COMPARISON OF THE STRENGTH AND MICROSTRUCTURE OF FRICTION STIR WELDING FOR ALUMINUM ALLOY AA6061

Abstract

The study looks at the microstructure of welded specimens to assess the surface in both the welding and heat-affected zones. The inspection was carried out using scanning electron microscope (SEM), and Universal testing machine (UTM). The mechanical qualities of the welded connections were found to be impacted by the friction stir welding (FSW) process parameters. FSW specific circumstances produced the best results. Furthermore, the paper notes the scarcity of research on the FSW of aluminum alloy AA6061. As a result, the process parameters for FSW testing on AA6061 were derived from existing literature on related aluminum alloys. The paper highlights the impact of FSW process parameters, such as traverse feed rate (TFR), tool rotational speed (TRS), and tool tilt angle (TPP) on the mechanical properties of the welded joints, including ultimate tensile strength (UTS), yield strength, percentage of elongation, and hardness. The paper presents the optimum results obtained under specific FSW conditions, including 2000 RPM (TRS), 60 mm/min (TFR), and tapper (TPP).

Keywords: Friction stir welding (FSW), traverse feed rate (TFR), tool rotational speed (TRS), ultimate tensile strength (UTS).

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I. INTRODUCTION

Friction stir welding was brought into existence in the year 1992 but saw its patent enter the public domain in the year 2015. Consequently, this particular welding technique represents the current state of progress for manufacturers operating in the aluminum industry and serves as a highly advantageous method for assembling parts that range in length from a mere few centimeters to several meters. This particular welding practice effectively creates a bond between two components in a solid state by simultaneously applying intense pressure and friction at the precise point of contact between two adjacent surfaces. The rotation of the specific tool utilized in the process generates a considerable amount of heat, which subsequently "plasticizes" the material along the welding axis, ultimately leading to the mixing of the interfaces. However, it is important to note that the heat generated is exceptionally controlled and is relatively well-defined within the welding area. Indeed, during the welding process, the temperature required to melt the welded metal is not reached but rather remains at a range of 60- 80% in comparison to the melting point. Friction stir welding (FSW) is known to possess numerous advantages, particularly for the aluminum industry. First and foremost, it is capable of producing welds of exceptionally high quality, free from any porosity, solidification defects, or cracking. Secondly, FSW yields welds that boast outstanding mechanical properties, such as exceptional strength and fatigue resistance. This, in turn, renders it especially useful for joining thin aluminum sheets, which are commonly employed in both the aerospace and automotive industries. Thirdly, the process of FSW is characterized by its relative simplicity and its ease of automation, making it a particularly valuable tool for high-volume production. This, in turn, renders it an ideal choice for the aluminum industry, which necessitates both high-quality and high-volume production for a multitude of applications.

The investigation conducted in this study [1] focuses on examining the microstructure and mechanical properties of a friction stir welded joint in a 20 mm-thick AZ31 magnesium alloy plate. Reference [2] delves into the exploration and analysis of the characteristics and microstructure variances in lap joints made of aluminum alloy and steel, both with and without ultrasonic vibration. Furthermore, the study [3] establishes a connection between underwater friction stir welding (UFSW) of 1Cr11Ni2W2MoV steel and conventional friction stir welding, showcasing that UFSW exhibits reduced peak temperatures and carbide percentages in the heat-affected zone (HAZ) compared to NFSW. Moreover, UFSW demonstrates higher ultimate tensile strength and a narrower HAZ width [4] when compared to NFSW. Lastly, an investigation [5] is carried out to analyze the impact of rotational speed on the microstructure, mechanical properties, and corrosion resistance in dissimilar friction stir welding of AA2024 aluminum alloy.

The investigation presented in this study [6] introduces a novel slip rate model designed to anticipate the interfacial contact condition in friction stir welding (FSW) by utilizing welding parameters through finite element analysis. The slip rate model illustrates that the rate of slip escalates with welding velocity and diminishes with rotational velocity, offering valuable insights into the thermal generation mechanism and temperature distribution while conducting FSW on aluminum alloys. In a separate inquiry [7], alterations in the toughness and tensile characteristics of friction stir welds in Al 2024-T3 alloy are explored over a period, particularly post 24 months of natural aging. The toughness of the weld diminishes by 19% as it ages, attributed to a reduction in ductility. Furthermore, the elongation of the material experiences a decline of 27%, yet its ultimate tensile strength shows an improvement of 9%. Another study [8] employed a thermal-mechanical coupling finite element model to examine the impacts of various friction stir welding (FSW) processes on the temperature, residual stress, and deformation of Ti62A alloy joints.

The investigation carried out in this study [9] explores the impacts of auxiliary assistive heating on various parameters, such as maximum forces and torques, in the process of friction stir spot welding of AA2024-T3 plates. The act of preheating the workpiece before engaging in the plunge phase leads to a significant reduction in peak pressures, potentially resulting in an extended lifespan of the tool, reduced costs of machinery, and an expanded range of material applications. Although friction stir welding serves as a solid-state welding technique commonly employed in the aerospace sector, inaccuracies in alignment have the potential to diminish the quality of the welds [10]. The study uses tensile testing to explore the influence of three alignment problems (gap, linear misalignment, and tool offset) on weld quality. The research [11] examines the FSW approach for connecting aluminum and magnesium alloys, concentrating on the interfacial enhancement and joining processes. It explains the process parameters, mechanical characteristics, and strategies to modify the interface for better strength and performance of Al/Mg butt welds. The analysis of heat production and dissipation during the friction stir welding of thick plates made of high-density polyethylene is detailed in citation [12], employing both numerical simulation and experimental validation. Citation [13] delves into the exploration of employing a tilted hemispherical tool on the retreating side for welding 6061-T6 aluminum alloy via friction stir welding, showcasing the capability to create seamless joints without any internal voids and weld thicknesses reaching 3.5 mm.

After reviewing the literature, it was discovered that several gaps in previous studies are introduced and addressed in the current work. This study focuses on investigating the procedure involved in acquiring weld joints of aluminum alloy plates through the Friction Stir Welding (FSW) process. The primary emphasis is placed on considering the various aspects of the FSW process parameters that are necessary to achieve successful and strong weld joints. It should be noted that there is limited research on the FSW of aluminum alloy AA6061, resulting in a scarcity of available works. Therefore, the process parameters required for conducting FSW experimentation on AA6061 are identified from existing literature on the FSW of similar aluminum alloys. To provide a comprehensive understanding, Table 1 presents the process parameters and their respective ranges for different types of aluminum alloys. The examination of weld beads in friction stir welded AA6061 aluminum alloy for butt joints holds great importance as it affects the overall quality of the joints. To thoroughly analyze the weld zone and its properties, the study employs a range of microstructural and mechanical characterization techniques, enabling a comprehensive understanding of the weld beads. One technique employed in this research involves conducting optical microscopic studies. These studies accurately identify the specific areas within the friction stir welded joints that make up the weld zones. This information is crucial for further investigations. Additionally, the researchers perform SEM analysis on the weld beads of various aluminum alloys. This analysis offers valuable insights into the structural composition and characteristics of the weld beads. By examining the weld beads under the scanning electron microscope, the researchers can observe and analyze the intricate details of the weld zone. Furthermore, mechanical characterization plays a significant role in this study. The researchers carry out a series of tests, including UTS (ultimate tensile strength), yield strength, and hardness tests, on the weld beads of different aluminum alloys. These tests allow the researchers to assess the mechanical properties of the weld beads, providing valuable information about their strength and durability.

To acquire a more profound comprehension of the friction stir welding procedure and its impact on the AA6061 butt joint and weld beads, the researchers examined the effects of different process parameters. This examination involved observing the mechanical nature of the weld bead samples and studying how the various process parameters affected their properties. By carefully analyzing the relationship between the process parameters and the mechanical characteristics of the weld beads, the researchers were able to draw significant conclusions regarding the welding procedure. To further investigate the impact of process parameters on weld beads, tests were conducted on standard specimens to assess their mechanical properties. These tests were specifically designed to understand how different process parameters influenced key mechanical properties such as UTS, yield strength, and hardness, as these properties are crucial for the overall quality and performance of the weld beads. To ensure precise and reliable results, the tests were performed on specimens cut perpendicular to the weld joint. This approach allowed for consistent and standardized testing conditions, ensuring that the obtained data accurately represented the properties of the weld beads. Before conducting the actual tests, trial tests were carried out to verify the validity and reliability of the experimental setup. The average values obtained from these trial tests were considered for further analysis. By taking into account these average values, the researchers were able to eliminate any potential anomalies or inconsistencies that might have influenced the final results.

Table 1: L18 orthogonal array Experimental design and their results

RUN	TRF	TRS	TPP	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness of weld zone (HV)
1	100	1000	SCL	80.67	55.67	0.11	30
2	63	1000	SCL	120.39	105.69	0.31	48
3	80	1000	SCL	100.23	80	0.22	38
4	100	1400	SCL	115.69	98.96	0.48	39
5	63	1400	SCL	149.75	120.54	1.03	50.36
6	80	1400	SCL	133.35	111.52	0.95	45
7	100	2000	SCL	128.56	100.03	0.55	49.08
8	63	2000	SCL	151.05	125.22	1.05	58.26
9	80	2000	SCL	142.36	109.68	0.93	56.3
10	100	1000	TCL	118.69	98.68	0.56	27.02
11	63	1000	TCL	149.02	129.58	1	40
12	80	1000	TCL	123	108.28	0.89	32
13	100	1400	TCL	128	102.6	0.22	39
14	63	1400	TCL	150.2	139.29	1.05	53.69
15	80	1400	TCL	140.2	111.68	0.82	49.9
16	100	2000	TCL	110	82	0.32	51
17	63	2000	TCL	154.38	114.62	1.2	60.2
18	80	2000	TCL	130.2	105.52	1	56

In summary, the examination of weld beads in friction stir welded AA6061 aluminum alloy for butt joints is an intricate and multi-faceted process. Through the utilization of various techniques for microstructural and mechanical characterization, the researchers were able to thoroughly analyze the weld zone and its properties. By conducting studies using optical microscopy, SEM analysis, and mechanical property tests, the researchers gained valuable insights into the composition, structure, and mechanical properties of the weld beads. Furthermore, through the analysis of process parameters and the conduction of trial tests, the researchers ensured the accuracy and reliability of their findings.

II. PROCESS PARAMETERS ON MECHANICAL PROPERTIES FOR BUTT JOINT

1. Tensile Strength Testing Results

This particular section aims to provide a detailed explanation of the process of welding an A.A6061-T6 aluminum alloy using friction stir welding. Friction stir welding is a technique that involves joining materials by applying heat and mechanical pressure through a rotating tool. The welding process utilizes a taper and cylindrical pin profile H13 grade high-speed steel (HSS) tool, which is crucial for achieving successful welds. To ensure desirable and reliable welded joints, various parameters are intentionally modified and adjusted. It is important to note that the weld bead, which is the material deposited during the welding process, shows a significantly reduced number of defects at the macro level, indicating the satisfactory overall quality of the welded joint. However, a closer examination of the specimen's cross- section reveals the presence of certain imperfections, which can be attributed to the movement of the tool during the welding process. Interestingly, when the tool rotates at a speed of 2000 revolutions per minute (rpm) and the table feed rate remains constant at 63 millimeters per minute (mm/min), the resulting weld bead appears to be defect-free. On the other hand, other specimens exhibit imperfections, possibly due to an improper combination of process parameters during friction stir welding. Therefore, it is crucial to evaluate and analyze the impact and significance of these process parameters by conducting a tensile test on the welded specimens. This section provides detailed information on the execution and implementation of the tensile test, which follows the ASTM B557 standard, a widely recognized and accepted standard in the field. Additionally, it is worth mentioning that the shape required for the tensile test is accurately machined using a wire electrical discharge machining (EDM) machine, as shown in Figure 1 of this study.

Figure 1: Tensile Test specimens.

With a total of five different combinations of processing parameters, the first sample, which is made of aluminum AA6061 alloy, is obtained by cutting it from the bulk plate. The rest of the specimens, on the other hand, are joined together using the process of Friction Stir Welding (FSW). To evaluate the mechanical properties of these samples, including the ultimate tensile strength (US) and yield strength (YS), a Universal testing machine equipment is utilized. The obtained values of US, YS, and the percentage of elongation are then presented in Table 1. The histogram, which is a graphical representation that organizes and displays data using bars to represent the frequency or distribution of values within specific ranges or intervals, is showcased and depicted in Figure 2, providing a visual representation of the input and output parameters in an easily understandable and accessible manner.

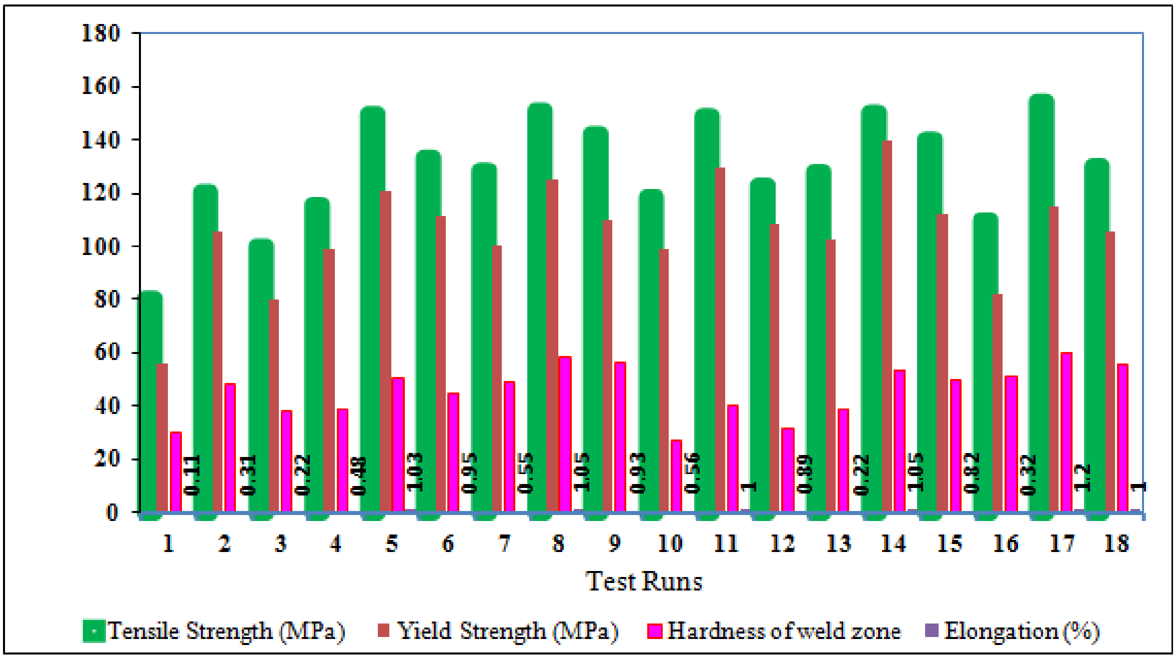

Figure 2: Comparative values of tensile strength, yield strength, and hardness values.

The original aluminum specimen, which was not welded, demonstrated an ultimate tensile strength of 160MPa and a yield strength of 133MPa when subjected to tension. On the other hand, the friction stir welded specimen, which was the 17th run as indicated in Table 1, exhibited an ultimate tensile strength of 154.4MPa and a yield strength of 114.4MPa under tension. This means that the friction stir welded specimen retained 96% of the original sample's ultimate tensile strength and achieved up to 86% of its yield strength. Consequently, this suggests that the ductility nature of the specimen was preserved after undergoing friction stir processing. The correlation between the tensile strength of the original and welded specimen is depicted in Figure 3, showcasing the stress vs. strain in tension tests.

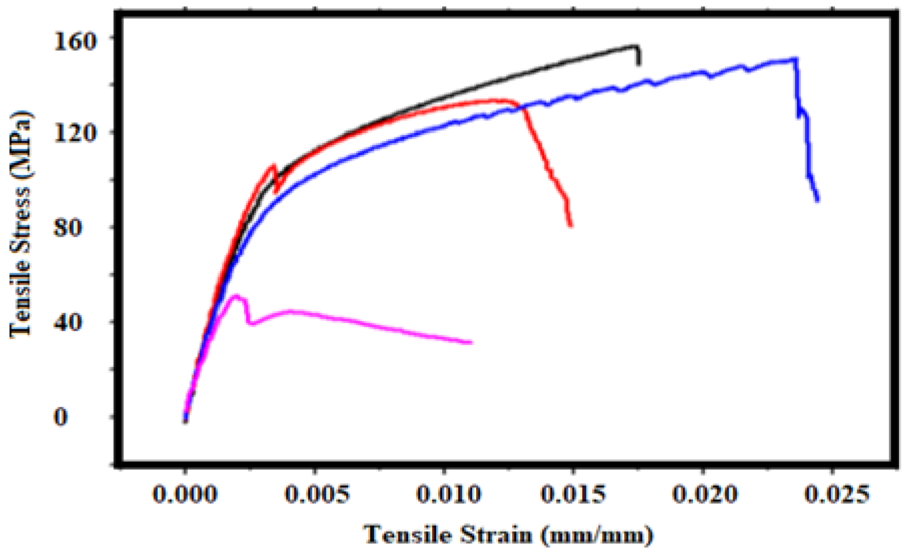

Figure 3: Stress-strain curves.

The contribution of welded joints' tensile behavior in determining weld standards is crucial, and as a result, the configuration of various FSW regions plays a pivotal role. The UTS of FSW AA6061 joints has been measured to TRS, TFR, and TPP. At lower TRSs, the UTS of FSW joints is lower and increases accordingly with an increased TRS up to a certain level. This holds regardless of the tool pin shape. The UTS is higher when using the taper pin profile compared to the straight cylindrical pin profile, as depicted in Figure 4. At lower TFR, the UTS of FSW joints is higher and decreases accordingly with an increased TFR up to a certain level. This is true regardless of the tool pin shape. The taper TPP, which has a higher TS, is shown in Figure 5. Under normal FSW conditions, the material AA6061 has a high TS. The taper tool pin has higher mating edges compared to other straight cylindrical pin profiles; hence, the material is well-stirred under these conditions.

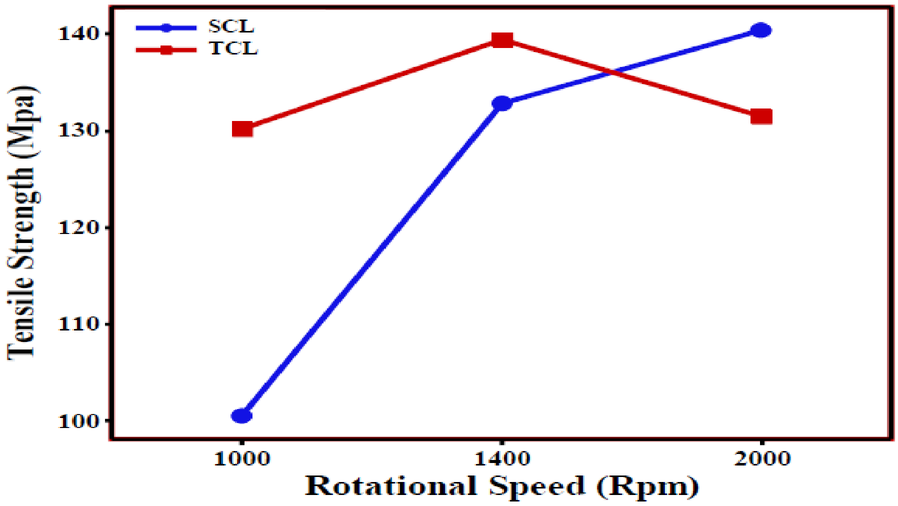

Figure 4: Strength results of various tool geometry and tool rotational speed.

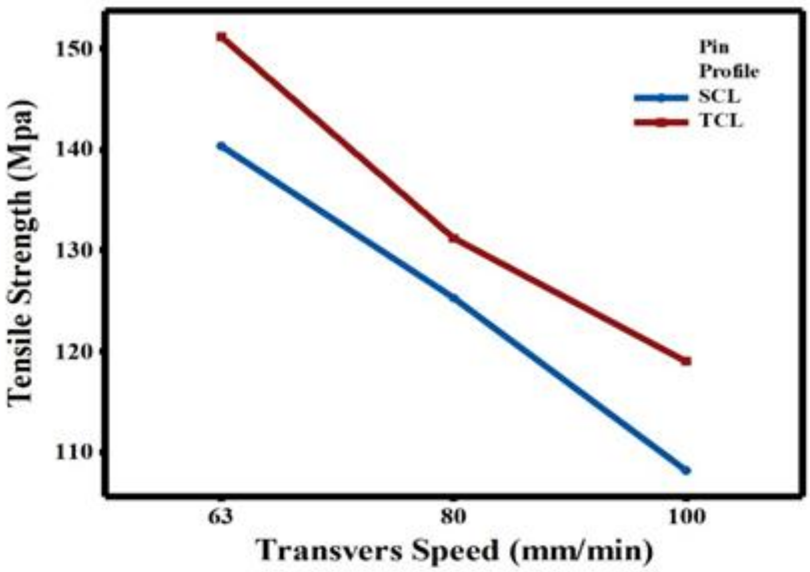

Figure 5: Strength results of various tool geometry and tool transverse speed.

2. Hardness Testing Results

Rockwell Hardness measurements were taken on AA6061 samples that had undergone friction stir processing (HRB). A load of 200 Kgf was applied and held for 5 seconds. FSW samples were prepared using different controlling parameters of rotation (RPM) and translation (feed) speed. The resulting average hardness values were determined. According to Table 1, when the transverse speed was set at 60mm/min and the RPM was 2000, the Rockwell hardness value was measured at 60.2. On the other hand, when the transverse speed was 80mm/min and the RPM was 1000, a void appeared across the joint, resulting in a Rockwell hardness value of 32.7. However, the best result was achieved with specimen no.17, which showed no void and had a reasonable hardness value of HRB 60.2 and an elongation percentage of 1.05. This indicates that the specimen exhibited ductile behavior comparable to the original specimen. The hardness of FSW AA6061 joints was examined in terms of TRS, TFR, and TPP. The hardness in the FSW nugget zone decreases at lower TRSs but improves as the TRS increases. This holds regardless of the design of the tool pin. Compared to the straight cylindrical pin profiles shown in Fig. 6, the taper pin profile exhibits higher hardness. The hardness value of FSW joints is lower at higher TFRs and increases with lower TFRs up to a certain point, irrespective of the design of the tool pin. Fig. 7 shows that the square TPP has a greater hardness. These conditions effectively stir the material because the taper tool pin has higher mating edges compared to other TPPs.

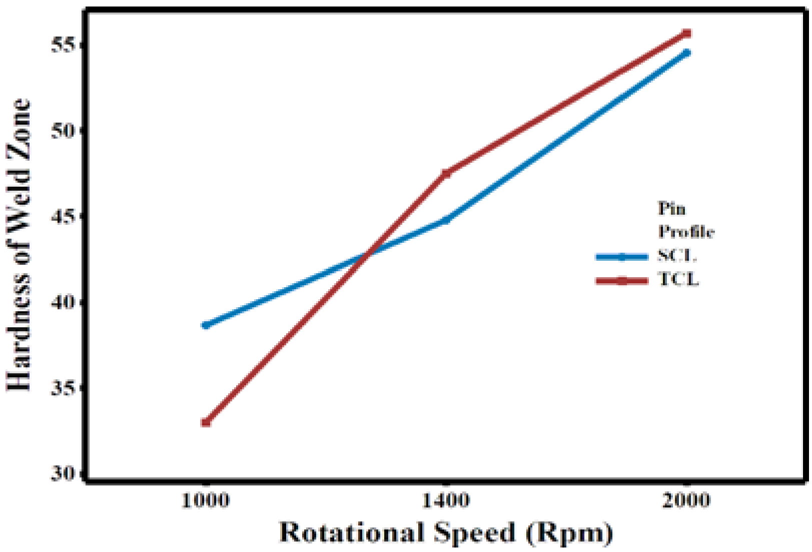

Figure 6: Hardness results from various tool geometry and tool rotational speeds.

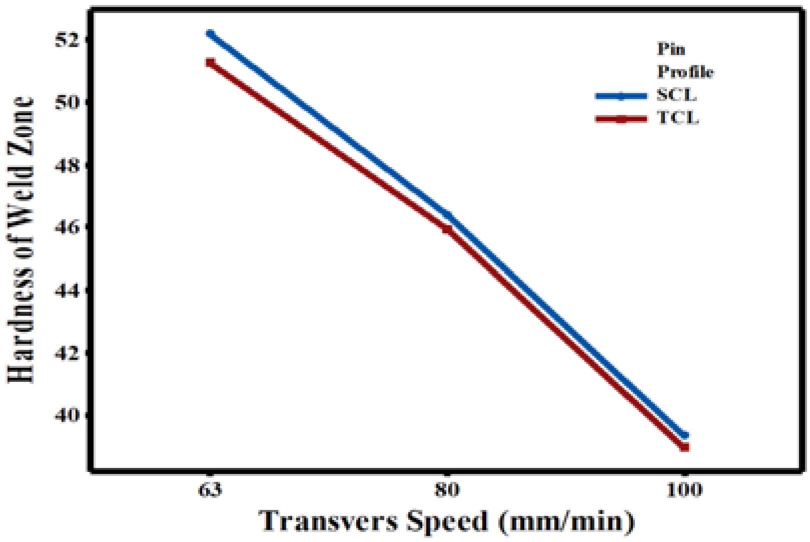

Figure 7: Hardness results from various tool geometry and tool transverse speed.

III. MICROSTRUCTURE RESULT FOR BUTT JOINT

The investigation of the microstructure is conducted on the welded specimens to examine the surface at the welding point as well as the surface at the heat-affected zone. To examine the microstructure, the specimens are ground using emery paper made of silicon carbide with different grit sizes (320, 500, 800, and 1000). After grinding, the specimens are polished using diamond paste with a grain size of 0.5µm. To achieve a mirror-like polishing surface, the polishing surface is etched using kellers regent (composed of 90 ml H2O, 2.6 ml HNO3, 1.6 ml HCI, and 1.0 ml HF). The surface is then washed with water and alcohol and dried in an oven.

The investigation was conducted using a SEM (Scanning Electron Microscope). The photos demonstrate the grain structure, with distinct grain boundaries in the weld nugget zone created with the taper tool. This indicates the production of moderate grains with more surface area and fewer vacancies. The dark patches represent voids that develop at a lower rpm of the plunging tool. Figure 8 depicts the specimen welding at the taper tool in two separate areas.

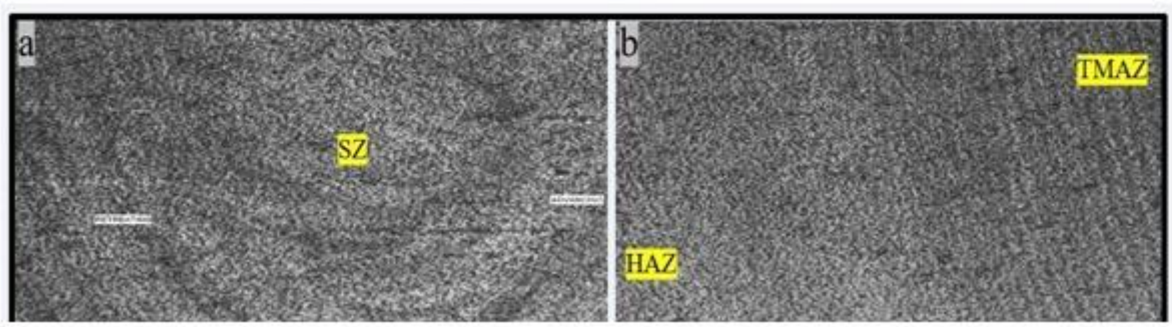

Figure 8: Optical micrographs of friction stir welded AA6061 (a) Stair zone (b) HAZ, TMAZ

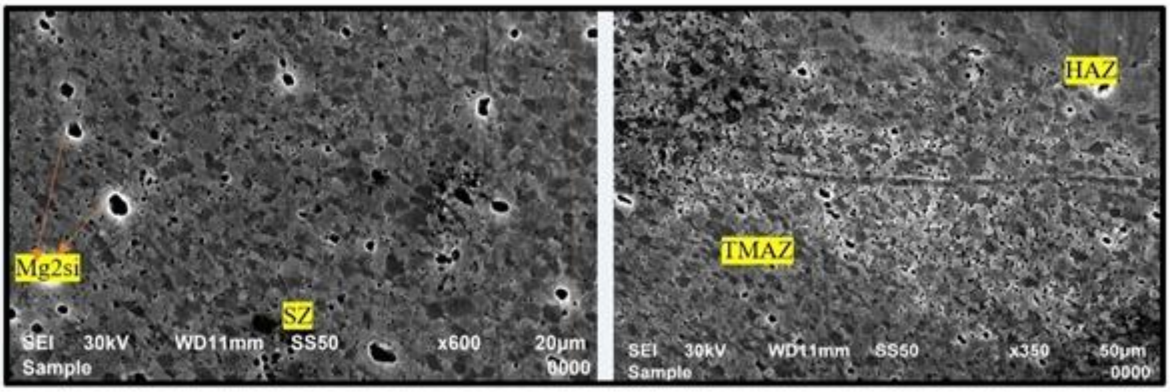

Figure 9: SEM photograph ofAA6061 (a) Stair zone (b) HAZ, TMAZ

The right side represents the thermo mechanical zone (TMAZ), while the left side represents the heat- affected zone (HAZ). These two sections highlight the influence of torque and heat production during the FSP process, which results in larger voids in the TMAZ than in the HAZ. The TMAZ also has more pronounced grain boundaries and noticeable voids. The welded area at 20 micrometers reveals that the joint is free of surface voids. The heat-affected zone on the joint is also substantially less than under the same conditions but using a different instrument. Figure 9 shows topographic views of the welded and heated zones of the specimens. It was discovered that the joint had an excellent grain structure and a small heat-impacted zone.

IV. CONCLUSIONS

The AA6061 materials were expertly combined using a conventional Friction Stir Welding (FSW) technique, which has proven to be highly effective in joining metals. This FSW approach includes manipulating and controlling a number of process parameters, including the Tool Rotation Speed (TRS), Tool Feed Rate (TFR), and Tool Pin Profile (TPP), all of which have a major influence on the mechanical qualities of the resultant weld joint. When analyzing the impacts of these process factors on the welded joint, it was discovered that the aforementioned parameters impacted the Ultimate Tensile Strength (UTS), Yield Strength, Percentage of Elongation, and Hardness. To achieve the most favorable outcomes, a thorough analysis was conducted, leading to the identification of the optimal conditions: a Tool Rotation Speed of 2000 revolutions per minute (RPM), a Tool Feed Rate of 60 millimeters per minute (mm/min), and the implementation of a tapper-shaped Tool Pin Profile (TPP). By adhering to these specific parameters, the desired results were successfully attained, ensuring the highest levels of weld joint performance and overall quality.

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