Lap Joints of 6061 Al Alloys by Friction Stir Welding

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Abstract. Lap joints of 6061 aluminium alloys were obtained using friction stir welding. The welding parameters used are: rotational speed, welding speed and pin Length. There were two levels of each factor involved. Rotational speed levels were 900 and 1120 rpm, welding speed levels were 1 and 1.5 mm/sec and pin length levels were 4.5 and 5.5 mm. Successful lap joints were produced for the different combinations of the above welding parameters. The joints quality tested under tensile testing and the microstructure of the welding zone were studied. Fracture mostly occurred in the base metal for most lap-shear welded joints. The exception was joints with welding parameters as follows: rotational speed 900 rpm, the welding speed 1.5 mm/sec and pin length 4.5 mm. In this case, the fracture occurred in the welding zone.

1. Introduction
Friction stir welding (FSW) is a solid-state joining process. 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 [1–3]. Lap joints are widely used in the assembly of parts and products in the transportation industry. Common examples include ship decks, railway tankers, goods wagons, and stringer to skin in aircraft fuselages. Most aircraft and aerospace sheet metal structures involve lap joints over a range of different material joint combinations [4, 5], so there has been growing interest in recent years in utilizing FSW for joining Al alloys and Al-Cu alloys [1] in lap configuration. Conventionally, these joints are produced using riveting, given the limited fusion weldability of many high-strength Al alloys and difficulties in welding Al-Cu alloys. This also because of the difference in physical and mechanical properties of both metals, as well as its chemical affinity at temperatures higher than 120°C [5, 6]. Thus using FSW instead of riveting for joining Al alloys and Al-Cu alloys in lap configuration can help achieve significant weight and cost savings with improved mechanical performance and reduced manufacturing complexity [7].

FSW of lap joints is obtained by fixing the adjoining blank edges on a properly designed fixture, inserting a specially designed rotating pin into the sheets to be welded, penetrating them both and then moving the tool all along the welding line. A proper support has to be given to the joining edges in order to avoid the forward extrusion of the blanks material due to the tool pin action. Furthermore, the upper sheet must be properly supported to prevent any bending mechanics during the welding process [8]. The friction caused by the rotating tool shoulder at the upper sheet surface heats the sheets up and a thermal softening of sheet materials occurs at a region under the tool shoulder. This allows the tool pin to stir up the sheets materials, mix them together and make the welded joint without any melting taking place [4, 9–11]. However, there is another strategy to produce FSW lap joints, in which the process is done by “pin-less” tool configuration and using filler material lying between the two sheets [12].

Recently many researchers investigated process parameters that significantly affect the quality of lap joints produced using different Al alloys such as AA 5083 [13], AA 2024 [14], and AA 7075 [11]. In
In general, the quality of lap joints produced by friction stir welding depends mainly on weld exists and extends in the form of three different defects: hooking defects, kissing bonds and top sheet thinning. The hooking defects can be seen mostly at the thermo-mechanical affected zone of the advancing side when the sheets interface is pulled up into the top sheet. This defect causes a local thinning at the top sheet and works as crack initiator which affects joint strength. The kissing bond defect results from insufficient heat transfer to the interface of the sheets, thus leading to separated interfaces with some resident oxide layers among them. This defect usually occurs at the advancing side because of its lower temperature during friction stir welding. Finally, top sheet thinning is observed on both sides, this thinning is due to the upward pulling of the interface into the top sheet thereby reducing its cross section [11].

Several attempts were carried out to fully understand FSW process mechanics [8] in order to overcome the above stated defects and consequently improve joint efficiency. Geometrical parameters and technological parameters are the main factors that affect joint efficiency. Geometrical parameters include: dimension of the shoulder, dimensions of the pin, and the pin profile. Technological parameters include: tool rotating speed, tool feed rate, and the tool depth sinking into the sheets to be welded. These process parameters have to be properly chosen on the basis of the blank material in order to maximize the joint strength [4, 7–9, 15].

In all the examined researches it was found that to improve the mechanical resistance of the obtained FSW lap joints, a significant consideration must be given to the geometrical characteristics of the tool; in particular, the diameter of the pin. Turns out that a large tool pin diameter is required in order to extend as much as possible over the welded surface. However, large tool shoulder diameter is also required in order to increase the heat flux generated by the frictional forces [4, 8].

Emad et al. [4] carried a friction lap stir weld for AA5456 sheets of two thicknesses 5 and 2.5mm. They studied the influence of the tool geometry and the rotation speed on the strength of the lap joints. They used four different pin geometries (conical thread pin, cylindrical-conical thread, stepped conical thread, and flared triflute) with two rotational speed 600 and 800rpm. It was found that the optimum lap joints properties were obtained using the stepped conical pin and the rotation speed of 600rpm.

Babu et al. [7] used two different tools (triangular and threaded taper cylindrical pins) to produce friction stir lap welds in 3mm thick Al clad sheets of Al alloy 2014-T4. The effects of tool geometry on weld microstructure, lap-shear performance and failure mode were investigated. It was found that the pin profile can significantly influence the hook geometry of the weld. Thus affecting the joint strength and failure modes. Buffa et al. [8] reported on investigating lap joining AA2198-T4 by FSW through experimental and numerical analyses. The joint configuration, tool geometry and rotational speed were varied. It was found that using cylindrical-conical pin tools and the appropriate relative sheet positioning increase the welded nugget extension and integrity. Thus, improving the mechanical performances of the obtained joints.

The effects of tool travel and rotation speed on weld quality and defect generation were also investigated. Bisadi et al. [10] investigated the effects of FSW process parameters including rotational and welding speeds on the microstructure and mechanical properties of aluminium 5083 alloy in lap joint welding and analysed different joint defects. They reported that the nugget area had the best grain size as well as higher hardness in comparison with other welding areas. It was also reported that the best joint properties were achieved at a rotational speed of 825rpm and a welding speed of 32mm/min. There seems to be vigorous investigations on friction stir welding of different types of Al alloys but the studies that considered FSW on Al6061 alloys are very few. Moreover, all the cited work above were focused into tool geometry and/or process parameters; mainly tool rotational speed and welding speed. As a result, the current study will investigate FSW on Al6061 alloys considering the rotation speed of the tool, the welding speed and also the pin length to obtain a set of optimum conditions for welding Al6061 alloys through FSW.

2. Experimental Work

A 6061 aluminum alloy plates with a thickness of 3 mm were used to fabricate lap joints by friction stir welding process. The chemical composition of the studied material is given in table 1. Two
rectangular aluminum plates of 300 x 150 mm were lap-welded by friction stir 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. The lap joints were prepared for single lap-shear load.

Table 1: Chemical composition of Al6061 alloy

| 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 |

The welding tool was made out of high carbon steel with 24mm shoulder diameter and 20mm height. A 6mm square pin profile was used in this investigation. The welding parameters used in this investigation are given in table 2. Microstructure examinations were done using an 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. A lap-shear fracture load are prepared according to ASTM: D 1002-01 for single lap shear fracture load. The tensile test specimens had a shape as shown in Fig.1. The test specimens are place in the grip of WDW-20 computer controlled electromechanical universal testing machine and pulled at 1.3 mm/min.

Table 2: The used welding parameters for single lap-shear load

| Experiment no. | Rotational speed rpm) | Welding speed (mm/sec) | Pin length (mm) |
|----------------|-----------------------|------------------------|----------------|
| 1              | 900                   | 1                      | 5.5            |
| 2              | 900                   | 1.5                    | 5.5            |
| 3              | 900                   | 1                      | 4.5            |
| 4              | 900                   | 1.5                    | 4.5            |
| 5              | 1120                  | 1                      | 5.5            |
| 6              | 1120                  | 1.5                    | 5.5            |
| 7              | 1120                  | 1.5                    | 4.5            |
| 8              | 1120                  | 1.5                    | 4.5            |

Figure 1. Tensile specimen

Further analysis of the experiment was also carried out. A characterization of the adhesive bonds between the welded surfaces was necessary to further investigate the performed welding in the study; namely a peel test. Peel testing is used to determine the maximum peel load extensively to evaluate the bonding strength of tape, adhesives and flexible substrates, including rubber, films, biomaterials, dental materials, medical packaging and consumables. This method is used to test lap welded joints within the standard parameters recommended by ASTM. In this study four samples are peel tested to study the effect of welding parameters on the peak peel load.
3. Result and Discussion

3.1. Microstructure

Microstructure of 6061 aluminium alloy lap joint produced by friction stir welding and the base metal was studied by employing optical microscopy. In this study, the microstructure of the stir zone only was studied. Fig. 2 shows a typical microstructure of the base metal used in these experiments. Heat input during welding process controls the temperature of welding zone. The heat input during the welding process depends on the friction stir welding parameters. Heat input increased as the rotational speed increased and is also proportional to applied axial force and the contact area between shoulder face and the welded surface. As the rotational speed increases, the heat input during the friction stir welding process also increases. The evolution of microstructure in the stir zone (SZ) depends on the recrystallization temperature and the cooling rate of welding region. The stir zone of welded lap plates was cooled by ambient air.

Figure 2. Microstructure of base material on the left. Microstructures of the welding joints welded (a) 900 rpm, and (b) 1120 rpm

The effect of the tool rotational speed on the microstructure of the stir zone was considered. The welding speed and the pin length were maintained at 1.5 mm/sec and 5.5 mm respectively whereas the rotational speed changed from 900 rpm in the first case to 1120 rpm in the second case. Fig. 3 shows the effect of the rotational speed on the microstructure of the stir zone. At a rotational speed of 900 rpm, the SZ zone is composed of a fine equiaxed grains formed under high temperature and large deformation in the weld centre due to the stirring process (Fig. 2a). At higher rotational speeds (1120 rpm), more heat is induced during the welding process which gives prolonged heat dissipation with constant welding speed. Fig. 2b shows coarser and deformed grain size. Thus, the heat input during welding process controls the temperature in the welding area.

The effect of the welding speed is considered next. Fig. 3 shows the effect of the welding speed on the microstructure of the stir zone. At low welding speeds (1 mm/sec), the microstructure has a deformed and coarser grain size where observed, Fig. 3a. This is due to the additional heat input that leads to severe plasticity of the metals under the shoulder face. At higher welding speeds (1.5 mm/sec), the microstructure shows deformed and a coarse grain size but with less deformation and size as compared to the microstructure when the welding speed was 1mm/sec, Fig. 3b. Thus, the welding speed controls the rate of heat input during welding per unit length.

Figure 3. Microstructure of welding joints welded at pin length of 5.5mm, rotational speed of 1120 rpm and a welding speed of (a) 1mm/sec and (b) 1.5mm/sec.
3.2. Mechanical Properties

The strength of a lap-welded sample cannot be expressed using the normal load/area, as the stress distribution along the joint area during tensile-shear test is highly uneven [16]. Instead, lap-shear fracture load is used in this study to express joint strength. The quality of the produced lap joints by friction stir welding depends mainly on exists. Which, may extend of three different defects: top sheet thinning, kissing bonds and hooking defects [11]. However, the existence of these defects is commonly influenced by many parameters. The most effective parameters in friction stir welded joints are the tool characteristics and process the parameters such as the rotational and welding speeds the process [17].

In this study, the effect of rotational speed, welding speed, and pin length on the lap-shear fracture load of 6061 aluminium lap welded joints was investigated. Table 3 shows welding parameter combinations and the lap-shear fracture load. In addition, it also shows the fracture location of the tested joints observed in this study. It is clearly shown that all of the tested samples are fractured outside the stir zone except sample 4 which fractured within the stir zone. This sample was welded at a rotational speed of 900 rpm, welding speed of 1.5 mm/sec, and pin length of 4.5 mm. The cross sectional area of the welding area is twice the area of the base metal in lap-joints. Also, the thickness of the welding area is twice the thickness of the base metal since both plates have the same thickness. This indicates that good bonding resulted from successful mixing will occur in the welds. As a result, weldments are most probable to fracture under tensile testing in the base metal particularly in the heat affected zone and/or the thermos-mechanically affected zone.

Sample 5 fractured at the heat affected zone at the top sheet in advanced side due to sheet thinning unlike sample 4 that was discussed earlier. Sample 4 had a pin length of 4.5 mm, and a rotational speed of 900 rpm with a high welding speed of 1.5 mm/sec. This low rotational-high welding speed combination allowed less heat per unit length to be induced to the welding area. Low welding temperature may produce insufficiently stirred sheet interface and cause many defects like kissing bonds. On the other hand, extremely high welding temperature may lead to unexpected joint microstructure or alloy melting.

### Table 3: Strength and elongation of the samples tested under tensile test

| Sample 1 | Sample 2 | Sample 3 |
|----------|----------|----------|
| Rotational speed | 900 rpm | Rotational speed | 900 rpm | Rotational speed | 900 rpm |
| Welding speed | 1 mm/sec | Welding speed | 1.5 mm/sec | Welding speed | 1 mm/sec |
| Pin length | 5.5 mm | Pin length | 5.5 mm | Pin length | 4.5 mm |
| Elongation | 13.71 mm | Elongation | 10.16 mm | Elongation | 9.88 mm |
| Fracture load | 5908 N | Fracture load | 5796 N | Fracture load | 4780 N |

| Sample 4 | Sample 5 | Sample 6 |
|----------|----------|----------|
| Rotational speed | 900 rpm | Rotational speed | 1120 rpm | Rotational speed | 1120 rpm |
| Welding speed | 1.5 mm/sec | Welding speed | 1 mm/sec | Welding speed | 1.5 mm/sec |
| Pin length | 4.5 mm | Pin length | 5.5 mm | Pin length | 5.5 mm |
| Elongation | 6.56 mm | Elongation | 10.86 mm | Elongation | 10.27 mm |
| Fracture load | 4469 N | Fracture load | 5932 N | Fracture load | 6092 N |
3.3. Peel Test
It has been found that the joint welded at a rotational speed of 1120 rpm and welding speed of 1.5 mm/s possess the highest peak peel load as given table 4 sample 2. This result due to suitable balance between rate heat generated due to high rotational speed with the rate of heat dissipation that happened by the forward moving of the tool. Sample 4 in table 4 possess the lowest peak peel load where the joint produced under a rotational speed of 900 rpm and welding speed of 1 mm/s. Fig. 4 shows the fractured samples under peel test. It has been shown that samples 1, 2 and 3 were resist the fracture where some elongation happened to the samples before fracture, where it clear in the samples legs where some cracks appeared due to elongation and reduction in area.

Table 4: Peak peel load of the tested samples under peel test

| Sample No. | Rotational speed rpm | Welding speed mm/s | Pin length mm | Fracture Load N | Location of fracture |
|------------|----------------------|--------------------|---------------|-----------------|---------------------|
| 1          | 1120                 | 1                  | 5.5           | 1672            | Welding area        |
| 2          | 1120                 | 1.5                | 5.5           | 3024            |
| 3          | 900                  | 1.5                | 5.5           | 2304            |
| 4          | 900                  | 1                  | 5.5           | 672             |

4. Conclusion
In this research, friction stir welding of Al6061 alloys was successfully accomplished. Sheet metals were successfully lap-joint welded for a specific range of process parameters. The tool rotational speed seemed to affect the microstructure of the welded material; as the speed increased from 900 to 1120 rpm, the microstructure became coarser and showed more deformation. In addition, high quality lap welded joints can be achieved by adjusting the welding parameters so that a balance between heat input and heat dissipation is reached. As far as the lap-shear fracture load, the welded joints in this investigation seemed to have relatively high lap-shear fracture load. Moreover, the fracture in most cases was observed in the base metal instead of the joint itself. Finally, the lap-joints produced at a rotational speed of 1120 rpm and a welding speed of 1.5 mm/sec had the highest fracture load and seemed to fail at the heat affected zone.

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