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Effect of Friction Stir Welding Process Speed and Tool Pin Length on the Mechanical Properties of the Resulting Weld Joint between AA7075 and AA6061 Aluminum Alloys

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Abstract

Aluminum alloys have received wide attention in the field of industry in recent times due to their lightweight, high resistance to corrosion, and ease of formation. In addition to their availability and affordability, the problems that occur in the welding of aluminum by traditional methods make the friction stir welding process one of the most important welding processes. This solid-state welding process was discovered in 1991 by TUW and is widely used in the welding of dissimilar aluminum alloys. In our research, we welded two important aluminum alloys in the industry (A7075/AA6061) with a thickness of 3mm. We changed some welding process parameters, including tool pin length, feed rate, and rotational speed. After placing an alloy (AA 6061) in the advanced side and tilting the tool, we examined the welded samples to find out the effect of the aforementioned parameters on the tensile strength and resulting hardness. We found that the length of the tool pin has the greatest influence on these properties, as they increase with the increase in the length of the pin. We also noted that the rotation speed and feed rate have a joint effect on the mechanical properties. The highest hardness was obtained at feed rates of 20 and 45 mm/min and rotational speeds of 1200 and 900 rpm, respectively. The highest tensile strength of 209 Mpa was obtained at a rotation speed of 1200 rpm and a feed rate of 20 mm/min.

Keywords: Friction stir welding; pin length; AA7075 and AA6061 aluminum alloys

Introduction

The aluminum industry has evolved over the past years, transitioning from limited production of products and alloys to its inclusion in the mass manufacturing of various products [1]. This shift is driven by the increasing need to reduce the weight of vehicles and structures [2]. Many production processes in this industry require bonding operations, and traditional welding methods often result in defects in the resulting weld joint when joining aluminum and its alloys. To address this issue, the Friction Stir Welding (FSW) process was developed as a method to eliminate these defects. FSW is commonly used for welding similar and dissimilar metals, particularly aluminum alloys, as it does not involve melting the metal like traditional welding methods do. Instead, it induces severe deformation in the solid state, leading to dynamic recrystallization of the granules and facilitating the flow process through sliding between the recrystallized granules, which are typically less than a micron in size in the weld zones [3, 4]. The principle of the FSW process can be summarized as shown in Fig. 1.

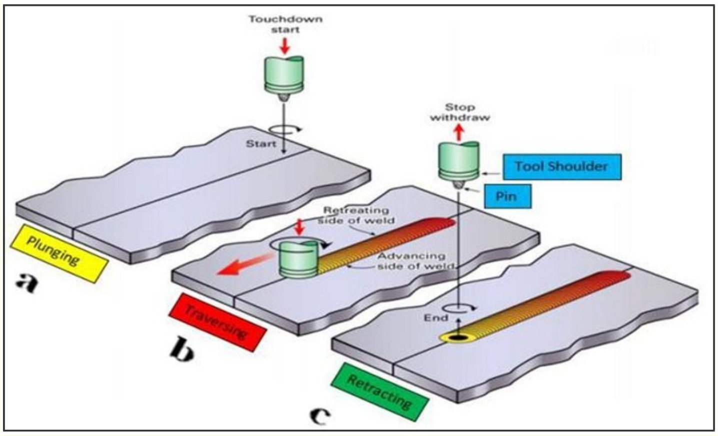

Figure 1: Schematic of three main processes in FSW [5].

The three main processes of FSW are as follows:

a. Rotating the tool, consisting of a shoulder and a pin, and inserting it inside the materials to be welded until the shoulder touches the surface of the materials. The tool keeps rotating for a few seconds until the materials around the pin are softened.
b. Initiating the horizontal movement of the tool towards the welding line, where the pin mixes the molten materials and transfers them from the front to the back side. Meanwhile, the shoulder presses these materials inside the welding area, preventing them from leaving and resulting in the formation of a welding joint with mixed plastic materials.
c. Stopping the horizontal movement of the tool and pulling it up, which leaves behind an exit hole that needs to be disposed of, either by cutting or sawing [6-8].

Sometimes the tool is tilted to the back edge of the tool to increase the pressure of the materials into the welding area and prevent the formation of voids behind the pin, as shown in the Fig. 2 and often this angle ranges from (1° - 3°.)[9].

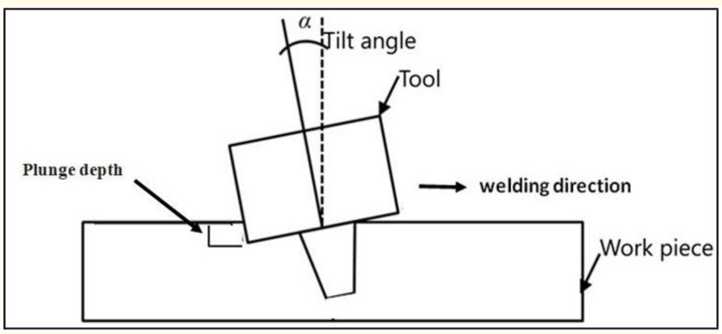

Figure 2: Tilt angle tool of FSW.

Four areas are formed during the welding process, their characteristics are mentioned in the Fig.3.

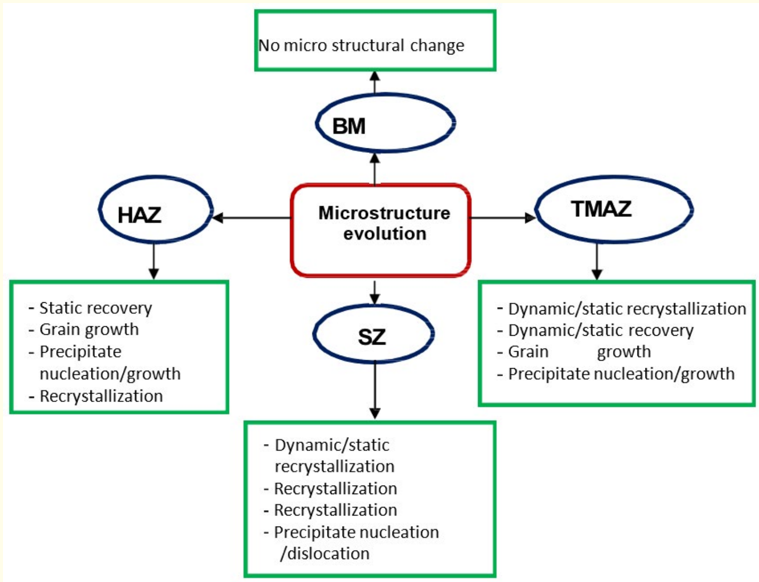

Figure 3: Microscopic developments of the zones formed during FSW [10].

The researchers have carried out many studies to know the effect of friction parameters on the properties of the weld joint, V. Balasubramanian, 2008[11], They did several welding experiments on different alloys of aluminum (AA7039,AA1050, AA7075,AA2024 and AA6061) using friction welding to find out the extent to which the mechanical properties of the weld joint are affected by the parameters of the welding process (feed rate, speed of tool rotations and axial force) and their relationship to the base metal. It was concluded that the hardness, ductility and yield strength of aluminum alloys played an effective role in the success of the weld joint. P Bahemmat, MHaghpanahi1, MK Besharati, et al, 2010[12]. They studied the effect of the parameters of the friction stir welding process (feed rate), as well as the location of its alloy, on the mechanical properties of the weld joint resulting between two aluminum alloys (AA7075-T6 and AA6061-T6) with a thickness of (5 mm) and the examinations showed that there are severe defects in the weld area resulting from the feed rate (160 mm/min). And small defects at a feed rate of (120 mm/min). As for the average hardness of the area (sz), it increases with the increase in the welding speed, and the results showed that placing alloy (AA6061-T6) on the advanced side gives better results. A.A.M. da Silva, E. Arruti, G. Janeiro, el at., 2011[13]. In this study, they explained the effect of friction stir welding process parameters (fixed feed rate and variable spindle rotation speed) on the mechanical properties and material flow of the resulting weld joint between two aluminum alloys (AA2024-T3 and AA7075-T6) with a thickness of (3 mm), where it was found that the welding efficiency is (96%) in terms of tensile strength occurs at Rotational speed (1000 rpm) among the other two speeds (400 and 2000 rpm). The study also showed that at the reduced rotational speed there was a weak mixing of the materials. N. T. Kumbhar1 and K. Bhanumurthy, 2012 [14]. They studied the effect of the feed rate and the speed of rotation of the tool on the mechanical properties of the weld joint resulting from friction stir welding between two alloys of aluminum alloy (AA5052 and AA6061) with a thickness of (5 mm). The tests showed that there is a similar texture for both materials, despite the weak mixing of materials in the interface region, and the tensile strength was good as a result of the dispersion of elements in the solid mass. Prashant Prakash, et al, 2013 [15] In this study, the effect of the parameters of the friction stir welding process (feed rate and rotational speed) was investigated on the tensile strength of the weld joint resulting from welding two aluminum alloys (AA6061) with a thickness of (6 mm), and the tensile strength was (142 MPa) at the feed rate (20 mm/min) and the rotation speed (1120 rpm). and the length of the tool pin (5.2 mm), and when the feed rate became (25 mm/min), the rotation speed (1400 rpm), and the length of the pin (5.7 mm), the tensile strength reached

(182 MPa), from here we notice that when these coefficients were increased, the tensile strength increased. S. Ravikumar, V. Seshagiri Rao and R.V. Pranesh, 2014[16]. They studied the parameters of the friction stir welding process feed rate (110, 100, 90 mm/min), rpm tool rotational speed(1000, 900, 800 rpm) and tool pin profile (Taper cylindrical threaded, Taper square threaded and Simple Square) on the mechanical properties (hardness and tensile strength) of the resulting weld joint between two aluminum alloys (AA6061and AA7075) with a thickness of (6.35 mm) and the results showed that the best mechanical properties are obtained at the feed rate (100 mm/min) and the rotation speed (900 rpm) with (Taper cylindrical threaded tool) and the strength of the Stirred zone was higher than heat-affected zone(HAZ) and(TMAZ). R.I. Rodriguez, J.B. Jordon, P.G. Allison, el at. 2015[17], They investigated the effect of the tool rotation speed on the mechanical properties and material flow of the weld joint resulting from friction welding only for two aluminum alloys (7075-T651 and 5083-H111) with a thickness of (6 mm) and they concluded that the mixing of materials and the strength of the joint increases with the increase in the speed of rotation of the tool and with the low rotation speed there is a poor mixing of materials This results in a failure in the stir zone. M Saeidi1, B Manafi, MK Besharati Givi, el at,2016[18] They conducted friction stir welding on two aluminum alloys (AA5083 and AA7075) with a thickness of 5mm. The study examined the impact of spindle rotation speed (500, 630, and 800 rev/min), feed rate (30, 41.5, and 50 mm/min), and tool with a square-shaped pin on the mechanical properties of the resulting weld joint. The highest tensile strength was achieved with spindle rotation speeds of 800 r/min and a feed rate of 50mm/min. Furthermore, all links produced at this speed were free of defects. Mohammed M. Hasan1 & M. Ishak1 & M.R.M. Rejab, 2017[19], In this research, the study focused on the impact of tool geometry and the variables of the friction stir welding process (tool tilt angle, axial and rotational welding speeds) on the material mixing and mechanical properties of the weld joint between two aluminum alloys (AA6061 and AA7075) with a 3mm thickness. The tool design was found to play the most significant role in producing a high-quality weld joint with increased tensile strength, a solid stir zone, and a smoother surface. Specifically, using a welding tool with a threaded truncated cone pin and a single flat resulted in a better weld joint, while a tool with a smooth cylindrical or tapered pin produced the opposite effect. Izabela Kalemba-Rec1 & Mateusz Kopyściański1 & Damian Miara, el at.2018[20], they investigated the impact of friction stir welding process parameters, such as tool rotational speed, tool geometry (pin design), and the configuration of joined alloys, on the mechanical properties of the welding joint between two aluminum alloys (7075-T651 and 5083-H111) with a thickness of 6 mm. The highest mechanical properties were attained when alloy 7075-T651 was positioned on the retracting side and alloy 5083-H111 on the advancing side, with a tool rotation speed of 280 rpm and a Triflute pin shape. The findings also indicated that the formation of the stirring zone is significantly influenced by the stirring direction and rotation speed, and that an increase in rotation speed results in better material mixing but reduced joint efficiency and mechanical properties. Mohamed M. Abd Elnabia, Abou Bakr Elshalakany,2019[21], they studied the mechanical properties of the weld joint resulting from friction stir welding between two alloys of aluminium alloy (AA5454-AA7075) with a thickness of (3.5 mm), the effect of welding parameters (tool tilt angle, feed rate, plunge depth and tool rotation speed) and tool geometry (shoulder diameter(D), pin diameter(d) and ratio (D/d), the pin profile (based on taper angle) and the location of the materials, and it was found from the results of this study that the most effective factors on the ultimate tensile strength are the speed of tool rotation, the rate of feed, the plunge depth and the ratio (D/d). The highest contribution to the ultimate tensile strength was the rate of feed (about 18.5%). G. S. V. Seshu Kumara,_, Anshuman Kumara, S. Rajeshb, el at.2021[22], attempts to study the effect of friction stir welding parameters (axial force, tool tilt angle and tool rotation speed) on the resulting welding joint between two aluminum alloys (AA7075-T6 and AA6061-T6) of thickness (6.5 mm) and the results showed that the effectiveness of the tensile strength increases as well as the impact force increases with the increase in rotational speed until it reaches the highest Force at (900 rpm), and the force begins to decrease when the rotational speed reaches (1100 rpm), and the same is the case with the axial force, where the force increases until it reaches the highest value at (2.5 KN), then it begins to decrease when the force reaches (3 KN). Tilting the tool, its increase leads to an increase in the impact force. As for the hardness (HV), it increases with the increase in the tilt angle and the rotation speed. As for the axial force, it directly affects the hardness until it reaches (2.5 KN), then the hardness begins to decrease slightly when the axial force reaches (3 KN).

Experimental Procedure

In each process, there are steps that depend on the characteristics of the process and the implementation from start to finish. In the process of friction fusion welding, these steps are categorized as follows:

Preparing the work pieces

Welding has been performed on aluminum alloys (AA7075 and AA6061), which are of great importance in the industry. The panels have dimensions of (3 x 100 x 150) mm. Subsequently, the panels are collected and undergo a milling process on their edges to ensure straightness and full compatibility with each other during welding. The edges are then cleaned from any excess resulting from the milling process using a soft file tool, followed by cleaning with acetone to prevent aluminum oxide [23]. Table No.1 presents the chemical composition of the alloys used in this research [24]. As for the mechanical properties of these materials, they are shown in Table 2.

Alloy	*Fe*	*Cr*	*Si*	*Mn*	*Cu*	*Zn*	*Ti*	*Mg*	*Al*
AA6061	0.7 max	0.04-0.35	0.4-0.8	0.15 max	0.15-0.4	0.25max	0.15 max	0.8-1.2	Bal.
AA7075	0.5 max	0.18-0.28	0.4 max	0.3 max	1.2-2.0	5.1-6.1	0.2 max	2.1-2.9	Bal.

Table 1: Percentages of components of aluminum compounds (%wt) AA6061 and AA7075 [24].

Alloy	*Tensile strength (MPa)*	*Yield strength (MPa)*	*Elongation (%)*	*Hardness (0.1HV)*
AA 6061	283	235	26	105
AA 7075	571	531	13	175

Table 2: Mechanical properties of aluminum alloys.

Welding tools

The friction stir welding process tool has a big role in producing successful weld joints; it is responsible for the friction and flow of materials in the joint area, so it is under high forces and severe corrosion. Therefore, according to the type of materials used and the process conditions, the tool must be suitable for the working conditions to which it is exposed to perform the work as required without corrosion or fracture, which affects the welding joint's productivity and production delay. Therefore, a tool made of steel (5xhm) was used. The table (3) shows the chemical composition of the tool used in the welding process.

Tool5XHM	*C*	*Cr*	*Si*	*Mn*	*Ni*	*Mo*
	0.5-0.6	0.5-0.8	<=0.35	0.5-0.8	1.4-1.8	0.15-0.35

Table 3: Percentages of components of tool (%wt).

The dimensions of the special tool were designed in our research based on most previous studies such as the diameter of the pin, the diameter of the shoulder, and the tilt angle, for example, which adopted that the length of the tool pin is less than the thickness of the material to be welded by about (0.1-0.5mm) As for the diameter of the pin (d) and the diameter of the shoulder (D), the ratio between them is (D/d) approximately (3-4) for materials with a thickness of (3 to 6 mm), preferably the shoulder diameter (18mm) and the pin diameter (6mm) should be for plates of this thickness [6-26]. Fig. 4, shows the dimensions of the tool that was used in this research depending on the above.

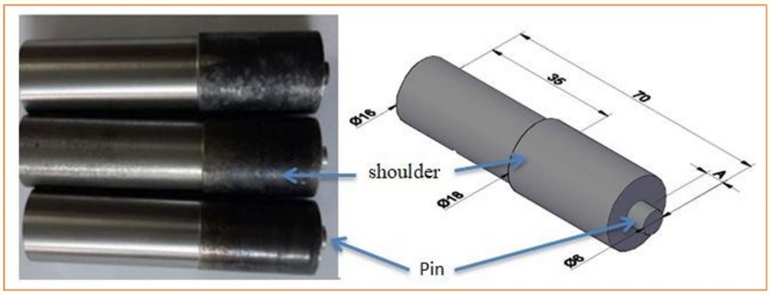

Figure 4: Dimensions of the tool used in the welding process.

Milling machine

One of the advantages of the friction welding process is the possibility of using the available equipment, as it does not require specialized equipment. Therefore, in our research was used, a German-made vertical milling machine, model (2012), as shown in Fig. 5, as it provides linear and rotational motion. The motor capacity is (5.8 kW) and (400 volts), with maximum spindle speed (1710 rpm) and maximum table speed (360 mm per minute) and table moving in three perpendicular directions. The movement of the table up and down is controlled by an electronic board with an accuracy of (0.001mm). The machine head can also be tilted according to the required angle.

Figure 5: Vertical milling machine.

Install work pieces on the machine

Before starting the welding process, the two plates are connected and fixed on a plate prepared for this purpose in a good way, as shown in Fig. 6, to prevent the movement of the plates during the welding process. Because the friction resulting from the process will generate large vibrations that may lead to the movement of the plates if they are not fixed well. and just as the process of arranging the plates on the advancing side and the retracting side, has a significant impact on the quality of the weld, where the harder plate (AA7075) is placed on the advancing side and the softer plate is placed on the retreating side (AA6061), but in this research, we followed the results of previous researches [29-32] on these two materials, which proved that placing the plate (AA6061) on the advancing side and placing the plate (AA7075) on the retreating side will give better results than if the boards are reversed.

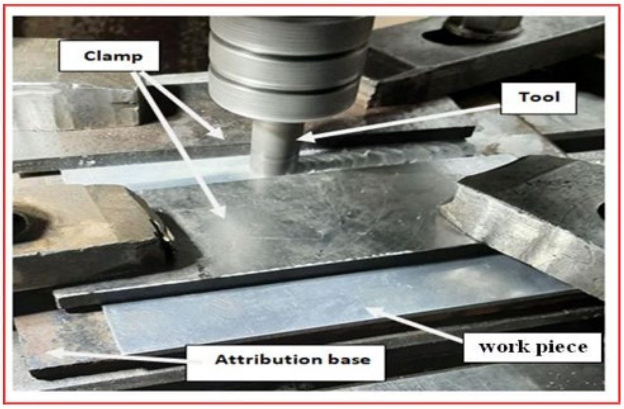

Figure 6: The method of fixing the plates on the machine table.

The parameters selected for optimization. The parameters to be studied in this research that affect the weld joint resulting from the welding of different aluminum alloys by the friction welding process are:

1. Feed rate.
2. Rotational speed.
3. Length of tool pin.

For the rest of the other parameters, constant values for them were chosen without change during the welding process. The values of the process parameters are shown in Table 4.

Parameters (unit)	***Symbol***	***Levels***		
		L1	***L2***	***L3***
Tool rotational speed (rpm)	TRS	660	900	1200
Welding speed (mm/min)	F	20	45	70
Pin tool length(mm)	L	0.4	0.6	0.8
shoulder diameter (mm)	D	16		
Pin diameter (mm)	d	6		
Tool tilt angle (°)	α	1		
Dwell time (s)	t	30		
Tool rotation direction	ccw	counter clockwise		

Table 4: FSW process parameters.

Design of experiment

Experiments were designed using the Taguchi L9 orthogonal method [33]. An orthogonal matrix of three parameters with three levels was constructed using Taguchi experimental design, which was constructed following Minitab software. It results in nine experimental operations, as shown in Table 5.

Experimental Serial No.	*Speed of rotation (rpm)*	*Feed rate (mm/min)*	*Tool pin length(mm)*
1	660	20	2.4
2	660	45	2.6
3	660	70	2.8
4	900	20	2.6
5	900	45	2.8
6	900	70	2.4
7	1200	20	2.8
8	1200	45	2.4
9	1200	70	2.6

Table 5: L_9, design of experiments.

Preparing test models

After completing the welding process, it is cleaned from the excesses that may have resulted from the welding process, then we prepare test samples to study the effect of the FSW process parameters on the resulting weld joint to find out the appropriate and most effective parameters on the welding joint. It is preferable to use the wire cutting machine. The samples are cut so that the solder joint is in the middle of the sample, as shown in Fig. 7 to perform the following tests:

1. Tensile strength tests.
2. Hardness test.
3. (SEM) Test.

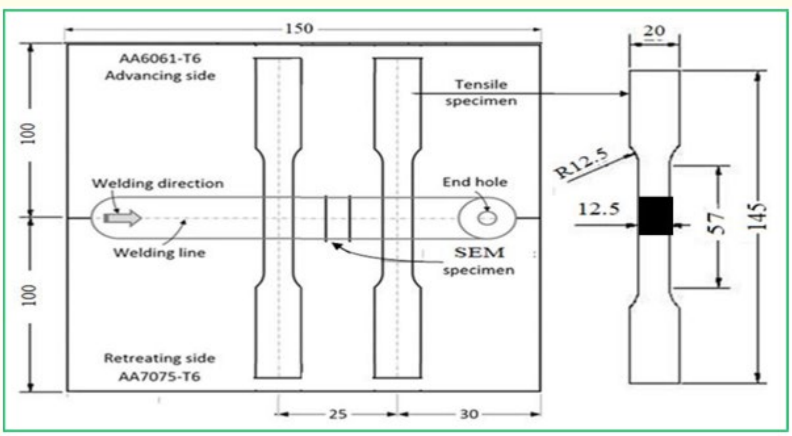

Figure 7: Schematic drawing of tensile samples.

Results and Discussions

Visual inspection

After completing the welding process, the welded samples were examined with the naked eye, and the penetration at the back was good except in some samples, as the penetration was very good when the length of the tool pin was 2.8 mm, and there were no visually noticeable defects. Rings were clearly formed on the surfaces of all samples, as shown in Fig. 8, and the distance between the rings was almost uniform.

Figure 8: The upper surface of the weld joints.

Analysis of tensile strength

Tensile strength is one of the most important mechanical properties by which the quality of dissimilar weld joints can be determined. Where tensile samples were prepared in Fig. 10 according to the ASTM E8/E8M standard [34]. The examinations were conducted and the results of the final tension force were recorded in a table 6.

No. sample	***Rotation speed***	***Feed rate***	***Pin length***	***ULT Mpa***	***Joint efficienes AA6061***	***fracture zone***
1	660	20	2.4	115	32.6	SZ
2	660	45	2.6	195	55	HAZ of 6061
3	660	70	2.8	200	56.7	HAZ of 6061
4	900	20	2.6	198	56	HAZ of 6061
5	900	45	2.8	201	57	HAZ of 6061
6	900	70	2.4	126	34.3	SZ
7	1200	20	2.8	209	59	HAZ of 6061
8	1200	45	2.4	165	46.7	SZ
9	1200	70	2.6	190	53.8	HAZ of 6061

Table 6: Ultimate tensile strength test results with specimens fracture locations.

We often notice in tensile tests that the fracture of the samples occurs in the (HAZ) region on the side of the material with the lowest strength [35-37], and in our research we noticed that most of the specimens fractured in the region (HAZ) on the side of the weaker alloy (AA6061) as shown in the Fig. 9 and this is due to grain density in this zone is lower compared to other zones and the welding joint is smooth in this zone [38, 39].

Figure 9: Fracture locations in tensile samples after testing.

Fig. 10 depicts the impact of each process parameter on the tensile strength of the welded joint, and we will discuss its influence on the weld joint properties in the following.

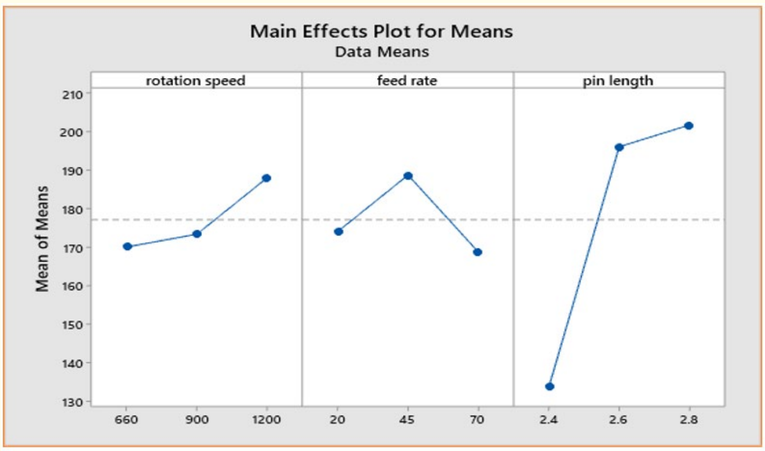

Figure 10: Effect of welding parameters on the ultimate tensile strength.

Tool pin length

The tool pin plays a crucial role in material movement and regulates the feed rate (welding speed) [40]. After the tensile test, it was observed that some samples (1,6,8) experienced a fracture in the SZ or the line between the two alloys, especially those welded with a 2.4 mm long tool pin, as shown in figure 9. This occurred because the materials at the weld root did not reach a sufficient temperature to soften and mix properly, resulting in inadequate penetration and full weld to the weld root [41]. Friction stir welding is a thermo-mechanical process, involving simultaneous mechanical mixing and thermal cycles [42, 43]. When the pin length is insufficient, the material at the weld root may be exposed to temperatures without proper mechanical mixing, leading to local thermal hysteresis and coarse sediment distribution, prone to melting and sedimentation again [29]. Incomplete penetration of the pin into the base metal may result in a kissing defect, occurring when a portion below the SZ is not welded [44], and causing inadequate cracking of oxide layers within the material boundaries [45]. This defect can be addressed by improving welding process parameters, particularly by increasing tool rotation speed, decreasing feed rate, and increasing tool pin length [46]. This was evident in the research results, where the ultimate tensile strength was achieved with a 2.8mm tool pin length, as shown in Fig. 11a indicating an increase in tensile strength with the length of the tool pin.

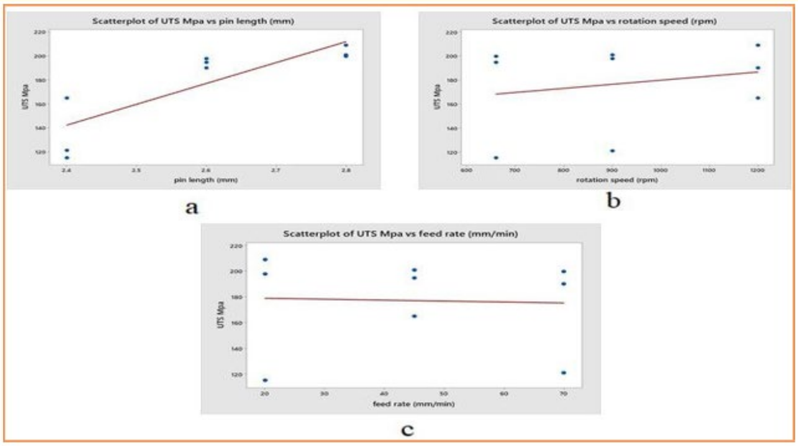

Figure 11: Effect of welding process parameters on ultimate tensile strength.

Tool rotation speed

The rotation speed of the tool is a crucial parameter in the friction welding process, playing a significant role in heat generation and material mixing [47,48]. It also affects the transfer of materials from the advancing side to the retreating side. Our experiments have shown that an increase in rotation speed results in higher tensile resistance, with the highest value of 209 Mpa achieved at 1200 rpm (as shown in Fig. 11b). Higher rotational speed leads to increased friction temperature, softening of materials, and more intense mixing and stirring of materials [49]. Conversely, a decrease in rotation speed results in a noticeable decrease in tensile strength, reaching the lowest value of 115 Mpa at 660 rpm. This decrease may be attributed to a defect in the stirring action, reducing the movement of plastic material and leading to a weak weld joint. Additionally, the decrease in rotational speed leads to a decrease in thermal input, resulting in incomplete plastic deformation of materials and affecting the grain structure and mechanical properties of the weld joint [50].

However, it is not possible to establish a fixed relationship between the tensile strength and the speed of rotation of the tool, as this relationship remains ambiguous. Many researchers have observed that the tensile force increases when rotation speed increases, but decreases with another increase in rotation speed, while others have noticed an opposite relationship [51-53]. Therefore, the relationship of the tool rotation speed with the mechanical properties (especially the tensile strength) remains unclear and largely depends on other parameters such as the feed rate, the shape of the tool pin, the material to be welded, and others.

Feed rate

Feed rate or the forward movement speed of the tool that transfers plastic materials located below the shoulder from the advanced side to the back side of the submerged pin affects the welding speed, mechanical properties, and microstructure of the resulting weld joint. The thermal insertion effectiveness of the materials to be linked is largely dependent on the feed rate. In our research, the highest feeding rate of 70 mm/min effectively reduces the extension of the heat to the welding zone [53]. A decrease in the thermal input leads to a weak flow of materials to the lower side [54]. The tool moves from one area to another without depositing the materials behind it sufficiently to fill the voids, which may result in defect tunneling [53, 55], and thus leads to poor mechanical properties of the weld joint, as shown in figure (11c). Increasing the feed rate will lead to an increase in torque in the tool's pin and thus increase the pressure on the tool pin, which may lead to a break [53]. From the results, the highest tension of 209 Mpa was obtained at a feeding rate of 20mm/min because at the lower welding speed, there is enough time for heating per unit length, and the heating reaches materials far from the welding line, which increases the width of the heated area around the tool and reduces the temperature gradient, resulting in a decrease in thermal mismatch when cooling [57]. This leads to a rise in temperatures and very good mixing of the deformed materials in the area (SZ), thus improving the grain structures in this area and increasing the tensile strength of the resulting welding joint [58, 59]. Through Fig. 11, we can see that the effect of the feed rate on the tensile strength is the least compared to the rotational speed and the length of the tool pin, which has the greatest effect on the tensile strength.

Micro hardness

Hardness is defined as a measure of a material's resistance to cracking and notching. It is one of the quantifiable mechanical properties of a material at the microscopic level [60]. The main factor that indicates the location of the fracture is the characteristics of the hardness in the different areas of the welding joints. This is the case for welding joints that are free of defects. In the case of defective welds, the strength is low at the defect site and the stresses are concentrated. These two factors are considered to determine the location of the fracture [61]. In the process of friction stir welding, the area (SZ) has a higher strength compared to the area (TMAZ, HAZ) because it has small grains. Therefore, fracture occurs in the less solid areas (TMAZ, HAZ), especially in the zone (HAZ), and this occurs when the (SZ) area is completely free of defects, or it contains small defects in the root of the area, but the strength of (SZ) overcomes the concentration of stresses in it [12]. This is what we have noticed in the broken samples shown in Fig. 9. A micro-hardness test was carried out for the resulting weld joints, and five points were examined for each weld joint (a point in each of the weld joint areas on both sides, the advanced and the retreating). The results were proven in Table 7.

No.	***Rotation-feed- pin length***	***Advanced side AA6061***		***Hardness***	***Retracted side AA7075***	
		HAZ	***TMAZ***	***SZ***	***TMAZ***	***HAZ***
1	660-20-2.4	52	65.2	96.2	82.5	62.6
2	660-45-2.6	71.5	82.5	89	89	82.5
3	660-70-2.8	55.2	82.5	100	96.6	89
4	900-20-2.6	62.6	89	96.2	89	71.5
5	900-45-2.8	55.2	69.2	104	104	100
6	900-70-2.4	55.2	55.2	89	62.5	62.5
7	1200-20-2.8	62.6	71.5	104	82.5	71.5
8	1200-45-2.4	62.6	82.5	96.2	96.2	71.5
9	1200-70-2.6	71.5	85.6	96.2	85.6	82.5

Table 7: Hardness values for the weld zones on advance and retraction sides.

In all cases, we notice that the hardness decreases as we move away from the welding center as shown in the Fig. 12.

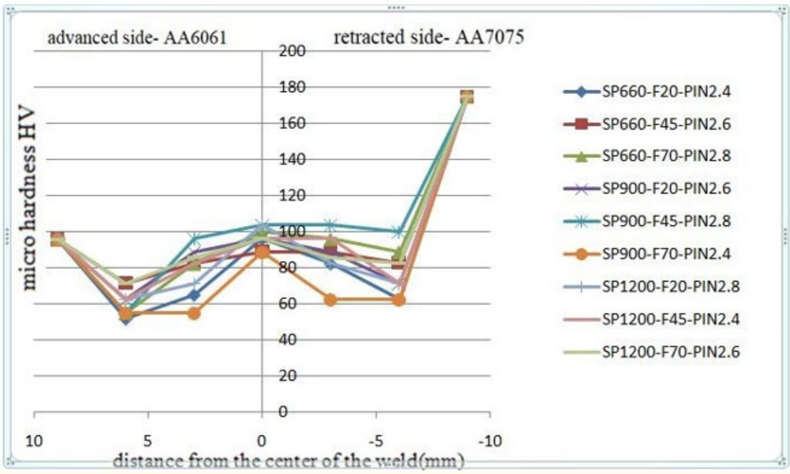

Figure 12: Micro hardness value at different location in transverse direction.

In Table 4, we observe a clear decrease in micro hardness values in the Heat Affected Zone (HAZ) compared to the base metals. This is mainly due to melting, flaking, and rearranging of the strengthening deposits caused by the thermal cycles of the Friction Stir Welding (FSW) [62]. As we approach the Stir Zone (SZ), we notice that the difference is less because the material in this area suffers from the highest temperatures and largest stress rates, resulting in continuous dynamic re- crystallization and dissolution of the reinforcing deposits. This, in turn, leads to the dynamic re- crystallization of the large granules present in the base metal in the SZ area due to high temperatures and high plastic deformations [63]. The results also show that there is almost a significant difference between the hardness of the TMAZ, HAZ, and SZ zones. The hardness in the TMAZ zone decreases despite being subjected to plastic deformation, but it does not recrystallize due to insufficient deformation stress. However, in this region, the process leads to the dissolution of some sediments and the increase in aging and roughness as a result of exposure to high temperatures in the FSW process [64, 65]. Therefore, the hardness in the TMAZ area is less compared to the SZ area. As for the HAZ region, it is subjected to a thermal cycle without exposure to any plastic deformation, leading to excessive aging and roughness of the reinforcement deposits, which, in turn, causes the disappearance of Guinier-Preston (G.P.) regions and a decrease in hardness in this region [29]. We note that most of the welding joints failed in the HAZ region close to TMAZ on the side of the weakest alloy (AA6061). Where the highest hardness was achieved, which was (104) when the tool length was (2.8 mm). This is because an increase in the length of the pin leads to a larger area of friction, which in turn raises the temperature of the welding area. Additionally, the increase in the length of the tool enhances the stirring of the deformed plastic materials and effectively mixes them, transferring them from the front of the tool to the back side. It also delivers the welding process effect to the root of the welding line.

This is related to the design of the tool (the length of the pin). Regarding the parameters of the welding process, represented by the speed of the tool rotation and the feed rate, we can observe their effect on the hardness of the welding joint through Fig. 13. It is noted that the highest hardness value was obtained at the higher rotation speeds (1200, 900 rpm) and the lower feed rate (20, 45 mm/min), respectively. This is because the higher rotation speed and the lower feed rate lead to the materials in zone (SZ) suffering from the highest temperatures and the largest stress rates, which increases the hardness in the area (SZ) [66]. This effect can be more clearly observed in Fig.14.

Figure 13: Effect of welding parameters on the micro hardness.

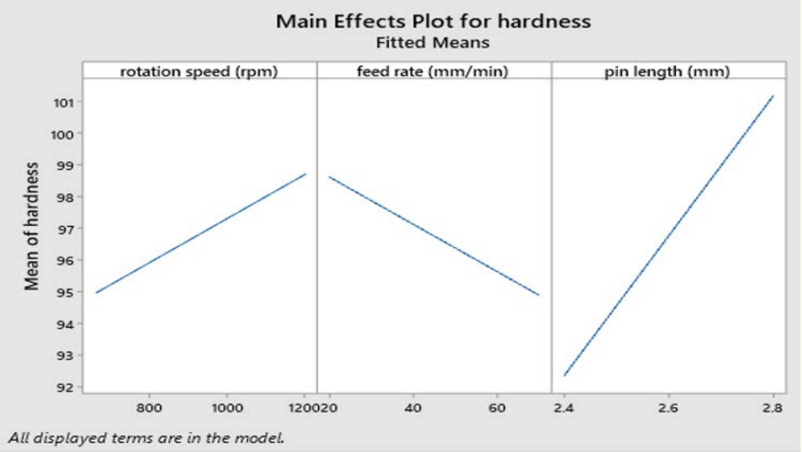

Figure 14: Relationship of welding parameters with the micro-hardness HV.

Conclusions

During this research, welding joints of two aluminum alloys (AA7075, AA6061) were fabricated using a pin tool of varying lengths to investigate its impact on the mechanical properties of the welding joints, while keeping the parameters of the friction stir welding process (feed rate and rotational speed) constant. Laboratory tests of the weld joints led to the following conclusions:

1. The weld joint produced with a pin length of 2.8mm, feed rate of 20mm/min, and rotation speed of 1200rpm achieved an ultimate tensile strength value of 209 Mpa.
2. The highest micro hardness value of 104 HV was obtained from two experiments: the first with a pin length of 2.8 mm, feed rate of 45mm/min, and rotation speed of 900 rpm, and the second with a pin length of 2.8 mm, feed rate of 20 mm/min, and rotation

speed of 1200 rpm. The second experiment was deemed the best due to its higher micro hardness and ultimate tensile strength, despite a longer execution time.

3. The mechanical properties of the weld joint (tensile strength and hardness) improved with an increase in the tool pin length, with the highest tensile strength and hardness achieved at a pin length of 2.8 mm.
4. The experiment with the lowest tensile strength (115 Mpa) was conducted with a pin length of 2.4 mm, feed rate of 20 mm/min, and rotational speed of 660rpm. The experiment with the lowest hardness (82.5 HV) was carried out with a pin length of 2.4mm, feed rate of 70 mm/min, and rotation speed of 900 rpm. It can be concluded that a decrease in pin length resulted in a decrease in the mechanical properties of the weld joint in terms of tensile strength and hardness.
5. We observed that the weld joints produced with a 2.4 mm pin length failed in the (SZ) region during the tensile test. This indicates a lack of fusion between the two alloys at the root of the weld, proving that reducing the length of the tool pin will result in the welding process not reaching the root of the weld.
6. The fracture occurred in the welded samples along a 2.6 mm to 2.8 mm pin during the tensile test in the (HAZ) area of the AA6061 alloy. This suggests that the welding joints were good, as the fracture occurred in the weakest zone.
7. Based on the values of the welding parameters, we conclude that the same values cannot be used for welding other materials due to the joint effect of the welding parameters. Our research showed that the highest and lowest tensile strength were obtained at the same feed rate (20 mm/min), and the highest and lowest hardness were obtained at the same rotational speed (900 rpm). This indicates that the mechanical properties of the weld joint result from the joint interaction of the welding parameters.

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