Spot Welding of 6061 Aluminum Alloy by Friction Stir Spot Welding Process

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Abstract—**This study was focused on the effect of welding parameters on the lap-shear fracture load of the welded joints prepared by friction stir spot welding. Four different weld parameters were analyzed: rotational speed, dwell time, pin length and shoulder size of the welding tool. It was found that the lap-shear fracture load increases with an increase of the welding parameters to a limited value and decreases with further increase. The strong welded joints failed under nugget-pull out fracture.**

Keywords-friction stir spot welding; aluminum alloys; mechanical properties

I. Introduction

Friction Stir Spot Welding (FSSW) is a relatively new process that has recently received considerable attention from various industries including automotive [1, 2]. FSSW was first developed by TWI Abington, UK in 1991 [3]. This new spot welding technique has been successfully applied in the automotive industry due to its high product quality, over 90% energy saving and 40% equipment cost saving versus the traditional electrical resistance spot welding (ERSW) [4]. In the FSSW process, a rotation tool is inserted into the overlapping work pieces to an established depth and then held for a certain time before being retracted [5, 6]. The development of reliable techniques for joining Al to a steel sheet has become the subject of considerable interest [7]. Electrical resistance spot welding is currently the dominant method used for joining steel car bodies, because it is fast, versatile, and easily automated [8]. Unfortunately, when using ERSW to weld Al to steel, a thick intermetallic compound (IMC) reaction layer is formed which can badly affect the joint performance [9]. Friction stir spot welding is an alternative technology that has potential for joining multi-material structures [10–12].

There are many investigations in the literature about FSSW. In [13], authors investigated the microstructures and failure mechanisms of FSSW in aluminum 6111-T4 alloys. In [14], authors did some work on sheet aluminum joining. Moreover, in [15] authors conducted experiments to investigate structure-properties relations in spot friction welded 6111-T4 Aluminum. In [16], authors studied the FSSW properties relating to microstructure and strain rates for aluminum 7075-T6 alloys. In [17], authors investigated FSSW properties relating to local melting and tool slippage for aluminum 7075 alloys. Furthermore, in [18] authors developed an empirical relationship using surface response methodology to predict the maximum strength for FSSW joints [18]. In [19, 20], authors investigated FSSW properties for aluminum 5754 and AA2014 alloys respectively.

As for dissimilar material FSSW, the FSSW characteristics for Al and Mg alloys were investigated [21] and a feasibility study of FSSW in advanced high-strength steels such as AHSS has also been reported [22]. In [23], authors reported on the development of FSSW robot system for the automobile industry. One needs to optimize the weld parameters for similar materials; in this case, Al6061 and establish criteria for these optimum parameters. Following this, one would consider joining dissimilar materials using FSSW and find the perfect welding conditions for such applications. This paper investigated the effect of the friction spot stir welding on the lap-shear fracture load to establish an understanding of the optimum weld parameters.

II. Experimental Work

6061 aluminum alloy plates with a thickness of 3 mm were used to fabricate lap joints. The chemical composition of the studied material is given in Table I. Two rectangular aluminum plates of 100 x 30 mm were lap-welded by friction stir spot welding process. A conventional vertical milling machine was used for the welding process. The head of the milling machine was tilted 0.5 degrees and a special suitable fixture was designed to hold the plates during the welding process. The fixture was tightly secured on the milling machine table to prevent vibration occurring as a result of the frictional forces of the welding process. Sample geometry for the welded plates is shown in Figure 1. As indicated, the plates are 100 mm long by 30 mm wide and 3 mm thick. The overlap is 30 mm which is equal to the width of the samples. According to [24], the plate length is the most important factor affecting the test results. In addition, for the overlap to be sufficient, it should at least have the same length as the sample width. The welding parameters are discussed next; each of these welding parameters has five levels.

TABLE I. CHEMICAL COMPOSITION OF THE ALLOY USED (%WT).

Si	Mg	Cu	Fe	Mn	Ti	Zn	Cr	Al
0.75	0.9	0.5	0.5	0.15	0.05	0.03	0.03	Rest

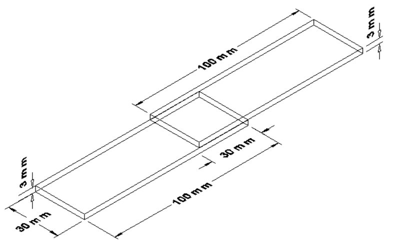

Fig. 1. Sample geometry for the welding process

The welding tool has a 4 mm square pin profile and was kept constant throughout the entire experiment. Moreover, the welding tool has a constant shoulder height of 20 mm. The variable welding tool parameters were the shoulder diameter, pin length, tool rotational speed and dwell time. The welding tools have flat shoulders and were made from high-speed steel. Five shoulder diameters were considered: 10, 12.5, 15, 17.5, and 20 mm. The second parameter was pin length which is the plunged length to produce the welded joint. Pin lengths of 3.5, 4.0, 4.5, 5.0 and 5.5 mm were used. The third welding parameter was the tool rotational speed. Tool rotational speeds of 350, 560, 900, 1120 and 1800 rpm were used. The last welding parameter was dwell time. Dewll times of 20, 25, 30, 35 and 40 sec. were used. Finally, shear load test on a universal tensile testing machine was carried out on all produced samples to measure the shear load of the welded plates. Pure bending was achieved by proper alignment of the samples during the shear load test. This was done by using vice grips and adjusting the grip insert from side to side, so that the centerline of the upper and lower grips pass through the centerline of the welded part. Finally, the focus of the study was to determine the max possible shear load and thus no stress calculations were carried out.

III. RESULTS AND DISCUSSION

Joint strength prepared by the friction stir spot welding process was examined using universal testing machine. The lap-shear fracture load is recorded as the average of three readings of the tested specimens. The effect of rotational speed on lap-shear fracture load of the joints is given in Figure 2. In these experiments the rotational speed changed as 350, 560, 900, 1120 and 1800 rpm, where the pin length, dwell time and shoulder diameter are kept constant at 4.5 mm, 35 sec, and 15 mm respectively. Figure 2 shows that the lap-shear fracture load increased as the rotational speed increased from 350 up to 1120 rpm then the value of lap-shear fracture load drastically dropped at higher rotational speed of 1800 rpm. The same results were obtained previously in [25], where it was reported that when the rotational speed increased more than 750 rpm the tensile shear strength decreased. However, in [26] it was stated that high tool rotating speeds also give hot welds. Hot welding parameters lead to low ultimate forces. In [27], authors stated that excessive heat input during FSW negatively affects the mechanical properties of joints. It has also been reported that the temperature goes up almost linearly with increase of rotation speed [28].

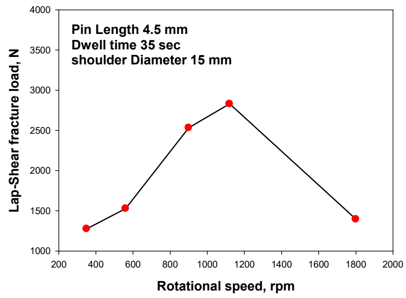

Fig. 2. Variation of lap-shear fracture load with rotational speed

In [29], it was indicated that the rotation speed and plunge depth were the main influence factors for tensile-shear strength. The effect of tool pin length on the lap-shear fracture load is shown in Figure 3. The pin length values changed from 3.5 mm to 5.5 mm with incremental 0.5 mm. The other welding parameters were kept constant. It has been shown that the joint strength increased as the pin length increased from 3.5 up to 4.5 mm, then the lap-shear fracture load fluctuate for further increases in pin length. The pin length of 4.5 mm resulted to have a higher joint strength. The welded aluminum sheets have 3 mm thickness in other words when the pin plunged to the mid depth of the lower sheet, the resulted joints have a maximum strength as shown in Figure 3. However, further increasing in pin length has a moderate effect on welded spot joint shear strength, where the lap-shear fracture load dropped at pin length 5 mm, and slightly increased again at pin length of 5.5 mm. There is an optimum tool pin height which gives the highest tensile shear strength [30]. Also, the same trend of lap-shear fracture load with the pin length was obtained by previous researchers [31].

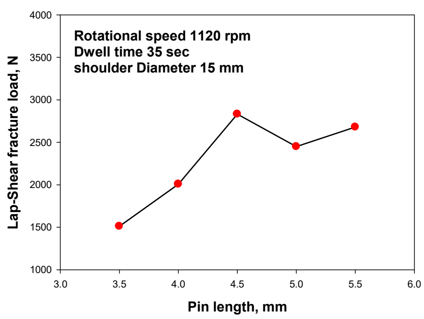

Fig. 3. Variation of lap-shear fracture load with pin length

Figure 4 shows the effect of dwell time on the variation of lap-shear fracture load of the spot welded joints. In these sets of spot welding, the rotational speed, pin length and shoulder diameter were kept constant, while the dwell time was taken as 20, 25, 30, 35 and 40 sec. It was found that as the dwell time increased up to 35 sec, the lap-shear fracture load increased as well. Excessive of frictional heat introduced to the welded parts due to longer thermal cycle reduces the lap-shear fracture load due to changes in microstructure [30]. Figure 4 shows that the lap-shear fracture load decreases when the dwell time increased more than 35 sec. The amount of frictional heat introducing during the spot welding depends on the friction area between the welding parts and the welding tool [32].

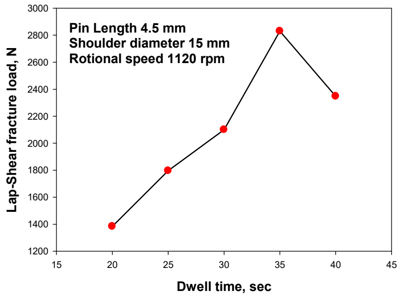

Fig. 4. Variation of lap-shear fracture load with dwell time

The shoulder diameter of the welding tool was taken as 10, 12.5, 15, 17.5 and 20 mm to study the effect of shoulder diameter on the lap-shear fracture load of welded joints produced by the friction spot stir welding process. Figure 5 shows that joints welded by a welding tool that has a 15 mm shoulder diameter possess the optimum lap-shear strength compared by other joints produced by smaller or larger shoulder diameters. In lap-shear tensile tests, there are generally three different fracture modes: interfacial shear fracture, nugget pull-out fracture, and upper or lower sheet fracture [33]. Figure 6 shows the typical fracture modes of the tensile-shear tests samples in this investigation. It was found that the joint with nugget pullout fracture had higher strength as also previously reported in [34]. For the nugget pull-out separation, two sheets tend to get separated at the partial bonding under loading. However, fracture modes mainly depended on the area of SZ [35].

IV. CONCLUSIONS

In this study, aluminum sheets of 3 mm thickness were spot welded by friction spot stir welding process. We concluded the following:

- The lap-shear fracture load is affected by FSSW parameters like rotational speed, dwell time, pin length and shoulder diameter.
- The lap-shear fracture load increased as the rotational speed increased up to 1120 rpm.
- There is an optimum pin length that produces sound joints, in this study and for this type of material and size it was found to be 4.5 mm.
- Increasing the dwell time more than 35 sec. reduces the lap-shear fracture load.
- The nugget pull-out fracture mode happened at relatively higher lap-shear fracture load.

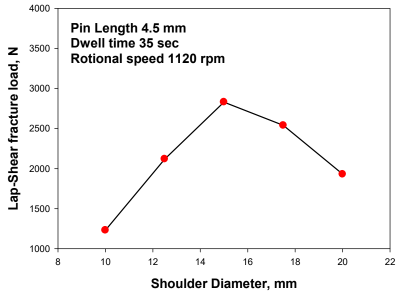

Fig. 5. Variation of lap-shear fracture load with shoulder diameter

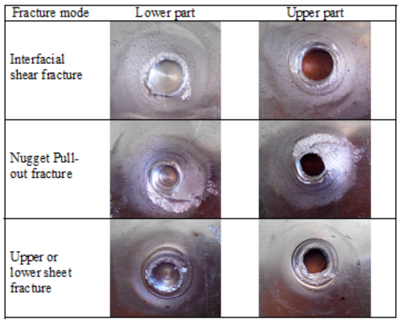

Fig. 6. Photographs of failure surfaces show the typical failure modes of test specimens.

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