

Effect of Processing Parameters on Microstructure and Mechanical Properties of Friction Stir Welded 6061 Aluminium Alloy Joints

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ABSTRACT

In this research, friction stir welding was successfully conducted on 6 mm thick Al6061 plates, varying tool rotation speeds from 1100 to 1500 rpm at constant traverse speed of 50 mm/min. Optical microscopy was used in order to carry out microstructural examinations of welded junctions. Significantly, joints produced at a welding speed of 1500 rpm demonstrated exceptional tensile characteristics. A discernible transformation occurred in the microstructure, wherein coarse grains within the parent material underwent a morphological change, transitioning into fine equiaxed recrystallized grains specifically within the nugget zone. Hardness assessments revealed that the hardness values of the nugget zones in all welded joints surpassed those of the parent material, with the lowest recorded hardness values observed in weld produced at a speed of 1100 rpm. This observed microstructural refinement and hardness variation signify the successful alteration of material properties, particularly within the nugget zone, as a consequence of the stirring action of tool.

Keywords: Friction stir welding, Mechanical properties, Microstructure, Aluminium alloy.

1. Introduction

In today's world, light weight aluminium Al6061 alloys are widely used in industrial sectors owing to their high strength to weight ratio, good corrosion resistance, weldability, recyclability, low density, excellent energy absorption properties and good ductility [1-6]. However, it do not possess good hardness and wear properties. So, while manufacturing welding of these alloys is frequently needed [2]. Generally conventional liquid state fusion welding techniques, which turns the material into molten state are employed to fabricate the joints. The primary technical challenges faced while welding aluminium alloys arise from its stable oxide layer. This layer makes it prone to weld cracking during liquid-state welding, mostly owing to the production of grain boundary films. These issues are effectively eradicated by friction stir welding because it creates solid-state welds (grain boundary films only develop in the liquid state) and because the tool's shearing motion compresses and distributes the stable oxide layer across the weld region, minimising any negative consequences [4].

Friction stir welding (FSW) is a novel method of joining materials without melting them, which was created in December 1991 by Wayne Thomas at The Welding Institute (TWI) in Cambridge, United Kingdom [3]. In order to create a straight weld in a butt joint arrangement, the workpieces are aligned on the backing plate such that their edges are in direct touch. The spinning non-consumable tool is inserted into the weld joint with a vertical force until the shoulder of the tool touches the upper surfaces of the work components. Frictional heat produced by the shearing action of tool in the workpiece plastically deforms the material and the stirring pin mixes the material of two plates with each other at plastic stage. Subsequently, the tool proceeds in a forward manner. Once the forced rotating tool completes the passage between the abutting plates, it is then removed from the surface thus, successfully completing of the whole welding process, leaving a hole created by tool's pin, often referred to as a pin hole defect. [1].

A welded junction is produced by plastic deformation and frictional heating at temperatures lower than the melting point of the alloys being joined when a non-consumable spinning tool impinges within the workpieces being welded[7]. Welding parameters include the speed at which the tool rotates, the speed at which it traverses, the shape of the tool, and the axial force. The microstructure development and subsequent mechanical characteristics are highly influenced by the changes in process parameters, resulting in a diverse spectrum of potential performances[8]. So a good parametric combination is required for achieving desirable properties of the weldment.

FSW is gaining recognition as a suitable alternative technique because of its cost-effectiveness, little distortion, ease of application, and strong joint formation. Additionally, this joining technique is environmentally sustainable since it does not need the use of flux, shielding gas, or filler material[3]. The aim of this study is to examine the impact of tool rotating speed on the mechanical and microstructural characteristics of Friction Stir Welding.

2. Experimentation

The workpiece material of Al6061 alloy plates in a T6 tempered condition, was cut on power hacksaw measuring 100 mm x 50 mm x 6 mm. Table 1 provides information about the alloy's chemical composition. Table 1. Chemical composition (wt %) of workpiece material.

Al	Si	Mg	Mn	Cu	Cr	Fe	Ti
Balance	0.61	0.69	0.025	0.04	0.004	0.251	0.004

A wire brush and acetone were used to clean a pair of workpiece materials in order to remove the oxide layer and any other greasy substance that was present on them. Next, they were firmly fastened and secured on a specially made fixture in the shape of a square butt joint and welding was performed on a vertical CNC milling machine (Deckel, Germany) with setup as depicted in Fig.1. The joint was fabricated utilising a non-consumable cylindrical threaded pin profiled tool constructed from high carbon steel as specified in Table 2.

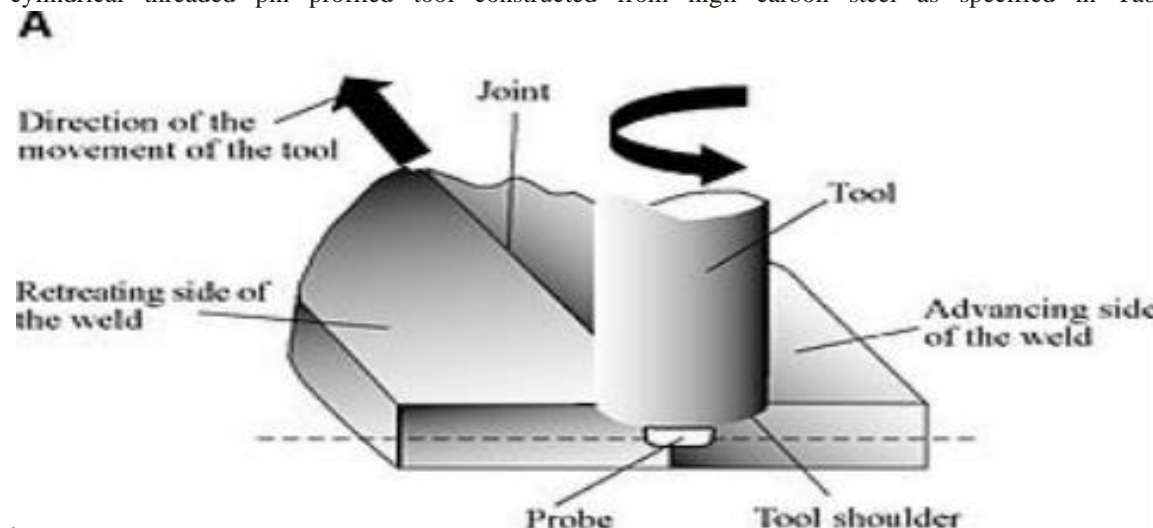


Fig.1. – Friction stir welding.

Table 2. Specifications of tool.

Tool length	90 mm
Tool diameter	18 mm
Pin diameter	6 mm

Pin length	5.7 mm
Pitch of thread	1.5 mm
Angle	600
Tool till angle	30

The tool fixed in collet was mounted on the vertical spindle of CNC milling machine hydraulically and was tilted at an angle of 3° with respect to the workpiece attached with the help of fixture on the bed of CNC milling machine. Then the rotating tool was made to plunge into the square butt joint configuration with an axial downward force. The tool is rotated as the pin is forced into a location on a surface until the shoulder impinges into the workpiece. Once the pin has fully penetrated and shoulder touches the workpiece the tool was traversed along abutting edges to accomplish welding of separate workpieces. A single pass welding procedure was used to fabricate the joint. The bed was given automatic feed and axial force was kept constant. Tool rotation speed was identified as critical welding parameters. So welding was performed by varying the tool rotational speed (1100 rpm, 1300 rpm and 1500 rpm) and other parameters were kept constant; shoulder diameter of 18 mm, transverse speed 50 mm/min and tilt angle 3°.

After welding the workpieces were removed and sliced on power hacksaw into required sizes for tensile test, hardness test and metallographic tests. The outer parts of 15 mm were discarded from both sides as shown in Fig. 2. For metallography, the specimens were collected from middle portion of the weldments to ensure a true representation of weld characteristics. Metallographic specimens were then polished by using emery papers having grit sequence of 400, 600, 800, 1000, 1500 and 2000 following standard metallographic procedure. After this the samples were polished using diamond paste of medium micron size on polishing cloth(velvet) on disc polishing machine thus obtaining a mirror image. Then polished specimens were etched with Keller's reagent to reveal the grain structure.

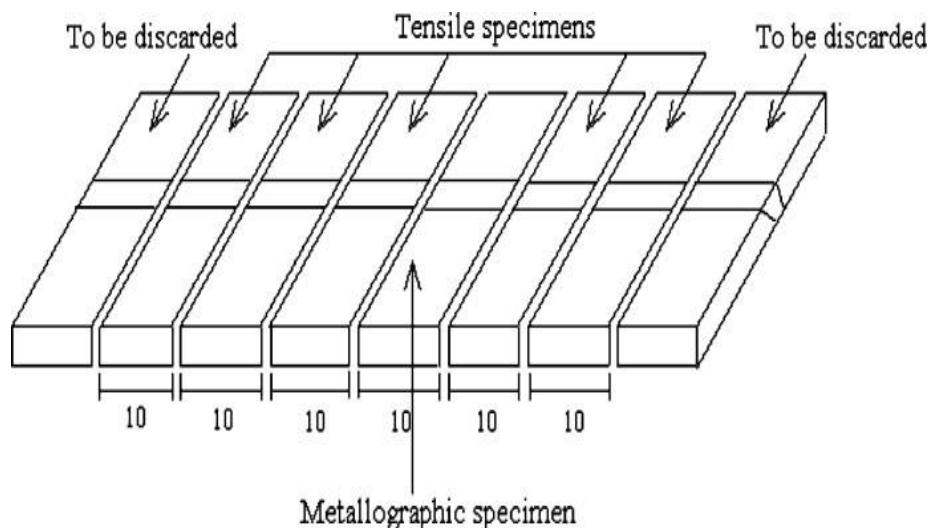


Fig. 2. Schematic diagram showing from where specimens were machined.

The microstructure on top, stir zone and HAZ was studied under inverted optical microscope (Make: Leica, USA). The samples for hardness test were kept same as that for microstructural analysis. Vickers microhardness tester (Omnitech, Pune) was used to check the hardness from top and cross-section of the weldment. It was done at a load of 100 gms for 10 seconds. X-ray radiography was carried out to see the internal defects like porosity voids and cracks in the weldment. The tensile test was carried out to check the tensile strength of the joint on Universal testing machine 60 KN (Make: Heico, New Delhi). The standards are taken from ASTM Internationals, Designation B 557M – 07.

3. Results and Discussion

3.1. Macroscopic analysis

Almost, all the weld joints prepared by FSW at various defined parameters shows smooth surface finish.

3.2. X-Ray radiography

X- Ray radiography was done on all the samples and it was observed that there is no porosity and voids present in the weld zone of friction stir welded except for a tunnel defect observed in the weld produced at a tool rotation speed of 1100 rpm (Figure 3). This anomaly may be attributed to the lower tool rotation speed, which fails to generate adequate heat for the plastic flow of material. These findings align with the conclusions drawn by Ghosh et al. [6]. Also voids/defects within the weld nugget are generated owing to difference in material transport and degree of consolidation.



Fig. 3. Defects in welded workpieces prepared at tool rotation speed of 1100 rpm.

3.3. Microstructure analysis

It was observed that fine equiaxed grains were formed in the process performed at tool rotation speed of 1100 rpm (Fig. 4(a)). With the increase in rotational speed from 1100 rpm to 1300 rpm the grain size reduced and microstructure got refine as shown in Fig. 4(b). Higher rpm of tool resulted in better stirring action and higher temperature which in turn improves the plastic flow of material resulting in fine equiaxed grains. At a tool rotation speed of 1500 rpm the grain size got refined (Fig. 6(c)) in comparison to grain size produced at tool rotation speed of 1100 rpm and 1300 rpm. This may be attributed due to reason that at high rpm the intensified stirring action took place which resulted in grain refinement, also at high rpm the heat generated in weld zone is high which resulted in proper plastic flow of material, resulting in grain refinement. It was observed that with the increase in rotation speed the temperature increases in the nugget zone and proper stirring takes place resulting in fine grain structure. This is consistent with the work reported by Hwang et al. (2008). During higher rotation speeds particles would suffer more fragmentation which leads to more recrystallization of coarse grains and formation of new grain boundaries and high dislocation density leads to ultra fine grain structure.

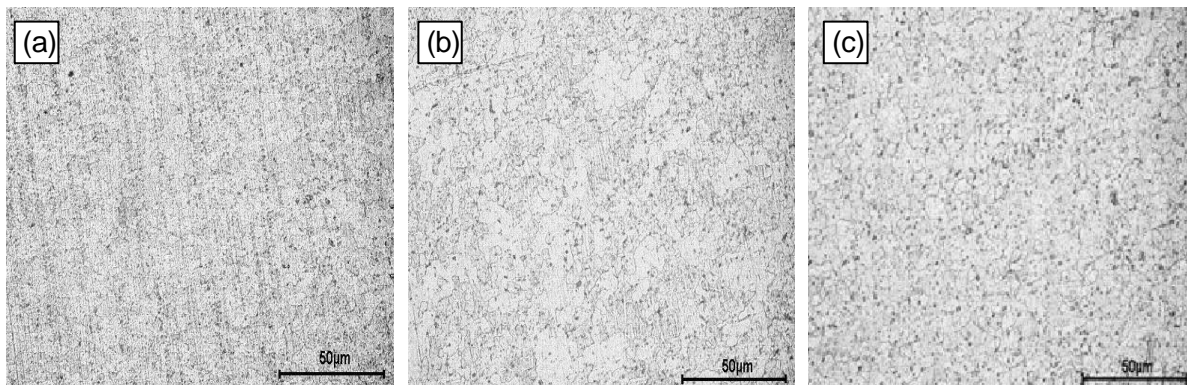


Fig . 4. Microstructure from top of the weldments joined at tool rotation speed of (a) 1100 rpm (b) 1300 rpm (c) 1500 rpm.

3.4. Tensile Test

Tensile strength of base material in T6 tempered state was found to be 226 Mpa and a maximum tensile strength achieved by FSW joint was found to be 155 Mpa at rotation speed of 1500 rpm (Fig. 5). The highest tensile strength of base metal was due to presence of fine precipitates Mg_2Si . Also the artificial aged T6 tempered state of base alloy was disturbed during FSW, this may be another reason for lower tensile strength of all the weldments as compared to base metal [9]. During tensile test all the specimens failed in the weld region which indicated that weld region is comparatively weaker than other regions and hence joint properties are controlled by weld region composition and microstructure. With the increase in rotation speed the temperature within the nugget becomes higher and more uniform. The volume fraction of coarse particles thus decreased which may be responsible for sound welding. Further at higher rpm the fine precipitates were uniformly distributed within the interior of grains and grain boundaries. This may be one of the reason for superior tensile strength at higher rpm. Further, lower value of rpm may result in improper plastic flow and insufficient consolidation of metal in friction stir processing zone which may be reasons for low tensile strength at low rpm.

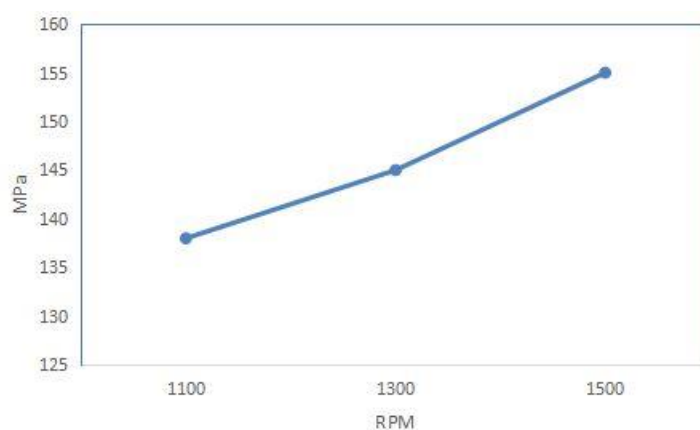


Fig. 5. Comparison of tensile strength on the basis of rotation speed of tool.

These findings align with the observations of Cavaliere et al. [10], who noted that a decrease in temperature within the nugget zone impairs the force's ability to induce proper plastic flow during continuous dynamic recrystallization. High temperatures resulting from high traversing speed can lead to improved ductility of weld joint. Similarly, Sundaram and Murugan [11] reported analogous outcomes, indicating that an increase in tool rotation speed leads to a rise in tensile strength. This is attributed to the hindrance of the clustering effect of strengthening precipitates, impeding plastic flow of material, and promoting the ductility of weld joint.

3.5. Hardness

Hardness from top of the weld along centre weld line was measured at different rotational speed as shown in Fig. 6. Hardness of the weld zone is found to be 15-25% more than the base metal. During friction stir welding, temperatures in the range of 300°C to 400°C can be achieved, as reported by Lakshminarayanan et al. [4]. Additionally, stable strengthening precipitates, which are effective up to temperatures of 280°C, undergo dissolution at these elevated temperatures, as reported by Hwang et al. [12]. The results depicted in Figure 9 indicate an increase in hardness with an increase in rotational speed. However, after 1300 rpm hardness slightly dropped due to high heat generation. This phenomenon can be explained by the heightened stirring action at higher rotational speeds, leading to grain refinement and consequently higher hardness values but after limit the hardened precipitates become unstable leading to slightly drop in values.

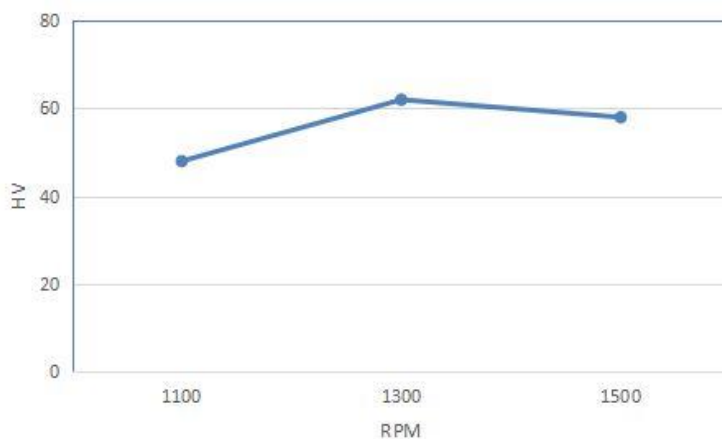


Fig. 6. Comparison of hardness on the basis of tool rotation speed

4. Conclusion

This study investigates the impact of tool rotation speed on the microstructure, tensile strength, and hardness of friction stir-welded Al6061 alloy. The microstructure within the nugget zone is found to be significantly influenced by the tool rotation speed. Tensile strength and hardness, crucial mechanical properties, are observed to depend on the microstructure evolution induced by various process parameters. The results indicate a trend where an increase in tool rotational speed leads to rise in tensile strength. However, A notable increase of 15-25% in hardness is observed, but hardness increases with the rise in tool rotation speed for a specific limit afterwards it shows the trend of drop in hardness value. The diminution in mechanical properties of friction stir-welded joints is attributed to the loss of the T6 tempered condition of the base metal. The findings shows the intricate relationship between microstructure evolution and mechanical properties in the context of varying tool rotation speeds during the friction stir welding process. So, it may be concluded that the selection of good parametric combination of tool rotation speed and traverse speed is of prime importance for the tensile strength hardness, microstructure and other properties of the welded joint in case of friction stir welding process.

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