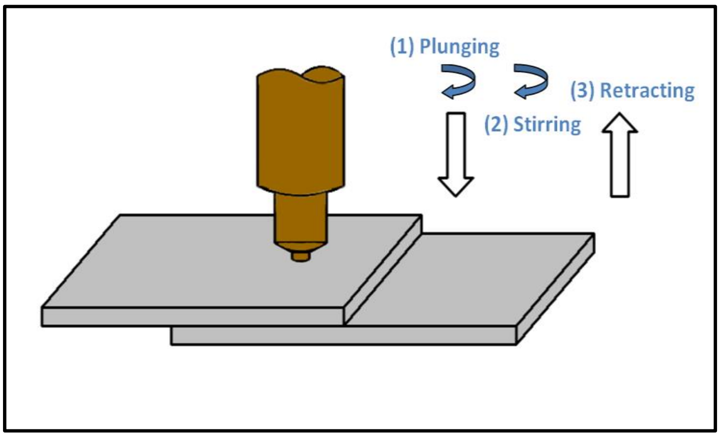


Figure 1. Schematic illustration of the FSSW process.

2. Materials and Methods

Error! Reference source not found.a shows a tool made of HISI H13 tool steel that used to perform the welds of this study, while the tool dimensions are shown in a schematic diagram in **Error! Reference source not found.**b.

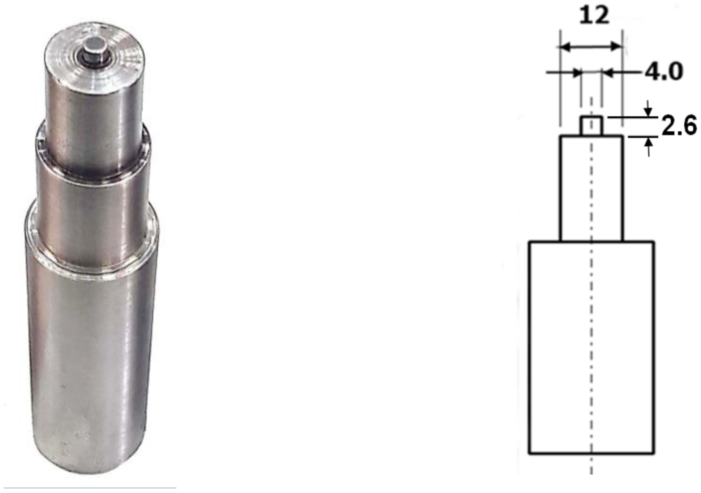
In the present work, 1.8 mm thick AA6061-T6 sheets were used to prepare the FSSW lap-shear specimens with dimensions shown in schematic **Error! Reference source not found.**. The chemical composition (Wt.%) of the tested alloy is 0.81 Si, 0.48 FE, 0.28 Cu, 0.13 Mn, 0.93 Mg, 0.009 Zn, 0.25 Cr, 0.088 Ti in addition to a balance of aluminium. **Error!**

Reference source not found. includes the process variants that were considered to carried out the FSSW process using a classic milling machine. Four weld joints were performed for each welding combination of process variants. Three joints were tensile tested and averaged to determine the tensile shear fracture load and the other specimen was cross-sectioned and examined for the microstructure and the micro-hardness.

The performed specimens were tested for the micro-Vickers hardness in the mid-thickness of the upper sheet cross-section with a step of 0.5 mm conditions of was performed for the upper sheet of the FSSW specimens performed at different welding conditions with 0.5 mm step, 300 g test load and a test cycle of 15 s.

Table 1. Variants considered for the FSSW process.

Variant	Value
Tool rotational speed (rpm)	426, 710, 960, 1400
Dwell time (s)	10, 15
Plunge depth (mm)	0.3
Plunge rate (mm/min)	10



(**a**) (**b**)

Figure 2. The FSSW tool: (a) Shape and design; (b) Schematic illustration.

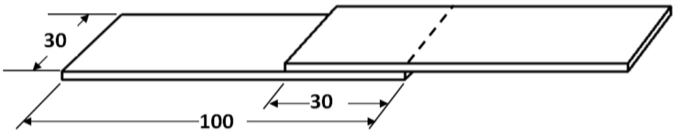


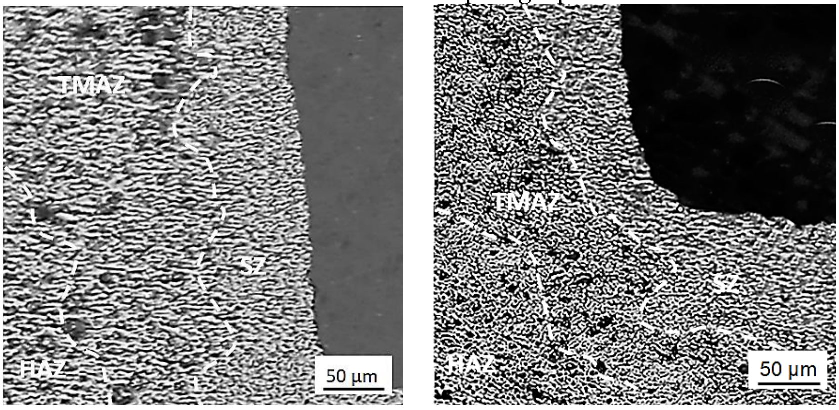
Figure 3. Schematic of the FSSW specimen in lap configuration.

3. Results and Discussion

3.1. Microstructure

Different welding parameters produce different morphologies of the FSSW weld region due to the corresponding differences in the welding conditions of each individual process [1]. ***Error! Reference source not found.***a,b represent a close-up views of specimens performed during this study at different welding conditions of tool rotational speed and dwell time of 426 rpm and15 s and 710 r.p.m and 10 s, respectively.

Higher grain refinement was observed in the SZ of the specimen shown in ***Error! Reference source not found.***a, which performed at a higher dwell time because of the higher heat generation, plastic deformation in addition to the uniform distribution of precipitates in the SZ and therefore full dynamic recrystallization. However, higher sized precipitates were observed due to the relatively higher dwell time [3,6]. On the other hand, the specimen shown in ***Error! Reference source not found.***b experienced excessive heat input as a result of the higher speed of the tool despite lower dwell time which did not exhibit a remarkable effect after passing a speed threshold 710 rpm, and the speed of the tool rotational exhibited higher impact in generating frictional heat than the dwell time. It seems to be a common metallurgical behavior regardless of the type of metal of the work piece. This finding coincided with previous studies [3–9] with some specific differences in the results related to tested materials and welding conditions. This difference in morphology negatively affects the mechanical properties and the joint strength, as will be discussed later in another paragraph in this section.



(a) *(b)*

Figure 4. A close-up views of FSSW specimens performed at different welding conditions. (a) Tool rotational speed of 426 rpm, dwell time of 15 s, (b) Tool rotation speed of 710 r.p.m, 10 s dwell time.

3.2. Tensile test

Tensile test was applied to the performed lap joints and the results were averaged to determine the fracture load for each process set of conditions. **Error! Reference source not found.** represents the relationship of the fracture load as a function of the speed of tool rotation at two values of dwell time 10 s, 15 s. At a rotational speed of 426 r.p.m and 10 s dwell time, a value of tensile shear fracture load about 4131 N was reported, while 5496 N was obtained at dwell time of 15 s with an increase of about 33%. This result was obtained by the higher material flow and maximum heat input required to achieve the higher refinement of grains in the SZ at the 15 s compared to 10 s dwell time. The positive effect of the dwell time began to decrease with increasing the speed of tool rotation until reaching 710 rpm. The fracture load then dramatically decreased by 14.8 %, 18.5 % for the 10 s and the 15 s dwell time values respectively with increasing the speed of the tool to 960 rpm affected by the excessive heat input in the weld nugget, which results in coarser grain size in the SZ. This finding agrees with Ugla et al. [8]. More increase in dwell time no longer had a remarkable effect on the tensile strength with tool rotational speed that exceeding 750 rpm. Thus, dwell time exhibited a lower effect on the tensile strength compared to the speed of the tool rotation. This finding is in agreement with previous studies [4,9].

Generally, tensile shear fracture load increases with increasing tool rotational speed and dwell time because of the higher generation of frictional heat which leads to finer grains and higher plastic deformation, while more increase in those two parameters leads to an excessive heat input in the weld nugget which induces coarser grains and higher quantity of intermetallic compounds in addition to the formation of a larger and continuous oxide layer, and therefore lower strength and lower TSFL [4–9].

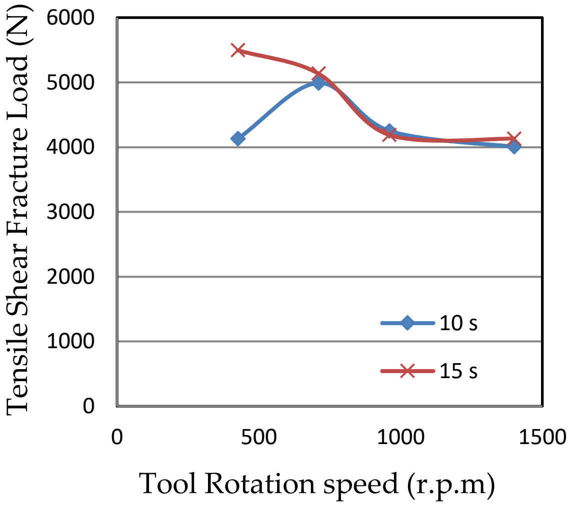


Figure 5. Tensile shear fracture load as a function of tool rotational speed at two values of dwell time (10 s, 15 s).

3.3. Micro-hardness

Error! Reference source not found. shows the Vickers hardness distribution profiles of two specimens performed at welding conditions of tool rotational speed and dwell time of 710 r.p.m, 10 s and 426 r.p.m, 15 s, respectively. A typical W-shaped profiles were observed because of the almost symmetrical heat inclusion, displaced material and forging force around the keyhole [4].

Higher SZ hardness observed with increasing the speed of the tool rotation because of the higher heat generation which leads to higher grain refinement and higher plastic deformation. While slightly lower effect of the dwell time was observed than that of the tool rotational speed. This result was attributed by Jambhale et al. [3] by the generation of a higher intermetallic compounds with the higher dwell time. Therefore, the speed of tool rotation plays the dominant effect in determining the hardness of the SZ of the FSSW welds [3,9].

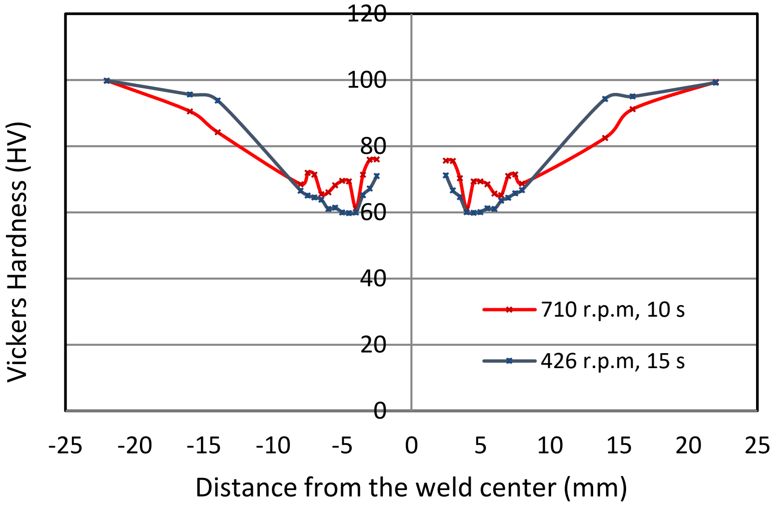


Figure 6. The hardness profile of two FSSW welds performed at rotational speed and dwell time of 710 rpm, 10 s and 426 rpm, 15 s respectively.

4. Conclusions

During the present work, the effect of two of the most effective parameters on the mechanical properties in the friction stir spot welding process were investigated, namely the tool rotational speed and the dwell time. By analyzing results, it is concluded that tool rotational speed and dwell time are the most dominant parameters in determining the FSSW weld strength, and the tool rotational speed has the most effective role. We indicated a maximum tensile shear fracture load of 5496 N at a rotational speed and dwell time of 426 rpm and 15 s respectively. Moreover, increasing the dwell time value from 10 s to 15 s increased the tensile shear fracture load by about 33% due to the full dynamic recrystallization and grain refinement achieved by the maximum heat input and material flow, while the higher dwell time did not have a noticeable effect. In addition, when the tool rotational speed was increased from 426 rpm to 710 rpm, we observed higher hardness in the SZ, while higher speed resulted in lower hardness due to the excessive heat input.

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