Effect of rotation speed and welding speed on Friction Stir Welding of AA1100 Aluminium alloy

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Abstract Aluminum AA1100 is the most widely used grade of Aluminium due to its excellent corrosion resistance, high ductility and reflective finish, the selected material was welded with Friction Stir Welding (FSW) process on a CNC machine, using a combination of different tool rotation speed (1500 rpm, 2500 rpm, 3500 rpm) and welding speed (10 mm/min, 30 mm/min, 50 mm/min) as welding parameters. The effect of FSW using this welding parameter was studied by measuring the ultimate tensile strength of the welded joints. A high-speed steel tool was prepared for welding the Aluminium AA1100 alloy having an 8mm shoulder diameter and pin dimension of 4mm diameter and 2.8 mm length. The welded joints were tested using the universal testing machine. It was found that Ultimate Tensile Strength of FSW specimen was highest with a value of 98.08 MPa when the weld was performed at rotation speed of 1500 RPM and welding speed of 50 mm/min.

Keywords: Friction Stir Welding, Ultimate Tensile Strength, Hardness Testing, Welding parameter.

1. Introduction
Friction Stir Welding is becoming a critical technology as it enhances efficiency by reducing the number of weld passes that traditional fusion arc welding requires. In addition, it offers safer, environmentally friendly operations than traditional welding by not creating hazards such as welding fumes, radiation or high voltage. This characteristic of FSW has made NASA’s next heavy-lift launch vehicle, the Space Launch System development faster [1]. FSW has become a critical technology, which is economical and environment friendly welding process of this generation for most of the industrial applications such as aerospace, automotive, railway, maritime, etc. [2]

Friction stir welding (FSW) is a solid-state joining process, invented by Thomas et al. [3] at The Welding Institute (TWI) of the UK in December 1991. In this method, a cylindrical shoulder tool with pin is rotated and plunged into the metal plate heating the metals to a temperature below recrystallization temperature and joining is performed with the pressure applied by the shoulder of the tool. For FSW, there is four major process parameter that should be controlled; they are down force, welding speed, the rotation speed of the welding tool and welding speed and tilting angle [2]. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of the tool moves the stirred material from the front to the back of the rotating pin and finishes the welding process. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. In this study, the effect of two welding parameters; rotation speed and welding speed on Aluminium alloy AA1100 is examined. FSW was applied on Aluminium alloys AA 1100 as it is the most popular grade of aluminium for general purpose sheet metal works where moderate strength is the required.
This paper demonstrates the Friction stir welding process on Aluminium Alloy AA1100 and studies the effect of welding parameters such as the tool rotational speed and rate of welding on the ultimate tensile strength of the welded joints.

2. Methodology
The steps followed for friction stir welding process is shown in figure 1.

![Figure 1. Methodology Friction Stir Welding](image)

2.1. Material characterization
Aluminium alloy AA1100 plates was utilized as the base plate for welding in this study. The composition of the material and its mechanical properties are given in the Table 1 and 2. The dimension of the base plate for friction stir welding was selected as 100 mm X 75 mm as shown in figure 2. The selected dimension was based on obtaining five tensile specimens and giving allowance for holding the specimen on the CNC machine. The mechanical properties of the material are shown in Table 2.

![Figure 2. Specimen geometry](image)

| Element      | Composition in % |
|--------------|------------------|
| Silicon + iron | 1                |
| Copper       | 0.05 to 0.20     |
| Manganese    | 0.0 to 0.05      |
| Zinc         | 0.0 to 0.10      |
| Others       | 0.15             |
| Aluminum     | Balance          |

Table 1. Composition of AA 1100

| Property         | Value     |
|------------------|-----------|
| Proof stress     | Min 75 MPa|
| Tensile strength | 110 to 125 MPa |
| Hardness Brinell | Approximately 32 HB |
| Modulus of Elasticity | 69 GPa |

Table 2. Mechanical Properties of AA 1100
All the edges of workpiece were machined by milling machine for proper alignment during welding and the surface of workpiece was cleaned with acetone.

2.2. Welding parameter

Before choosing the parameter for welding trial test was carried out in order to determine the welding parameters. In the trial test experiments speed less than 1500 rpm resulted in low mechanical strength, so speed less than 1500 rpm was not considered as test parameter. Also, it was noticed during the trial test that rotation speed above 3500 rpm reduce the mechanical strength. Considering the machine specification and trial tests, the test parameters were selected as rotation speed of 1500, 2500, 3500 rpm and welding speed of 10, 30, 50 mm/min. The specimens in this study are designated as FX_SY. Where F is the welding speed with X value and S is the rotation speed with Y value. Example F10_S1500 specimen was obtained when FSW was carried out with rotation speed of 1500 and welding speed of 10 mm/min.

2.3. Friction stir welding tool

A friction stir welding (FSW) tool typically consists of a rotating round shoulder and a cylindrical pin that heats the base plate to be welded, mostly by friction, and moves the softened alloy around it to form the joint [4]. The tool has two primary functions: (a) localized heating, and (b) material flow. From the heating aspect, the relative size of pin and shoulder is important. The shoulder also provides confinement for the heated volume of material. The second function of the tool is to ‘stir’ and ‘move’ the material. The uniformity of microstructure and properties as well as process loads is governed by the tool design [5].

For this study the steel tool having a hardness of HRC 60 was used for manufacturing the tool using a cylindrical grinding machine. The dimension of the tool was based on the thickness of aluminum plate to be welded which was 3mm. The dimension of the tool pin length was chosen to be 2.8 mm, 0.2 mm shorter than the thickness of the plate. Pin diameter of 4 mm and the shoulder diameter of 8 mm which is twice that of pin diameter was chosen. Shoulder length of 30 mm was considered assuming 25 mm of the cutter will be placed inside the tool holder.

2.4. Friction stir welding using CNC machine

FSW was performed on the CNC milling machine. A CNC part program was written using G and M codes for moving the FSW tool in a straight line with selected welding parameters. The two base plate which is to be welded was positioned on the backing plate in the fixture and was held in place using mechanical clamps as shown in figure 3 a. Tool offset was taken to define the datum of the workpiece and the CNC program was executed to perform the friction stir welding along the X axis. Figure 3 b shows the welded joint after FSW process.

CNC program was edited to have different values of welding parameter and executed to obtain welding joints at different weld parameters.
2.5. Tensile and Hardness testing
The tensile specimen was prepared according to the ASTM E8/E8M-09 standard test methods with a dimension of 100 mm specimen length, 6mm width, 3 mm thickness and 25 mm gage length. The tensile specimen was machined using water jet cutting machine. The tensile test on the specimen was performed on Instron Universal Testing Machine shown if figure 4 with a test speed of 2 mm/min. Five specimens were tested under each welding parameter.

![Figure 4](image)

**Figure 4.** Tensile test of the specimen F50_S1500 on Universal tensile testing machine.

Hardness testing of the specimen was performed using Vickers hardness scale HV1.

2.6. SEM
Fracture surfaces of the tensile test specimens were characterized through SEM. SEM images of the tensile fractured specimen were taken using FEI's Quanta 200 SEM machine at 30 X and 1200 X magnification for both F50_1500 and F50_3500 specimens.

3. Result and discussion
3.1 Tensile test
Ultimate Tensile Strength (UTS) of the specimens given in the Table 1 was measured using the Universal tensile testing machines. F50_S1500 specimen had the highest UTS of 98.08 MPa which is 19.12 % lower than the base metal. The UTS of the all specimens with welding speeds of 10 mm/min had around 40% reduction in the tensile strength compared to base metal. This shows that changing the rotation speed at welding speed of 10 mm/min does not change the UTS significantly. Similarly, it can be noticed that when the rotation speed is 3500 rpm the change in the welding speeds does not make significant changes in the UTS as shown in Figure 5.

The Yield strength of F50_S1500 specimen and base metal plate material was calculated as 66.76 MPa and 72.15 MPa, respectively by considering 0.2% offset on the stress-strain curve shown in figure 6. The close values of yield strength between the specimen show that the behavior of the F50_S1500 specimen is similar to the base metal. Also, it can be seen from the stress-strain plot that F50_S1500 underwent plastic deformation similar to the base metal. F50_S1500 specimen behaves similar to the base metal plate material in both elastic and plastic regions which clearly indicates that the quality of weld obtained using the rotation speed of 1500 rpm and welding speed of 50 mm/min had a strong joint. It is also seen from the SEM image shown in Figure 9b of the fractured tensile F50_S1500 specimen had a “cup and cone” pattern which is a characteristic of ductile fracture mechanism. The welded specimen during the tensile test fractured at an angle shown in figure 6 b and the failure starts from the bottom end of the welding specimen due to surface void from the bottom of the stir zone due to lower welding temperature and insufficient material flow.
Table 1. Measured UTS of welded joints at different parameters

| Test No. | Welding Parameters | UTS (MPa) | % Decrease in UTS of welded joints |
|----------|--------------------|-----------|-----------------------------------|
| 1        | Base metal plate   | 121.26    | -                                 |
| 2        | F10_S1500          | 72.53     | 40.19                             |
| 3        | F10_S2500          | 73.87     | 39.08                             |
| 4        | F10_S3500          | 74.54     | 38.53                             |
| 5        | F30_S1500          | 90.92     | -                                 |
| 6        | F30_S2500          | 78.49     | 35.27                             |
| 7        | F30_S3500          | 72.07     | 40.57                             |
| 8        | F50_S1500          | 98.08     | 19.12                             |
| 9        | F50_S2500          | 83.02     | 31.54                             |
| 10       | F50_S3500          | 69.93     | 42.33                             |

Figure 5. Welding parameter effects on tensile strength

3.2 Hardness
The cross-section of welded joint were mounted and polished. Micro hardness measurement was made using Vicker hardness indentor by applying a force of 1kgf with a hold time of 6 seconds on a universal hardness testing machine Duramin A2500.
The hardness measurement was made on F50_S1500 specimen at an interval of 1 mm as shown in the figure 7. It is also seen that hardness value in different welded regions is lower than the base metal. The Hardness value is in range of 32-40 which could be due to the alloy being recovery and recrystallization as a result of hot deformation during welding.

![Hardness measurement diagram](image)

NZ- Nugget zone, TMAZ- Thermomechanically affected zone, HAZ - Heat-affected zone, BM - Base metal

**Figure 7. Hardness measurement**

### 3.3 SEM

The fracture surfaces of the tensile test specimens were characterized through SEM and the fracture morphology is shown in figure 8.

![SEM image](image)

**Figure 8. SEM image of F50_1500 specimen.**
Microvoid coalescence shown in figure 8 b. Initiates the fracture in the specimen F50_1500 which creates a “cup and cone” pattern. This is a characteristic of a ductile fracture mechanism. It is noticed that the fracture on the welded side and on the bottom side of the specimen as shown in figure 8a are different. On the welded side material break due to shear stress, whereas on the bottom side the fracture looks brittle. Crates are seen at a few locations on an interior region of the fracture specimen F50_S3500 which is shown in figure 9a. A river marking characteristics as seen in the figure 9b indicates that the failure of the specimen was brittle. It was also noticed that there were no dimples seen in any part of the fracture of F50_3500 specimen.

4. Conclusion
An attempt has been made to study the effect of rotational speed and welding speed on friction stir welding of AA 1100 alloy using a CNC milling machine. The microhardness results in different weld regions show that the hardness is lower than that of base metal. Microvoid coalescence and cup and cone type of failure has been observed on the fractured specimens at low speed and at high speed craters are seen at a few locations on an interior region of the fracture specimen leading to brittle fracture. The optimum parameter for the friction Stir Welding on Aluminum alloy AA 1100 was found to be at rotating speed of 1500 rpm and welding speed of 50 mm/min which had a joining strength of 80.9% of the parent material.

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