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EXPERIMENTAL INVESTIGATION OF HARDNESS AND SURFACE ROUGHNESS IN THE FRICTION STIR WELDING OF THE 6061-T6 ALUMINUM ALLOY

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The interesting process of friction stir welding (FSW) has become popular for connecting a variety of materials. It is crucial for the industry to have an effective assembly process that uses little energy and has a lot of potential regarding mechanical strength. However, the complexity and unpredictability of FSW joints means that their behavior has a significant impact on the dynamic properties of such structures.
Therefore, the primary goal of this research project is to experimentally investigate the impact of rotational speed and feed rate on the surface condition of joints. The study takes into account the variance in surface roughness (*Rz*), which is crucial when determining the quality of joints. These experiments will help researchers to better understand how these two characteristics affect the surface quality of joints. Such knowledge is crucial for the industry because it may help to develop effective FSW joints with increased mechanical strength.

Keywords: friction stir welding (FSW), assembly, aluminum 6061-T6, hardness, surface roughness (*Rz*)

1. Introduction

Welding is a process which consists of creating a permanent connection between two or more parts whose compositions are identical or different by simultaneously applying heat, pressure or a combination of heat and pressure. Although metals and thermoplastics are typically welded, wood can also be. Friction stir welding (FSW) is an innovative welding process with numerous applications across various industrial sectors, including the naval, aeronautical, aerospace, railway and automotive industries [1]-[2]. During the early 1990s, FSW emerged as an innovative solid-state joining process, originally developed by The Welding Institute in the UK. This method produces high-quality, defect-free joints with enhanced mechanical properties in comparison to fusion welding [3]. FSW involves blending the base material through the utilization of a tool comprised of a pin and a shoulder that interact with the upper surface of the sheet to be joined [4]. The generation of heat in the FSW process is the result of friction between the metal tool and the workpiece material given its rotational speed and feed rate.

The tool also provides high mechanical and thermal resistance in order to guarantee a high-quality weld between the two parts to be welded, Therefore, loss of plasticity in the materials to be welded is essential for this technique to be executed smoothly [5]-[7].

Several researchers have conducted studies on experimental and numerical simulation methods of FSW, including thermal and mechanical responses [8]-[10]; residual stresses [11]-[12]; vibrational characteristics [13]-[15]; as well as fatigue and damage behavior [16]-[18].

FSW has demonstrated superior microstructural and mechanical attributes, overcoming the shortcomings associated with other welding techniques. The majority of research into FSW has been directed toward investigating its physical, mechanical, microstructural and metallurgical characteristics [19]-[24]. In the literature, numerous researchers have examined the effect of surface roughness on the condition of welded joints. Belaziz et al. [25] explored the influence of welding parameters, specifically the rotational and welding speeds, on the surface roughness of FSW joints.

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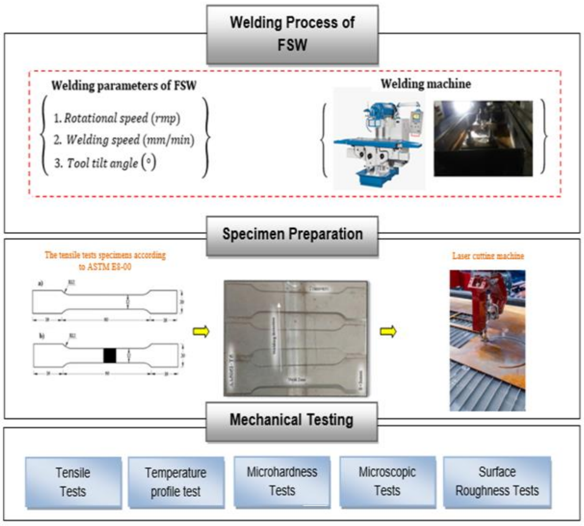


Figure 1: The various experimental stages of the FSW welding process

Figure 2: Milling machine used for FSW welding

The surface roughness of a 120 mm-long welded joint was assessed at five distinct locations, placing particular emphasis on both the initial and terminal sections of the welding tool. Satyanarayana et al. [26] examined how the surface roughness of austenitic stainless steel impacted heterogeneous friction stir welded joints. Boulahem et al. [27] introduced a Surface Roughness Model and undertook parametric optimization of the FSW of AA2017 using the Taguchi method and response surface methodology.

The objective of this research is to investigate the correlation between welding parameters, specifically rotational speed and feed rate, and the surface roughness (*Rz*) of welded joints in the case of 6061-T6 aluminum (Al 6061-T6) plates.

2. Experimental study

Experimenting with the FSW process and understanding the intricate interplay between welding variables, particularly the rotational speed and feed rate, as well as their influence on the surface quality of welded joints between Al 6061-T6 plates entails the execution of several technical stages. *Figure 1* illustrates the key steps of the study.

2.1. Materials

Plates of the Al 6061-T6 wrought aluminum alloy that were 5 mm thick, 250 mm long and 100 mm wide were joined using FSW. *Table 1* shows the chemical composition and mechanical properties of the Al 6061-T6 aluminum alloy and XC 48 steel.

2.2. FSW process

The experimental process of FSW welding was conducted using a 301258 universal milling machine represented in *Figure 2*. FSW was conducted using a tool 16 mm in diameter and a threaded shoulder with a thread pitch of 1 mm.

The plunge depth and tilt angle were fixed at 0.1 mm and 2.5º, respectively. FSW was carried out at a traverse speed of 71 mm/min and a rotational speed of 1250 rpm.

This profile of the tool was established after several tests in order to determine its optimum diameter, which makes it possible to produce a weld without defects at the root of the joint and on its surface.

The configuration of the tool used in this study is shown in *Figure 3*.

The two plates used were fixed and tightened by a clamping system (*Figure 4*) to prevent them from moving and slipping. The welding tool rotated at a given rotational speed and moved at a determined speed known according to the transverse length of the plates. Although the shoulder of the tool exerts an axial force to keep the joint in contact with the support, it is the clamping system which must perform this function.

Table 1: Chemical composition and mechanical properties of the Al 6061-T6 aluminum alloy [25] and XC 48 steel [28]

Element/ Property	Si %	Fe %	Cu %	Mg %	*C* %	*Rm* MPa	*Re* MPa	*A* %
6061-T6	0.70	0.25	0.29	0.90	/	304	276	13.6
XC 48	0.38	/	/	/	0.48	535	468	11.2

Rm: maximum stress (MPa); *Re*: elastic stress (MPa); *A*: elongation (%)

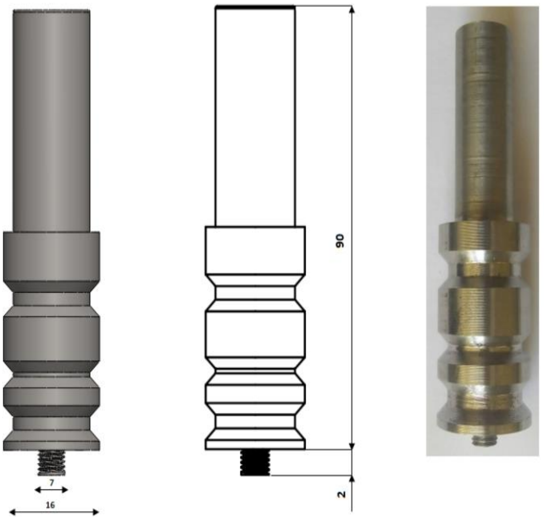
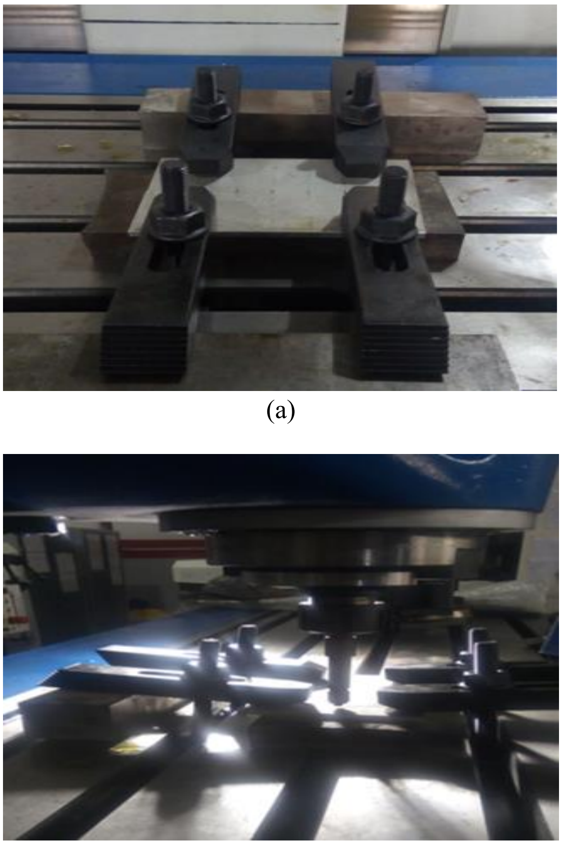


Figure 3: FSW tool

Table 2: The dimensions (in mm) of the specimens subjected to tensile tests

Nominal width	Specimen 1 12.5
G (Gauge length)	50.0 ± 0.1
W (Width)	12.5 ± 0.2
T (Thickness, mm)	Measured thickness of specimen
R (Fillet radius, mm)	12.5
A (Length of reduced section, mm)	60
B (Length of gripped section, mm)	75
C (Approximate width of gripped section)	20



(a)

(b)

Figure 4: Bridle system for FSW welding

The friction produced by the welding tool heats up the atoms of the solid metal causing them to disperse or migrate. In the absence of fusion, the metal deforms and the atoms of the two plates are joined. Heat is produced as a result of friction between the tool and the workpieces, allowing the material to soften and become more pliable. The plasticized substance moves as a result.

The present study consists of welding two Al 6061-T6 plates. During the tests, a single tool configuration was considered. 6 tests were carried out to compare the results with those welded by FSW.

The different steps of the FSW process adopted during welding are:

- Positioning of the welding tool above the plates at the beginning of the joint;
- Tool tilt angle of 2.5°;
- Rotational speed of the machine head of 1250 rpm;
- Penetration of the tool pin until the shoulder as a result of a vertical force to ensure it is in contact with the plates to be welded;
- Wait 4.5 seconds (pre-sealing time) until a thermal equilibrium is reached;
- Start moving the tool at a feed rate of 71 mm/min;
- Remove the tool from the two plates to be welded and stop the machine.

2.3. Joint characterization

The mechanical characteristics of both the base material (BM) and the friction stir welded material were evaluated by conducting tensile and impact tests. For the tensile tests, specimens were extracted from the plates both parallel and perpendicular to the FSW welding path with and without a weld. The specimens, conforming to the dimensions specified in ASTM E8-04 [29] and the specifications of Specimen 1 illustrated in *Figure 5*, were cut from straightened plates. The tensile strength of the specimens was measured by a universal testing machine model using IBERTEST software controlled at a crosshead speed of 1 mm/min. The tensile tests were conducted with a loading rate of 1 mm/min. The dimensions of the specimens subjected to tensile tests are given in *Table 2*.

The machine increasingly elongates the specimens while recording the applied force F and elongation ΔL. The test continued until the specimens ruptured to determine the ultimate elongation. The geometry and a photo of the machined specimens are shown in *Figures 5*.

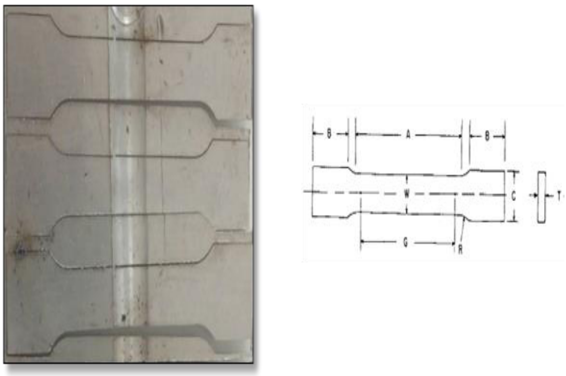


Figure 5: Tensile specimens [26]

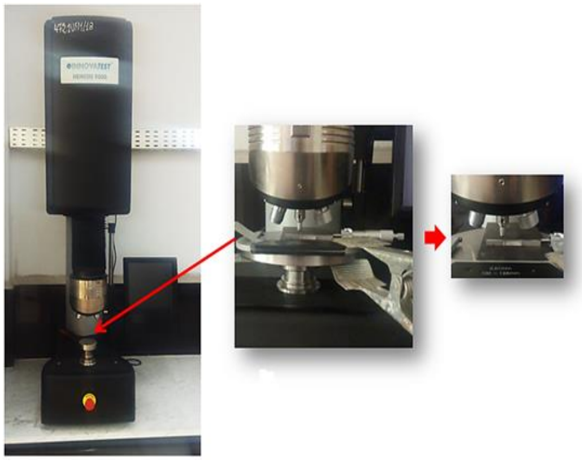
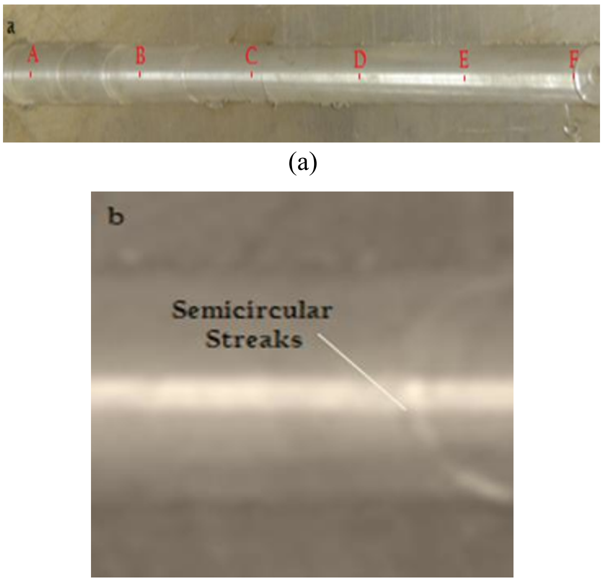


Figure 6: HB microhardness test equipment



(a)

(b)

Figure 7: Surface texture of a friction stir welded specimen: (a) general view and (b) area A highly magnified

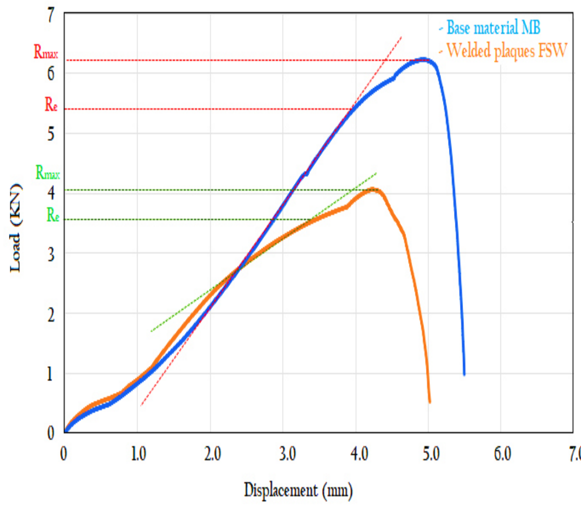


Figure 8: Curves of the tensile test conducted on the base and FSW welded materials

Following tensile shearing tests, the hardness of FSW joints on the sheared surfaces was assessed at the weld center. The Brinell hardness tester (*Figure 6*) was then used to evaluate the hardness (*HB*). At the interface with the plate, the metal of the welded plates was churned up.

Variations in hardness at the interface with the joint were induced by the stirring of two distinct metal alloys.

The difference in stirring between the advancing and retreating sides during welding might explain the hardness differential.

Several studies revealed that both the rotational and traverse speeds of the tool have a great influence on the quality of the surface. The surface roughness of the FSW specimens was most significantly influenced by the interaction between the tool's rotational and traverse speeds. In this work, the surface roughness of the specimens was also measured using a surface roughness tester. The full factorial design of the experimental approach was employed to examine the effects of the aforementioned FSW process parameters on the surface roughness. *Figure 7* shows a typical surface texture of a friction stir welded specimen at 1250 rpm and 71mm/min.

3. Results and discussion

3.1. Tensile test

The typical stress-strain curves which characterize the behavior law of base and welded materials in terms of FSW welding parameters proposed by us are presented in *Figure 8*, while the mechanical characteristics are illustrated in *Table 3*.

Table 3: Tensile test results

	Re kN	Rmax kN	Al mm	CE %
Base material (BM)	5.49	6.21	5.49	
Welded plates (FSW)	3.55	4.05	5.02	65.21

The results obtained show that the curve of the welded material with the parameters *N*=1250 rpm and *Va*=71 mm/min exhibits better mechanical characteristics when *Re*=3.55 kN and *Rm*=4.05 kN, while the elastic limit of the base material was *Re*=5.49 kN and *Rmax*=6.21 kN (*N*: rotation speed (rpm); *Va*: feed rate (mm/min)).

From these results, a significant reduction in the mechanical properties of the FSW welded joint compared to the BM was observed. The coefficient of efficiency (CE) was calculated to get a clear picture of the behaviour of the welded joint and its approximation to the behaviour of the base material. This coefficient is the ratio between the tensile limit of the BM and that of the welded joint, in our case it is 65.21%.

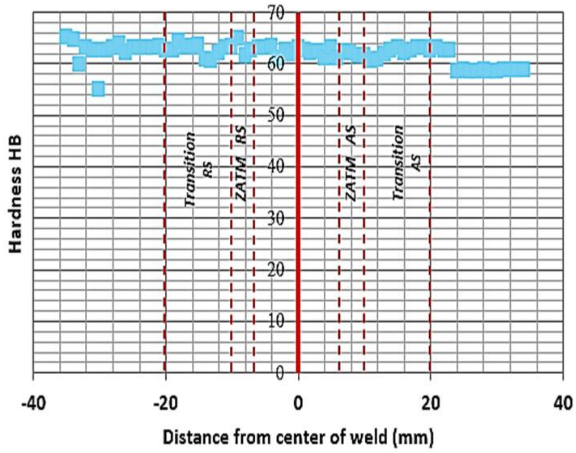


Figure 9: Hardness profile through a welded joint

3.2. Hardness of FSW

The hardness of the FSW joints with the welding parameters of 1250 rpm and 71 mm/min is shown in *Figure 9*. The hardness test was carried out in the transverse plane using a device on cross sections of the welded joints to evaluate, from a qualitative point of view, the mechanical resistance of the different zones of these welded joints.

The hardness profile shown in *Figure 9* is relatively symmetrical with respect to the joint surface. Minimum levels of hardness are achieved in the ZATM zone at approximately *HB*=61. In the welded core, a slight increase in the level of hardness is observed, in particular on the advancing side where the value reached *HB*=65.

The plastic metal could flow and recrystallize sufficiently due to the higher level of frictional heat and the precipitates were also more plentiful. However, the increased frictional heat at 1250 rpm caused grains to form and its hardness to be reduced since the lower exhibits the longest friction duration as can be seen in *Figure 9*.

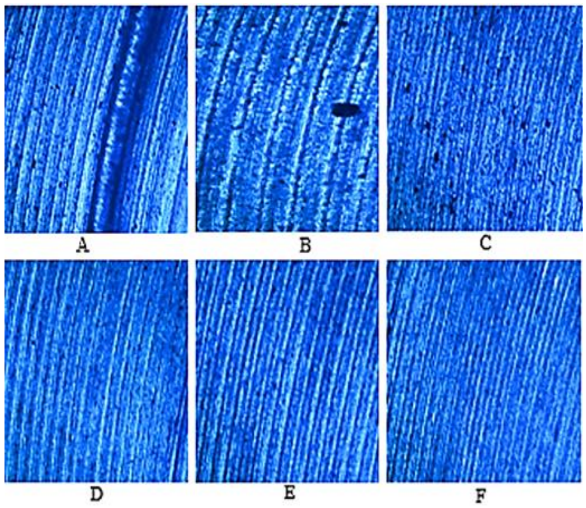


Figure 10: Micrograph showing the surface condition

3.3. Surface roughness measurements

The intrinsic abnormalities of the welded plates produce semicircular streaks that are influenced by the tool coming into contact with the workpiece, which is how the surface roughness of the welded joint is described in *Figure 10* that shows a typical surface texture of a friction stir welded specimen at 1250 rpm and 71 mm/min. In the present investigation, the surface quality of the FSW specimen was evaluated by the average *Rz* value using a PCE-RT 1200 roughness tester instrument. Average *Rz* is one of the profile roughness parameters, it is the average value of the absolute values of the heights of five highest-profile peaks and the depths of five deepest alleys within the evaluation length.

The surface roughness (*Rz*) increased along the entire weld length as illustrated in *Figure 11* which varied between 15.83 and 25.56 μm for the advancing to retreating tools, respectively. It was observed that the retreating tool yielded higher surface roughness values compared to the advancing tool due to the heterogeneity of the FSW weld joint.

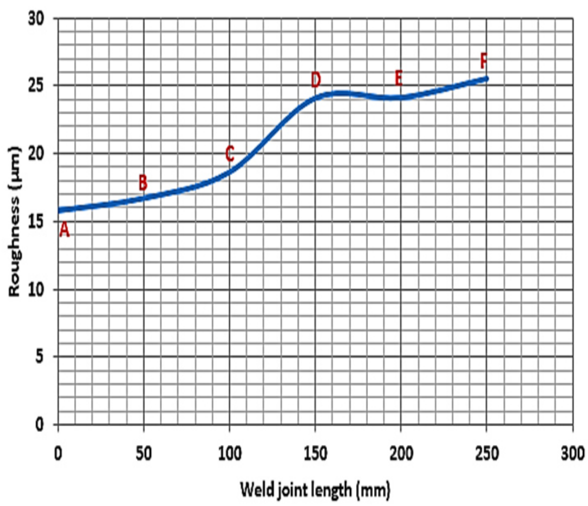


Figure 11: Roughness data points

Table 4: Surface roughness test results

Weld joint length (mm)	0	50	100	150	200	250
Roughness (µm)	15.83	16.74	18.66	24.12	24.16	25.56

The values of the surface roughness (*Rz*) are displayed in *Table 4*.

4. Conclusions

Although the FSW welding process has been applied since 1991 for assembling different metal structures, its development has intensified over recent years due to the need to better understand the physical and mechanical behaviour of welded joints.

In this study, FSW joints were characterized from the results of tensile tests. Specimens subjected to tensile tests were prepared from plates in a perpendicular direction to the FSW travelling path including and excluding the weld. The hardness measurements first allowed the different welding zones (Core, ZATM, ZAT and Base metal) to be delimited and the variation in hardness through these zones to be determined. The main conclusions are as follows:

- The quality of the FSW solder joint significantly depends on the feed rate and rotational speed;
- The interaction between the rotational speed and displacement of the tool most significantly influenced the surface roughness of the friction stir welded 6061-T6 plates.

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