

Influence of Welding Parameters and Tool Pin Profile on the Microstructure and Mechanical Properties of Dissimilar Friction Stir Welded AA2024-T3 to AA6061-T6 Alloys

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Abstract

This study aims to produce joints from dissimilar Al alloys welded by the FSW process with a minimal defect rate. The investigation focuses on the mechanical behavior and microstructural characteristics of 2 mm-thick dissimilar Al alloys, AA2024-T3 + AA6061-T6. The parameters of the welding process were welding speed, tool rotation speed, tilt angle, and pin profile geometry. The experimental work was conducted to determine the optimal welding conditions for producing defect-free welds with superior mechanical performance. Three pin profiles (Triangle, square, and hexagon), three rotational speeds (620, 920, and 1500 rpm), and three feed speeds (13, 23, and 28 mm/min) were used. Tensile testing, microhardness testing, and microstructural examinations evaluated weld-joint quality. The results indicated that a rotational speed of 620 rpm and a feed ratio of 28 mm/min, combined with a triangular pin profile, provided the best welding conditions. Under these conditions, the welded joints exhibited the highest tensile strength and microhardness. The highest tensile strength under ideal conditions was 150 MPa, and the hardness value of a welded joint at the weld zone under ideal conditions was 160 HV. Furthermore, lower rotational speeds improved both the tensile and hardness properties of the dissimilar FSW joints. Microstructural observations revealed sound weld formation, with adequate material mixing and no visible welding defects. Fracture surface analysis indicated a predominantly ductile fracture mode.

Keywords: influence of welding parameters, Friction stir welding, effect of pin profile, aluminum alloys, Mechanical characteristics for FSW

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1. Introduction

FSW (Friction Stir Welding): This solid-state welding method joins various materials, including metals and polymers, without protective gases or fillers. It is considered an environmentally friendly technology as it overcomes problems encountered in fusion welding. This type of welding operates by applying sufficient pressure with a pin-profile welding tool. This creates contact between the workpiece and the welding tool. The pressure generates Heat, which helps the two materials bond or mix, resulting in plastic deformation at the contact surfaces [1] and [2]. Pressure and frictional Heat are the two main factors in friction welding. There are two types of friction welding: FSW and crushing

friction welding (FCW) [3]. The FSW process has been successfully used to join many metals and alloys, including aluminum, copper, steel, and even titanium alloys. The Welding Institute (TWI) in the UK developed FSW specifically for joining aluminum alloys.

Aluminum alloys are separated into two chief groups: cast and wrought alloys, which are further divided into heat-treatable and non-heat-treatable alloys [4]. When welding aluminum alloys with traditional methods, cracks and porosity can form in weld joints, especially when dissimilar aluminum alloys are used. Other problems also occur, such as differences in thermal and mechanical characteristics, which negatively affect joint

durability [4,5]. Aluminum alloys are among the preferred alloys in construction, automotive, aircraft, and shipbuilding applications because they offer several advantages, most importantly ease of availability, light weight, high strength, and corrosion resistance [6,7].

In 2024-T3 alloy, copper is the main component, with alloying elements such as manganese, silicon, and chromium in smaller proportions to enhance strength and durability. This series (2xxx) is classified as a heat-treatable alloy, characterized by high toughness and hardness at both room and elevated temperatures. One characteristic of this alloy is its poor corrosion resistance, especially under normal weather conditions. Therefore, coating the alloy is recommended to improve its corrosion resistance. It also has low extrusion potential [8]. In this series, silicon and magnesium are the main elements, along with alloying elements in small proportions that provide strength and durability. These include copper and chromium, which improve its corrosion resistance, as well as manganese and other elements. It is also considered a heat-treatable alloy. It is utilized in aircraft, cars, and railway structures because of its light weight and moderate strength compared with other aluminum alloys. This alloy is also characterized by its ease of casting, forming, and extrusion [9]. For welding tool design, achieving a high-quality weld is paramount. Many researchers have studied how device geometry affects weld microstructure and mechanical characteristics.

Chenghang Zhang et al. studied the impact of rotating speed on microstructure and corrosion performance of heterogeneous AA2024/7075 aluminum alloy weld joints. The outcomes showed that rotational speed primarily affects asymmetric weld performance and the local microstructure. In the neutral weld zone, isoaxial fine grains form, and grain size gradually decreases in the following order: SZ, CZ, and BZ. The resistance decreases progressively with increasing rotating speed. The extreme tensile strength reached 411.4 MPa at 950 rpm, with a welding effectiveness of 87.6% for the AA2024 aluminum alloy. The fracture occurred in a less rigid region during the tensile test [10]. Tamilselvan Amuthan and colleagues studied FSW utilizing

different aluminum alloys, including AA6061 and AA7075, with dimensions of 100×50×6 mm, considering the impacts of the welding device's lateral and rotational speeds. The influence of welding processes on aluminum alloys and their impact on mechanical characteristics, for example, corrosion and Hardness distribution, has been studied. This alloy and welding process are used in the aerospace industry because this alloy is difficult to weld using traditional methods. Increasing rotational speed increased movement speed and, consequently, significantly increased weld hardness, with the highest hardness recorded at 55.80 BHN [11].

Biplab Ghosh et al. studied the impact of instrument rotating speed on microstructure and mechanical characteristics of rainfall-hardened aluminum 6061. Using AA6061-T6 alloy with FSW at a device rotating speed of 1300rpm was optimal for attaining an extreme combined effectiveness of 70.6% and a constant tool travel speed. We performed several tests: FESEM, optical microscopy, TEM observation, and fracture and micro-hardness tests. We obtained the best hardness result in the nugget zone (NZ), reaching ~69 HVN. This is due to a higher concentration of nano-sized reprecipitation. One characteristic of this region (NZ) is the presence of small, equiaxed, dynamically recrystallized grains, which are either free of strengthening precipitates or contain small reprecipitates. However, the TMAZ comprises coarse precipitates. With deformed and dynamically recrystallized grains present, rotational speed significantly affects particle growth; higher speed leads to greater particle growth. It also significantly affects precipitation characteristics and dislocation properties [12].

Sharda Pratap Shrivastava et al. examined FSW on various aluminum alloys, including (AA4018-AA8011), to improve their mechanical properties. This work examined the impact of Heat on the Mechanical characteristics of Al alloys, as well as the influence of heat curing on hardening, where friction-generated Heat increases joint strength. The maximum tensile strength value was determined using SEM. Microhardness was calculated in different areas of the welds to record and study their mechanical properties. It was concluded that the

tensile strength could be increased by adding Heat and cooling. A tensile value was obtained at 300 °C for 60 minutes of water cooling. As for hardness, it decreased with increased Heat [13]. Tiwan et al. examined the impact of rotating speed and pin shape on the microstructure and mechanical characteristics of unlike spot friction weld joints between the aluminum alloys AA2024-O and AA6061-T6. They used two pin shapes (cylindrical and stepped) at three rotating speeds (900, 1400, and 1800 rpm). They performed microstructural analysis using a microscope, along with microhardness measurements and surface analysis. The results showed that increasing the instrument's rotating speed increases roughness in the weld area. Rotating speed and pin shape directly influence material flow, and grain size and precipitation hardening are the primary causes affecting mechanical characteristics [14].

Bahman Meyghani and his colleague identified tool inclination angle as a crucial factor in their study. They used 6 mm-thick 6061-T6 aluminum to examine how tool inclination angle during welding affects thermomechanical behavior. The simulation employed a rotating speed of 800 RPM, a crosswise speed of 120 mm/min, and a plunging depth of 0.1 mm. When the tool's tilt angle was not accounted for, the simulation showed a typical symmetrical heat distribution, with the highest recorded temperature at 389°C. However, after incorporating the device's tilt angle into the welding process, the maximum temperature was verified on the back side of the tool (approximately 400°C). This Heat, in turn, improves the homogeneity of the material mixture, thus resulting in better welding. Temperature changes were observed at different points on the front and back sides, approximately 360°C on the front side and approximately 400°C on the back side for the welding device. A smooth, rapid rise in temperature is achieved on the back side at the welding tool's angle of inclination, which reduces defects, cracks, and gaps [15].

This research aims to achieve the best mechanical properties and a defect-free microstructure for the dissimilar aluminum alloys AA2024-T3 to AA6061-T6, where the alloy bonding process was optimized by varying welding parameters and three pin profile shapes (triangle, square, and hexagon).

2. Materials and Methods

FSW was performed using a vertical milling machine, as shown in Fig. 1. Three different welding tool shapes (triangular, square, and hexagonal) were used, with dimensions shown in Fig. 2. The welding tool was manufactured from low-carbon steel and tempered to increase toughness and strength. Table 1 shows the chemical composition of the welding tool and alloys. AA (2024 T-3 and 6061 T-6). X-ray Fluorescence (XRF) was used to analyze the chemical composition of the alloys and the welding tool at the Scientific Research Authority in Baghdad, Iraq. Two aluminum alloys, 2024-T3 and 6061-T6, were used. The plate was cut into 120 mm lengths, 60 mm wide, and 2 mm thick. These welds are widely used in aerospace, shipbuilding, automotive, construction, and other applications. A fixture was mounted on the milling machine to prevent the workpieces from moving during welding. The welding procedure was performed at rotating speeds of (620, 920, and 1500) rpm, with feed rates of (28, 23, and 13) mm/min, correspondingly, and an instrument tilt angle of 1°. Fig. 3 shows plates after cutting and welding.



Fig. 1 Vertical milling machine



Fig. 2 Tool pin profiles of FSW: Triangle, Hexagonal, Square (the shoulder diameter: 18mm, pin length: 1.5 mm, and tilt angle 1°)

Table 1: Chemical composition of AA 2024-T3, 6061 –T6, and welding tool

Material type	Al%	Cr%	Cu %	C%	Fe%	Mg%	Mn%	Si%	Ni%	Zn%	Other, total
6061-T6	78.36	5.287	0.413	---	---	0.499	1.355	0.14	0.141	0.51	Rem.
2024-T3	79.42	<0.0020	13.85	---	---	<0.16	0.169	0.150	0.131	0.3449	Rem.
Welding tool	0.0052	0.232	0.0675	0.211	98.4	---	0.710	0.17	0.052	---	Rem.

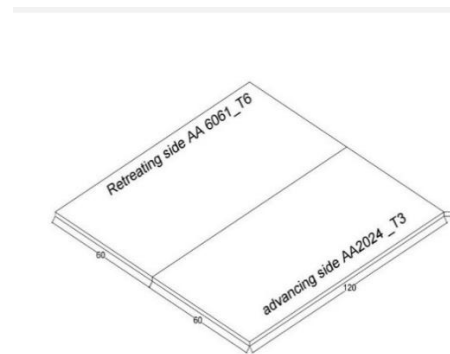
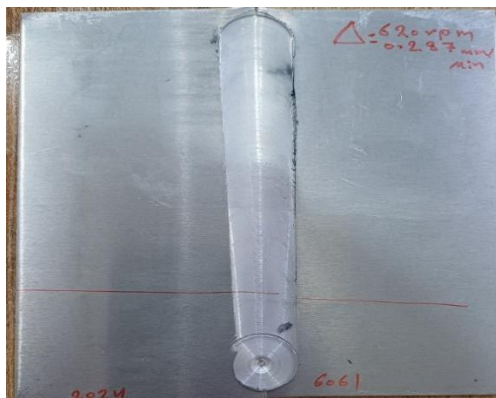


Fig. 3 shows plates after cutting and welding.

The X-Ray Radiography Inspection: This inspection used the ability of short-wavelength electromagnetic radiation (photons), specifically X-rays, to penetrate and partially absorb solid materials. The result was recorded on photosensitive paper or film and viewed on a fluorescent screen. This inspection was conducted at Al-Naba Engineering Inspection Company in Baghdad, Iraq. The inspection was performed on two welded samples under optimal conditions using a tool with a triangular pin outline at a rotating speed of 620 rpm and a feed ratio of 28 mm/min—similar weld joints of 6061-T6 and dissimilar joints of 2024-T3 to 6061-T6.

The tensile test was carried out to determine the tensile characteristics of welded joints under all welding conditions. Fig. 4 displays the shape of the samples after waterjet cutting, according to ASTM E-8 [16]. Each sample illustrates the rotational speed used and the pin profile of the different aluminum weld joints. All tensile investigations were conducted using a universal tensile testing machine at the Baquba Technical Institute, Iraq. Fig. 5 shows the sample dimensions. The examinations were

performed using a Computer Control Electronic Universal Testing Machine (Model WDW-100D) manufactured by Qingdao Chengyu Testing Equipment Co., Ltd., China, with an extreme load capacity of 100 kN (Manufacturing Date: June 2024). Figure 6 shows the tensile device



Fig. 4 Samples of tensile test

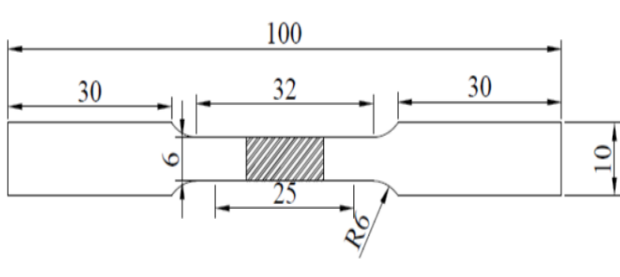


Fig. 5 ASTM-E8 sub-size specimen for tensile investigation; measurements in mm [16].

After welding, the samples were prepared for the tests required in this study. The most important tests included microhardness and microstructure testing. The required samples were sanded with coarse and fine-grit sandpaper ranging from 180, 220, 400, 600, 1000, 120, and 2000 grit. Then, a polishing cloth (velvet) was used with a polishing fluid containing fine Al₂O₃ particles. After polishing, smoothing, and drying the samples, a special aluminum alloy developer solution called Keller's Reagent was used. This solution consisted of 190 mL of distilled water, 5 mL of HNO₃, 3 mL of HCl, and 2 mL of hydrofluoric acid.

Subsequently, a microstructure examination was performed using a light microscope to reveal the grain shape, record weld zones, study changes, compare the two alloy zones, determine the influence of pin profile shapes on microstructure, and observe differences between the used parameters. This examination was conducted using a light microscope at the University of Diyala, College of Engineering, Department of Materials Engineering. Fig. 6 shows the optical microscope model (MTM-1A)

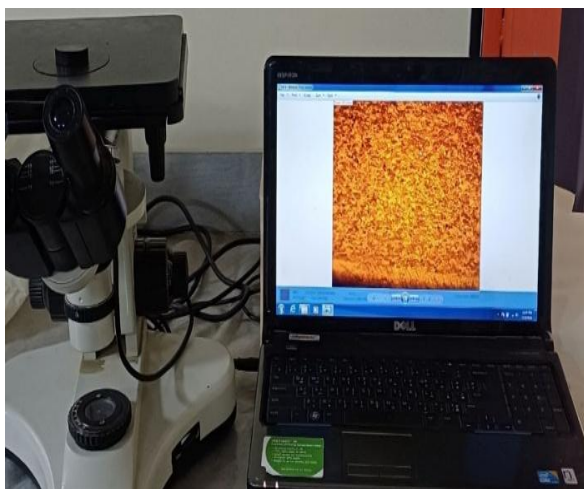


Fig. 6 The optical microscope.

A microhardness test was performed at a 0.989 N load at different points along the weld, with a holding time of 20-25 seconds per sample. This test was carried out using a Universal Hardness Tester, a digital microhardness tester (Model: HVS-1000 NO. 11200, made in 2011 by Laryee Technology Co., China). was used to measure the hardness. Hardness values were measured using a Vickers hardness tester. The examination was conducted at Baquba Technical Institute, Iraq. Fig. 7 shows the microhardness test device. For the hardness test, the samples were supported in molds, and the cold support process was prepared using a 1:1 mixture of epoxy and hardener. Fig. 8 shows the sample format for microhardness examination.



Fig. 7 Microhardness device

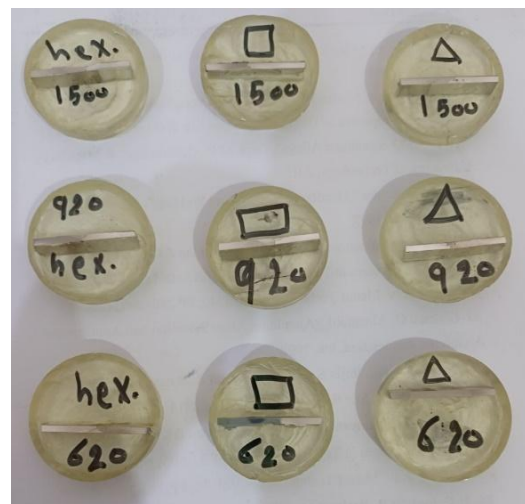


Fig. 8 Samples for microhardness examination and microstructure test.

SEM was performed to examine fracture surfaces of welded joints and the microstructure of weld zones in stir welds. The sample was examined in the stir zone under optimal conditions. The examination was conducted at the University of Technology, Baghdad, Iraq. Fig. 9 shows the SEM device.



Fig. 9 shows the SEM device.

3. Results and Discussion

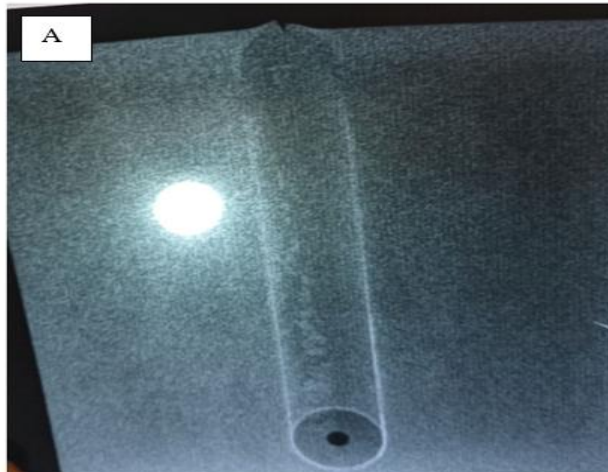
1. X-Ray Radiography Inspection

Pictures showing X-ray radiographic examination performed on friction-welded samples, using

(triangle pin profile, rotating speed 620 rpm, and welding speed 28mm/min) (optimal condition), as illustrated in Fig. 10.

Image 10-A shows a clean weld free of defects, including gaps, cracks, or even voids. Also, it indicates that the mixing process was successful. Image 10-B shows a defect (void) located in the middle of the weld line. This defect can be explained by pressure applied to the welding equipment during the welding process, as well as by the welding process being interrupted and then resumed. Image 10-B shows it is free of defects, except for the hole, which is considered a defect caused by the machine stopping and the welding subsequently resuming.

2. Tensile test



A) similar weld 6060-T6



B) dissimilar weld 2024-T3 to 6061-T6

Fig. 10 shows X-ray radiography inspection: A) similar weld 6060-T6; B) dissimilar weld 2024-T3 to 6061-T6

Table 2: Shows tensile-strength results for aluminum sheets welded by friction stir welding.

Experiment number	RS (rpm)	WS (mm\min)	PG	Mean tensile strength MPa
1	620	28	Triangle	150
2	920	23	Triangle	50
3	1500	13	Triangle	120
4	620	28	Hexagonal	75
5	920	23	Hexagonal	70
6	1500	13	Hexagonal	65
7	620	28	Square	40
8	920	23	Square	45
9	1500	13	Square	60

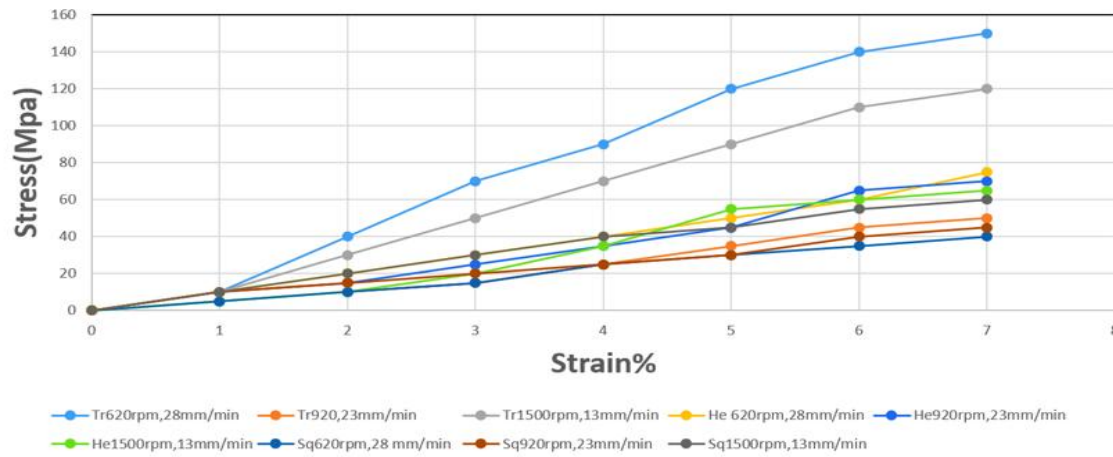


Fig. 11 Stress-strain curve for as-welded (triangle pin profile,620 rpm and 28 mm/min)

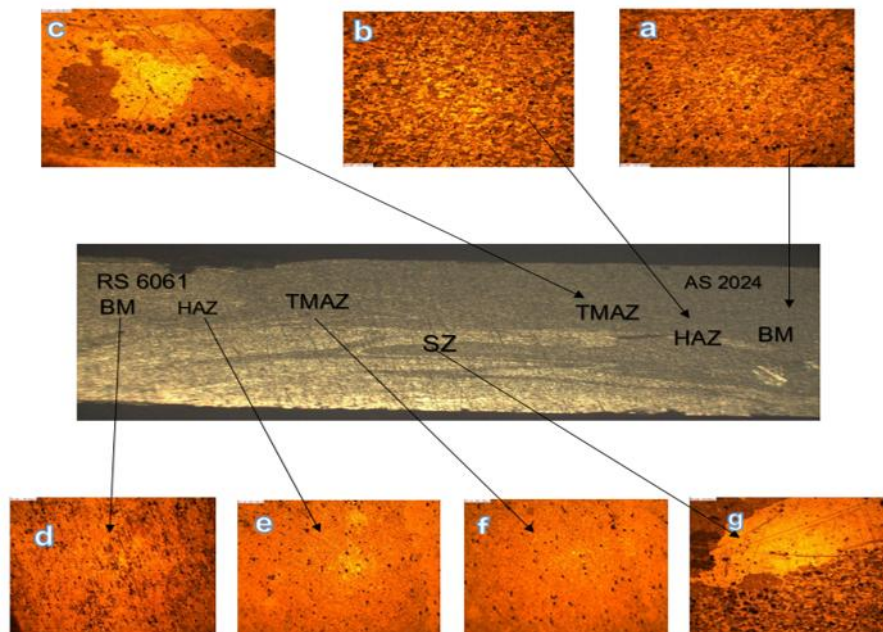


Fig. 12 shows the macro and microstructure of dissimilar FSW as weld (triangle pin profile, 620 rpm, 28 mm/min)

The influence of welding indices (pin shape, rotational speed, and welding speed) on tensile strength in this test: FSW was used on aluminum pieces. Three pin shapes (square, hexagonal, and triangular), three rotational speeds (1500, 920, and 620 rpm), and three feed proportions (28, 23, and 13 mm/min) were applied. Tensile samples were obtained, as revealed in Table 2, to evaluate the tensile strength of FSW aluminum sheets. The table shows that the best tensile strength for the aluminum sheets is achieved at 620 rpm and 28 mm/min with a triangular pin shape. From the table, we observe that the lowest rotation speed and highest feed ratio

achieve the best results, providing optimal material mixing in the weld region.

The triangular shape caused superior mixing, high homogeneity, and fewer defects, leading to increased tensile strength and improved mechanical properties. Lower temperature promotes better plasticization and uniform material flow, resulting in a better weld joint. Conversely, the square shape achieved the lowest tensile strength (40 MPa) under the same conditions. This is attributed to the square pin profile, which causes poor mixing and uneven particle distribution, leading to gaps and defects and ultimately the lowest tensile strength. The hexagonal shape yielded higher tensile strength than the square

shape. This is due to uniform material mixing and an even particle distribution in the weld zone. This is thanks to the geometric shape and design of the welding tool, which produced moderate tensile strength results depending on the rotation speed or feed rate. At high rotation rate (1500 rpm) and feed rate (13 mm/min), At high rotation speed (1500 rpm), high Heat is generated, which softens the weld and promotes particle growth.

This is also due to increased material mixing, resulting in modest tensile strength in some cases, as shown in other results. In FSW, input heat plays a vital part in the mechanical characteristics of weld joints. Increasing rotating speed leads to a rise in input heat and a reduction in mechanical properties; hence, it increases the stirring influence of the pin but may produce more metal flow in the external weld, resulting in channel defects in the weld region, which agrees with the observations of Ren et al. [17]. Fig. 11 Stress-strain curve for optimal welding (as-welded) (triangle pin profile, 620 rpm and 28 mm/min).

3. Macro and microstructure

Fig. 12 illustrates the overall structure and microstructure characteristics of a welded joint under optimal conditions. The image highlights the distinct alloy zones: the SZ, TMAZ, HAZ, and base metal. The advanced side (AS) is alloy 2024, and the retreating side (RS) is alloy 6061, with the retreating side exhibiting an almost uniform stress distribution in the welding area. In this case, the temperature on the receding side is higher than on the progressing side because of the alloy 6061 components; thus, the grain distribution is finer in this alloy. This welded joint shows high-quality welding and good flow between the two alloys. This is because the welding was good and the weld area was free of defects, such as cracks and porosity. Consequently, the homogeneity between the two alloys was perfect.

This welded joint shows relatively high-quality welding and good flow between the two alloys. This is because the welding was good and the weld area was free of flaws, for example, porosity and cracks. Consequently, relative homogeneity between the two alloys was good. Specifically, with respect to the advancing side of alloy 2024 in the BM region image

(12- a). The microstructure shows relatively medium-sized, closely packed grains. The HAZ region in the (12-b) image shows relatively large grains. This is due to grain growth and high temperatures, where this part is exposed to Heat. The TMAZ region (12-c) exhibits elongated, relatively asymmetric grains. This is due to heating and plastic deformation during welding. Grain deformation in this region results in elongated, curved grains. Traces of dragging or twisting are also observed in the grain movement. This movement was caused by the welding tool, which dragged and twisted the material as it moved.

The recrystallization process was incomplete in this region, as evidenced by the uneven grain size. Image (12-d) shows BM 6061; the microstructure of the base metal reveals that grain size in this region is comparatively fine and elongated in the rolling direction. Image (12-e) displays the microstructure of the metal in the HAZ for the 6061-T6 alloy. It has a large grain size due to the high heat input. In the TMAZ region (image 12-f), grains are heated and plastically deformed during welding, resulting in a distorted microstructure due to mechanical movement of the instrument. This plastic deformation in the TMAZ zone causes grains to become curved and laterally elongated. Image (12-g) shows the stir zone, where the grains are nearly equiaxed. The material is a mixture of 2024 and 6061 alloys.

The weld zone (SZ) is characterized by grains with the highest deformation and a tendency to recrystallize due to high stress. Inlet temperature and applied welding stress are related and directly affect grain size. Higher input temperature leads to a smaller grain size in the region. The high temperature and plastic deformation during welding in the tension region led to dynamic recrystallization of equiaxed grains. This is based on previous FSW studies. In aluminum alloys, elongated base-alloy grains mechanically transform into fine, equiaxed grains in the weld region during welding. These outcomes coincide with those of researchers [8] and [18].

4. Microhardness

In this study, a hardness test was performed on weld samples of alloys 2024-T3 and 6061-T6 at different welding speeds, feed rates, and pin shapes, as shown in Fig. 13. From this test and the fig., we conclude

that the stirring zone (SZ) displays a greater hardness value compared to the additional weld regions: the HAZ and the TMAZ. This is because frictional Heating and the plastic flow the metal experiences during frictional welding are generated in the stirring zone (SZ). The highest hardness value was recorded at 160 HV in the weld region under ideal conditions (triangular pin shape, welding speed 28mm/min, and rotation speed 620rpm).

While the highest value was recorded for the advancing side of alloy 2024 (133 HV) in the BM region under conditions of triangular pin profile, rotation speed 920 rpm, and welding speed 23mm/min compared to the retreating side of alloy 6061, this is due to the geometry of the pin profile, its dimensions, and the speeds used. The fine grains are equiaxed and dynamically recrystallized. In the thermomechanical influence zone (TMAZ), the grains are nearly elongated. In the HAZ, grain stiffness varies. The highest hardness value was 132 HV, and the lowest hardness value was 110 HV on the retreating side of alloy 6061 in the BM zone.

In general, the hardness distribution in aluminum alloys depends on the distribution of two-phase deposits. The lowest hardness values were observed on the retreating side of alloy 6061, corresponding to the advancing side of alloy 2024. This is attributed to the movement of the material or the welding tool

from front to back. Hardness variation is influenced more by deposits formed during welding than by grain size in the weld zone (SZ). These deposits occur mostly in the HAZ and TMAZ zones, approximately 10 mm from the weld. Researcher [19] confirms these results.

5. Fracture Surfaces

SEM was utilized to analyze the fracture surface of a sample that underwent tensile testing under optimal conditions (triangle pin profile, 620 rpm, 28 mm/min). Fig. 14 shows the microscopic image of the fracture surface of the friction stir welding joint between 2024 and 6061 Al alloys. The results show a ductile fracture with fine, equiaxed dimples, attributed to several microscopic voids of various sizes and shapes. Cavities were also observed in the HAZ region. The ductile fracture pattern indicates that the welding process was successful, homogeneity was achieved between the two alloys, and the weld joint underwent plastic deformation before fracture. The fracture surface, as shown in the image, is highly rough with widespread, uniform micro-pits, indicating the sample's ability to absorb energy and withstand stresses before fracture. These pits are attributed to precipitated phases within the alloy. These results were similar to those reported in reference [20].

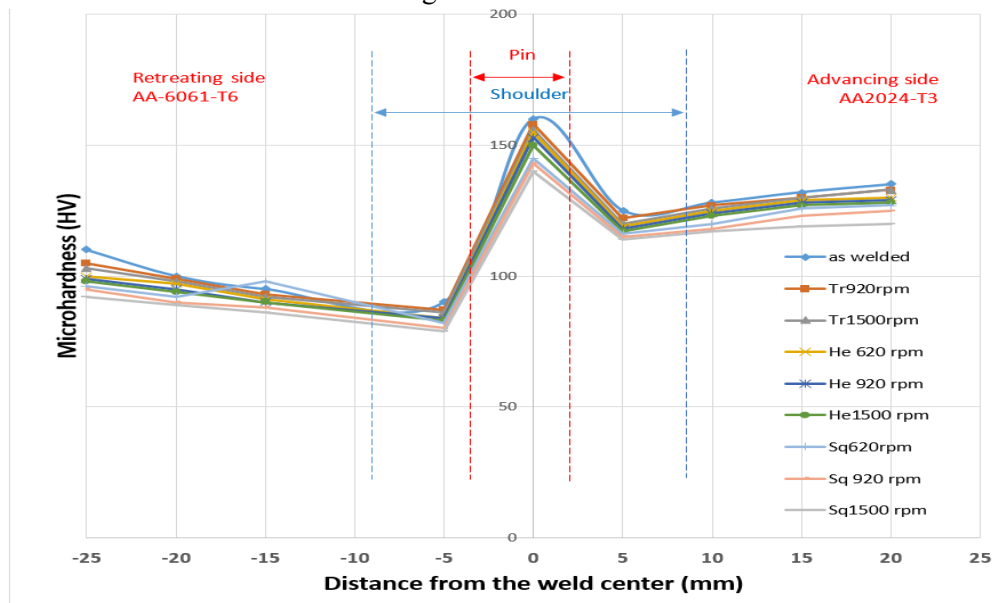


Fig. 13 Microhardness distribution across section of FSW joint of different rotation speed, welding speed, feed rates, and pin shapes.

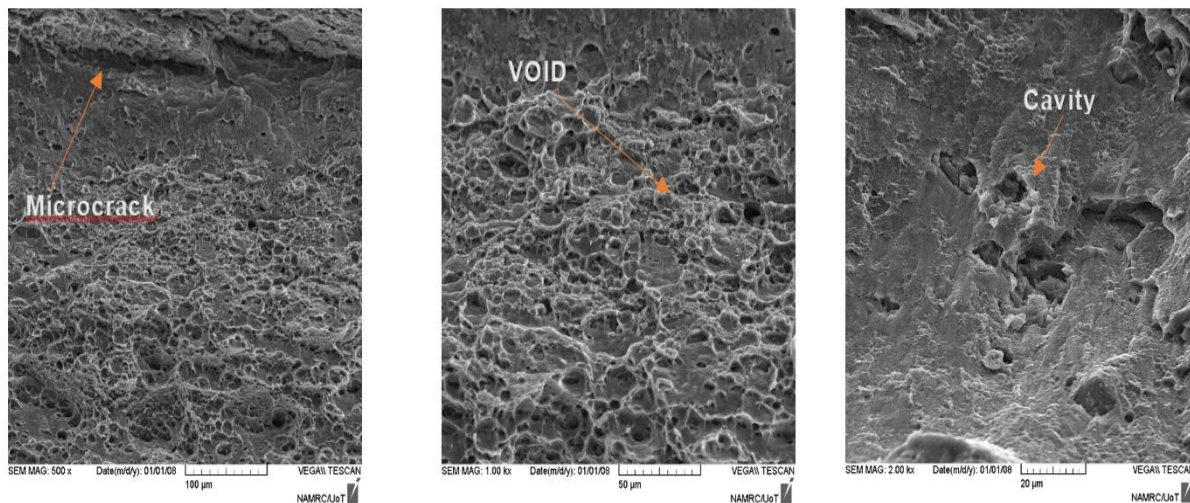


Fig. 14 SEM photographs of the fracture region of a tensile-tested sample in (SZ) for dissimilar FSW for as-welded specimen (triangle pin profile, 620 rpm, 28 mm/min).

6. Conclusions

The FSW process on 2024-T3 and 6061-T6 aluminum alloys was carried out utilizing several welding tools, rotation rates, and welding speeds. We examined the welded joint's microstructural and mechanical features.

The following conclusions can be addressed:

1. Using a rotational speed of 620rpm, a triangular pin profile, and a feed rate of 28mm/min, the best defect-free weld was achieved with dissimilar alloys.
2. Based on X-ray radiography testing, the weld joints were defect-free and clean when using triangular tool pin geometry at a revolution rate of 620 rpm and a welding rate of 28mm/min (optimal condition).
3. Based on tensile strength results, welding the joint at a rotation rate (620 rpm) and a welding rate (28mm/min) with triangular pin geometry yielded the best joints compared to other conditions.
4. The SZ recorded a maximum hardness of 160 HV. Under the optimal conditions of triangular pin geometry, rotation rate (620 rpm), and welding rate (28mm/min), the hardness of alloy 2024 was higher than that of alloy 6061. In addition, no defects were observed in the welding area.

5. Microstructure results showed excellent and homogeneous mixing in the SZ, with the welded joint free from defects under optimal conditions (triangular pin profile, a rotation rate (620 rpm), and a welding rate (28 mm/min).
6. Fracture surface analysis shows that the friction weld fracture is ductile.

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Conflict of interest

The authors report no competing interests that could influence the publication of this work.

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