Effect of welding parameters on the mechanical and microstructural properties of friction stir welded AA-2014 joints

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Abstract. In this study, the effect of processing parameters on the mechanical and microstructural properties of aluminum AA2014-T6 joints produced by friction stir welding was analyzed. Friction stir welding was carried out on a milling machine. Different samples were produced by varying the tool rotational rates (700, 1000 rpm) and travel speeds (45-105 mm/min). Tensile tests performed at room temperature were used to evaluate the mechanical properties of the joints. In order to analyze the microstructural evolution of the material, the welds' cross-sections were observed under optical microscope. The results shows that the resulting microstructure is free of defects and tensile strength of the welded joints is up to 75% of the base metal strength.

1. Introduction
The Friction Stir Welding (FSW), is a solid state welding process invented by The Welding Institute in 1991 [1-3]. Since then its industrial use has been increasing. For aerospace applications, this process is attractive to replace the traditional riveting process in fuselage panels, reducing the production costs (being faster) and weight of airframes. Further, it can produce high quality joints in most of the high strength and damage tolerant 2XXX and 7XXX series of aluminum alloys. Such alloys are not suitable for conventional fusion welding processes due to the poor solidification microstructure, resulting in low strength when comparing to the base metal. Further, such alloys have high propensity to develop solidification cracks [4-5].

In FSW process, the joint is obtained by a non-consumable rotating tool, containing a pin and a shoulder. The friction between the shoulder and the surface of the work-piece generates most of the heat that plasticizes the material at the joining surfaces [6]. Simultaneously, the pin penetrates the work-piece, stirring the material at the interface and promoting joint. Further, the shoulder imposes forging forces to the stirred material, resulting in a defect free weld. The combination of the tool rotation and its translation through the interface is responsible for the formation of a high quality welding line.

A review from Mishra and Ma [3] summarizes several studies in FSW of aluminum alloys that converge to the identification of three distinct regions in the welding line: the stirring zone, also known as nugget, the thermomechanically affected zone (TMAZ) and the heat affected zone (HAZ). The grain size in the stir zone is fine and equiaxed, resulting in higher mechanical strength and ductility [7-10]. The thermomechanically affected zone (TMAZ) surrounds the stirring zone and is formed by high deformed non-recrystallized grains. The interface between the highly deformed and the stirred zones is not well defined in the retreating side of the welding line, but it is very well defined in the advancing side. The third zone of the FSW bead, known as the heat affected zone (HAZ),
undergoes a thermal cycle without any plastic deformation associated. For aluminum alloys, the HAZ can be defined as the region starting at the TMAZ and extending up to regions where temperatures above 250°C are reached [6]. Below this temperature the microstructure seems to be unaffected, as the exposition time is very short. The 2014-T6 aluminum alloy is one of the 2xxx-series heat-treatable aluminum alloys and it has rarely been friction stir welded up to now. This paper aims to demonstrate friction stir weldability of AA-2014 alloy and the emphasis is laid on the relations of the tensile properties and microstructure of the joints in order to optimize the FSW parameters.

![Figure 1](image)

**Figure 1.** The schematic of FSW process, tool and tensile specimen used in present work

2. **Experimental procedure**

The material used in this study is 2014-T6 alloy, with the chemical compositions and mechanical properties listed in Table 1. The AA-2014 plates (600×1000×3mm) were cut and machined into rectangular welding samples 200mmx65mmx2.5mm. The test pieces were first ground using steel brush and sandpaper to remove the oxide film, and then cleaned with acetone to remove oil.

Welding was performed on a conventional milling machine (specially adopted for FSW by changing its mechanism in over arm spindle) driven by a 3hp motor with a 4A current rating using a square pin FSW tool. The schematic of friction stir welding process and tool employed for welding is shown in figure 1. There is an angle adjustment in the spindle, which allows setting of the tool tilt angle necessary for FSW. The feed speeds are gear driven with discrete speed options for both the specimen table travel and the spindle RPM. The welding parameters and welding tool size used in the experiments are shown in Table 2.

After welding, the welded joints were visually examined, were cross-sectioned transverse to the welding direction for metallographic analyses and tensile tests using Wire Cut machine. The cross-sections of the metallographic specimens were polished with a diamond paste, etched with Keller’s reagent and observed under optical microscope. Room-temperature tensile tests were carried out at a crosshead speed of 1 mm/sec using an Instron testing machine. The gauge length of each specimen was 25 mm, and the tensile properties of each joint were evaluated using three tensile specimens cut from the same joint.

| Table 1. Chemical compositions and mechanical properties of 2014-T6 aluminum alloy |
|----------------------------------|------------------|-----------------|------------------|
| **Chemical compositions (wt. %)** |                  | **Mechanical properties**               |
| Al  | Si   | Fe  | Cu  | Mg  | Mn  | Ti  | Zn  | Cr  | Tensile Strength (MPa) | Yield strength (MPa) | Elongation (%) |
| Bal | 0.55 | 0.16 | 2.06 | 0.33 | 0.34 | 0.02 | 0.08 | 0.02 | 470                  | 407.3              | 9.9          |


| Tool size (mm)       | Welding parameters |
|---------------------|--------------------|
| Shoulder diameter   | Pin dimension      | Pin length | Rotation speed (rpm) | Welding speed (mm/min) | Tool tilt (°) |
| 20                  | 5X5 square         | 2.3        | 700/1000             | 45–105                 | 2.5          |

3. Results and discussions

Microstructure

Figure 2 shows the microstructure of base metal plate. It constitutes large grains; typical feature of rolled structures with almost uniform distribution of second phase particles.

![Figure 2](image)

Figure 2. Microstructure of AA-2014 base plate

Figure 3 shows the cross section of joint welded at 1000 rpm and 105mm/min with low magnification. A complete penetration of the welding up to the root region of the sample was observed and no typical FSW defects like kissing bonds, voids, cracks etc. were observed.

![Figure 3](image)

Figure 3. Microstructure of Welded Joints at low magnification

The microstructures of distinct zones of welded joints at different travel speeds at 1000 rpm is shown in Figure 4. The grain size is remarkably smaller in the nugget zone as this region has experienced the high temperature and extensive deformation and is characterized by dynamically recrystallized grains. A clear interface is seen between the stirred (nugget) and TMAZ zone in the joint welded at lower travel speed (upto 65mm/min) indicating the insufficient flow of material. It is also obvious that region between the nugget and TMAZ zones always exhibit the poor property zone of the joint. The lower mechanical properties of the joints welded at lower travel speeds may be due to this reason. As the speed is increased the interface between nugget and TMAZ zone becoming diffused showing uniform flow of material and ultimately better mechanical properties.
Figure 4. Microstructures in Weld Nugget -TMAZ Zone at 700 rpm. (a) 45mm/min (b) 65mm/min (c) 85mm/min (d) 105mm/min

4. Tensile properties of joints

The transverse tensile properties such as yield strength, tensile strength, percentage of elongation and joint efficiency of friction stir welded AA-2014 alloy joints were evaluated. In each condition, three specimens were tested and the average of results is presented in Figure 5. It is observed that ultimate tensile strength of the joint increases with increasing travel speed irrespective of the tool rpm reaching about 75.6 of the base metal strength and then decreases. These values are amongst the highest reported in the literature for friction stir welded AA-2014 T6 alloys, which ranges typically 60-70% of base metal strength. [6].

The elongation of the joint reached about 66.6% of the elongation of the base metal. Nevertheless it remain around 6.6% showing good ductility. The joint strength is mainly due to microstructural aspects which in turn depends on the temperature generated during welding. As can be seen from Figure 4, difference in microstructures appear by varying the travel speeds. The decrease in joint efficiency at lower travel speeds may be due to improper heat input and non-uniform flow of material as is obvious in micrographs due to high speed.
5. Conclusion
The maximum joint/weld efficiency is achieved at 1000 rpm and 105 mm/min travel speed. This may be due to the diffused region between the stirred and TMAZ zone indicating the better flow of material during the welding.

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7. References
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