JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES
ISSN: 2289-4659 e-ISSN: 2231-8380
VOLUME 17, ISSUE 3, 2023, 9576 – 9585
DOI: https://doi.org/10.15282/jmes.17.3.2023.4.0758

RESEARCH ARTICLE

Influence of tool pin profile on the mechanical strength and surface roughness of AA6061-T6 overlap joint friction stir welding

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ABSTRACT - This study presents the tensile strength and surface roughness resulting from friction stir welding (FSW) on the lap joint method using AA 6061 –T6. FSW is conducted by comparing three different tool pin shapes: hexagon, thread, and square. Overlap welding using the FSW method is challenging if machine parameters, such as spindle speed and feed rate, are incompatible. The experiment was conducted using a conventional milling machine with a spindle speed of 1400 -1750 rpm and a feed rate of 20 – 30 mm/min. The results show that a spindle speed of 1750 rpm and a feed rate of 30 mm/min using a square tool pin results in 83.5088 MPa ultimate tensile strength and 0.85 µm surface roughness (R_a), which is much better than hexagon and thread type tool pins. In addition, the overall results on all three tool pin shapes show that higher processing parameters increase tensile strength and surface roughness. This study revealed the effect of parameters on AA6061 –T6 and the resulting implications of mechanical strength and surface roughness.

ARTICLE HISTORY

Received : 02nd Mar. 2023
Revised : 24th Aug. 2023
Accepted : 28th Aug. 2023
Published : 28th Sept. 2023

KEYWORDS

Friction stir welding
AA6061-T6
Spindle speed
Feed rate
Tensile strength
Surface roughness
Surface appearances

1.0 INTRODUCTION

Friction stir welding (FSW) is a solid-state welding with the potential for various applications. This process was invented to weld aluminium alloy-type materials [1,2]. In addition to aluminium alloy, Friction Stir Welding (FSW) can also weld various types of metals and other materials. FSW is a solid-state welding process that involves friction and pressure. This process heats the material without reaching its melting point, so it does not fully melt like in conventional welding. Instead, it involves the high-speed rotation of a stirring tool that stirs the material to create a strong joint. This is due to its benefits compared with other materials such as copper, magnesium, nickel alloy, and composite [3,4]. FSW has recently been used for additive manufacturing (AM) applications. During AM using FSW, a downward spinning tool head creates pressure, which welds materials in each layer. However, the first layer is the most crucial as it is the basis for the 3D structure formation and is the focus of this study. In the conventional welding process, high temperature is significantly developed, which causes changes in the metallurgical characteristics and affects the welded joints' strength. On the contrary, FSW showed significantly minimum deformation driven by mechanical and thermal stresses because the base metal's melting point is higher than the welding temperature [5,6]. Due to FSW's apparent low processing temperature, several welding imperfections such as deformation, solidification cracking, blowholes, spatters, and porosity can be reduced as an advantage to increase weld quality and joint quality [7,8]. In other words, the FSW process is an efficient method of welding for combining a wide range of metals and alloys that are similar and dissimilar in diverse fields of application [9,10]. The FSW process can also join aluminium composites, magnesium, fibre-reinforced polymers, and steels [11] .

In the FSW approach, an inconsumable rotary tool connects the component to be joined. In contrast, the tool geometry profile acts as a penetrating and mixing effect within connecting regions. Hence, the downforce is transmitted to the tool into the joint line, resulting in heat generation when frictional heating is adequate to elevate the temperature of the workpieces. It can plastically deform and locally plasticise. Then, the tool provided the transverse feed for forwarding movement [12-14]. Nevertheless, due to the producing defect-free welds and increased strength of the weldment, the tool pin profile (TPP) elements showed a significant effect in thermal developed input throughout the FSW parameter, as well as the tool transverse speed (TTS), rotational tool speed (TRS) and axial force [14,15] . Therefore, it significantly impacts the coarsening and dissolving of the precipitated phase. It reveals that the variables are a crucial factor in determining the properties of FSW joining[16] .

Previous studies have concentrated on exploring the influence of the FSW tool geometry profile and its variables in evaluating their influence on the morphology, yield strength, surface appearances, and joining quality of aluminium alloys. At the initial stage, the FSW process uses tool pins with features such as flat tool shoulders and cylindrical pins [17,18]. Rao et al. [19] found friction stir welding in ISO: 65032 aluminium alloy to investigate its influence on tool spindle speed and joining speed. Kundu and Sigh [20] have investigated the effect of spindle speed and feed rate of the

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FSW process on the microstructure of AA 5083 and its effect on the mechanical properties of the join. Venkata et al.[21] have used two types of tool pins, namely cone and triangle pins, by conducting FSW against AA2019 aerospace and defense aluminium alloy. His study found that grafts using triangular pins can increase mechanical strength compared to conical pins. Tool geometry shapes on welded joint yield strength and efficiency identified that tool geometry design significantly affected the yield strength properties of joints. In contrast, tapered cylindrical tool pin profiles performed the joints without the presence of weld tunnel and void defect. Das et al. [22] assessed the parameters, including tooling geometry characteristics, of mechanical and morphology property joints of FSW AA2014. The researchers discovered that the excellent mechanical morphology of the square tool pin (STP) was an effect of the distinctive stirring phenomenon induced due to the pulsating motion from the sharp edges of the pin's tool geometry and material propagation phase within at stirred region upon deployment of the tool rotation and welding speed during FSW process.

Kumar et al. [23] found that the threading tool design provides the highest yield strength and elasticity compared to the flat cylindrical tool geometry. Furthermore, the threading tool pins had higher welded efficiency than cylindrical tool pins. The finding also found that the threaded tool geometry joints are more ductile than cylindrical tool profile joints. Besides that, Ugender [24] analysed the influences of FSW tool geometry with rotating speed along the joining region using AZ31 magnesium alloy. The study evaluates the impact of process variable mechanical properties. The author discovered that tool geometry profiles and their rotating speed and joining speed combinations are the most critical elements influencing mechanical properties. In contrast, Palani et al. [25] found that the most crucial role in generating high weld tensile strength and more complex joints is a hexagonal pin profile on AA8011 and AA6061-T6 FSW. It depends on welding speed, rotational speed, plunge depth, and other pin profiles. Waheed et al. [26] investigate the impact of tool pin profile and process variables on peak temperature in friction stir welding analytically. The results revealed that the amount of thermal energy generated, and the peak temperature are directly associated with the number of edges in the pin profiles, with the heat generated and peak temperature increasing from the triangular pin profile to the hexagonal pin profile. Furthermore, the author concludes that the heat production and peak temperature rate in the flat shoulder are higher than in the tapered/conical shoulder. Mohanty et al. [27] studied the effect of three different tool geometries with different shoulder and pin profile types. The study found a significant effect of the tool geometry on weld reinforcement, microstructure, and weld strength.

Based on literature, tool pin geometry significantly influences the strength of the weldments. Other than that, the effect of material flow is crucial since the poor selection of process parameters, such as feed rate and spindle speed, causes insufficient stirring during the joining process. Hence, a suitable combination of process parameters and tool pin profile can reduce the risk of defect creation. Numerous researchers have attempted to join aluminium alloys using FSW. However, only a limited study article on the FSW tool pin profile in the lap joint of AA6061 –T6 aluminium alloys can be discovered. Therefore, this study uses the FSW approach to determine the correlation between tool pin profile and process parameter by analysing the tensile test, surface roughness, and surface morphological defect of lap joints AA 6061-T6 aluminium alloy.

2.0 METHODS AND MATERIALS

The selected base material of FSW is AA6061–T6 aluminium alloy plate, known for its medium to high strength with good toughness, strength, lightweight and virtuous weldability. Besides, this material is excellent in corrosion resistance in atmospheric conditions, with most applications in the aerospace and automotive industries—the nominal chemical composition of AA6061-T6 aluminium alloy, as shown in Table 1. Primary sheet materials were cut and machined to 120 mm x 50 mm x 4 mm using a conventional milling machine. The deburring process was performed to remove all sharp edges using a flat file.

Table 1. The chemical composition (wt.%) of the AA6061 – T6

Chemical Composition									
Element	Mn	Si	Fe	Zn	Ti	Cr	Mg	Cu	Al
Wt. %	0.03	0.61	0.2	0.02	0.01	0.13	0.81	0.29	Bal.

2.1 Tool Fabrication

The essential aspects of consideration during successive FSW processes are tool size, material, and geometry. Other than that, the tool material itself should be harder, and the higher melting point of the material must be stirred. Hence, this work selected the tool material from high carbon, high chromium D2 steel due to its excellent wear resistance and deep hardening characteristics. The raw material is ready-made in a cylinder bar shape of Ø25mm diameter. The machine of the tool process consists of a tool pin, tool pin height, and tool shank made using the CNC HAAS brand. Both tool specifications of square and hexagon were tool pin profile = 9 mm, tool pin height = 3.8 mm, tool shank diameter = 25 mm, and total tool height = 49 mm. In contrast, the tool pin profile has tapper 3º for thread, as shown in Figure 1, used in this study. A tool pin selection with a square or hexagonal profile that offers a higher pulsating effect and a lower dynamic-to-static volume ratio contributed to less defect formation.

(a) (b) (c)

Figure 1. FSW tool used in the present study: (a) square tool pin profile, (b) thread and (c) hexagonal

2.2 Experimental Setup

The conventional milling machine of the FULLMARK FVH 260S brand was used for the overlapped joint FSW process, as shown in Figure 2. The specimens were fixed on a custom fixture to prevent any vibration from occurring due to friction force during the joining process, especially using an overlap joint method in FSW. An overlapped FSW joint is a type of welding joint created using the friction stir welding process, where two pieces of material are joined together by overlapping them and using a specialized tool to create a robust and solid bond between them [28]. The fixture was clamped rigidly on a milling machine table with a machine vice, as shown in Figure 3. The constant plunge depth tool pin z –3.8 mm, 0^{o} tool tilt angle, and 25 mm diameter flat tool shoulder.

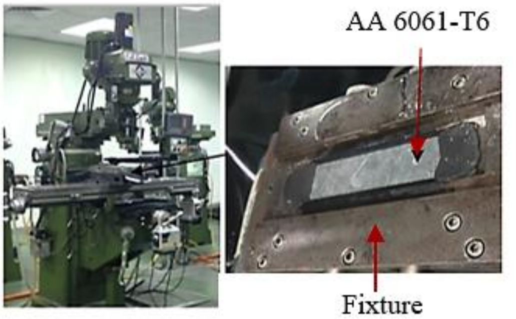

Figure 2. Conventional milling machine

Figure 3. Fixture clamp during joining FSW

During the experiment, a single-pass stir was carried out with the milling machine's spindle rotated in the clockwise direction based on the setting of the acquired variable. The 10 s of dwell time was applied after the tool plunged to AA6061-T6 to ensure sufficient heat was generated before the tool moved forward along 100 mm. The tool travels along the welding path at a constant plunge depth during the welding phase. Lastly, the specimens cooled naturally by atmospheric air. Table 2 shows the values of the FSW parameter.

Table 2. FSW process parameter

Spindle speed (rpm)	Feed rate (mm/min)	Dwell time (sec)	Tool 1	Tool 2	Tool 3
1400	20				
1575	25	10	Square	Thread	Hexagon
1750	30				

To fabricate the dog bone specimen, the joint AA 6061-T6 was sliced in the direction that was perpendicular to the weld seam using electrical discharge machining (EDM) wire cut brand Sodick VZ300L. Three transverse tensile test specimens were extracted from each joined plate according to the ASTM-E8M standard, as shown in Figure 4. Then, the welded sample of AA6061-T6 was tested for ultimate tensile strength (UTS) using SHIMADZU AG-100kN PLUS. The position of the welded samples was set perpendicular to the welding direction, and the weld seam was located at the centre of the dog bone specimen. In addition, surface roughness values, R_a were analysed using the Mitutoyo surface roughness tester (Surftest SJ-410). Surface roughness, R_a was measured with a stylus as the roughness test medium along 100 mm of the welded-length valleys. The R_a test was performed three times for one parameter and averaged to obtain accurate data.

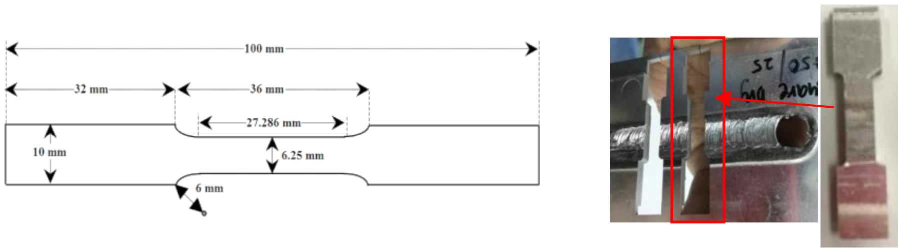

Figure 4. ASTM-E8M standard for tensile test

3.0 RESULTS AND DISCUSSION

Table 3 shows the results of the tensile strength and surface roughness. The results show the effect of various tool pin profiles used, and each of them affects tensile strength and surface roughness. The shape of the pin profile plays an important role and is one of the parameters process in FSW that can influence the material flow and joint efficiency [29].

Table 3. The data result of the tensile strength and surface roughness

No	Specimen	Tool Pin Profile	Spindle Speed (rpm)	Feed Rate (mm/min)	Average Tensile Strength (MPa)	Surface roughness (Ra)
1	1 2	Hexagon	1400	20	56.86	2.85
2	1 2	Hexagon	1575	25	66.18	1.47
3	1 2	Hexagon	1750	30	66.53	1.46
4	1 2	Thread	1400	20	46.12	2.69
5	1 2	Thread	1575	25	57.03	1.64
6	1 2	Thread	1750	30	60.18	2.14
7	1 2	Square	1400	20	70.05	1.25
8	1 2	Square	1575	25	80.58	0.93
9	1 2	Square	1750	30	83.51	0.85

3.1 Tensile Strength

Figure 5 shows the comparative effect between square, thread, and hexagonal tool pin profiles on the overlapped welded joint area produced at different spindle speeds and feed rates. Tensile strength is an essential properties of a material to resist tearing due to tension and determines its mechanical performance. Optimising the tensile properties also leads to excellence in the plastic effect flow process around the tool pins. The graph of spindle speed 1400 rpm, feed rate 20mm/min, and square tool pin profile show a recorded tensile strength of 70.05 MPa compared to thread and hexagonal pin profiles, which only recorded 46.12 MPa and 56.86 MPa, respectively. These low process parameters have low tensile strength. They are unsuitable for overlap join because the low spindle speed and feed rate have contributed to the lower heat input recorded as the main factor in this result. Heat input is a critical factor in FSW because it affects the temperature of the material during welding. Low spindle speed and feed rate lead to insufficient heat input, affecting the material's softening and flow behavior [30]. This is especially crucial in overlapped joints where proper softening and mixing of the materials are required for a strong bond. In addition, poor material flow during the stirring process is caused by the shape and size of the tool shoulder, which can influence material flow. An improperly designed tool shoulder might not exert sufficient pressure to facilitate material deformation and mixing [31]. A mismatch between the shoulder diameter and the weld joint can hinder material flow. Besides that, the tool's adequate axial force (downward pressure) is necessary to ensure proper material deformation and flow. Material flow might be compromised if the axial force is too low [32] . When the spindle speed and feed rate increased from 1400 to 1750 rpm, and the feed rate was used from 20 to 30 mm/min, the tensile strength increased significantly for all tool pin profiles. The graph shows that tensile strength tremendously increases through the difference of feed rates 20 and 30 mm/min on the square tool pin profile, which recorded up to 16.12 % of tensile strength from 1400 to 1750 rpm. It was expected because higher spindle speed and feed rate can cause sufficient heat input during stirring. This increase in tensile strength pattern also applies to threaded and hexagonal tool pins, showing a significant increase. Therefore, increasing spindle speed and appropriate feed rate will increase strength significantly [33]. This study revealed that when spindle speed and feed rate increase simultaneously, agitation offers less frontal resistance due to uniform heat distribution during processing. The increase in spindle speed and feed rate will directly increase the heat generation, thus causing smooth material flow [34-35]. Due to this process, the softening material under the tool shoulder caused by the frictional heat after plunging increases the plasticisation of the material, thus helping the material to mix and stir during the joining process. A low feed rate can cause the production of groove defects to a very low level [36]. Furthermore, the feed rate is one factor that affects the workpiece's tensile strength in friction stir welding [37].

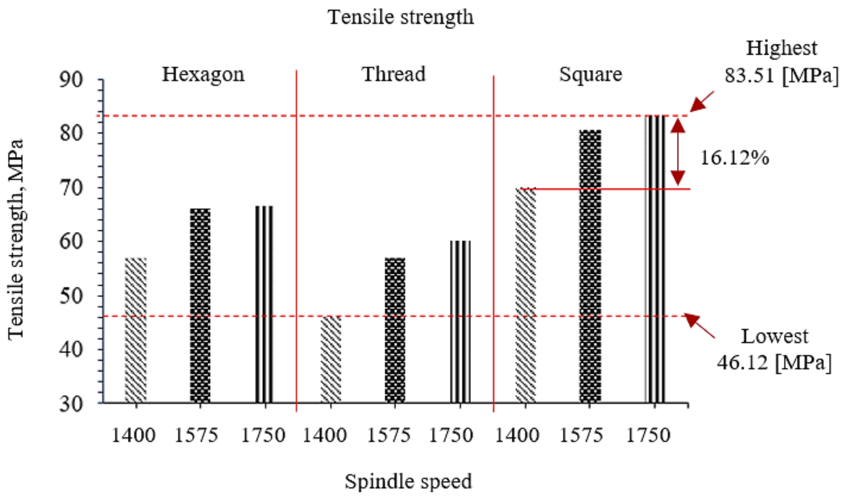

Figure 5. Spindle speed versus average of tensile strength

Based on this study, the suitable processing parameter for three types of pin profiles is a spindle speed of 1750 rpm at a feed rate of 30 mm/min. Nevertheless, square tool pin profiles show higher tensile strength than threaded and hexagonal ones. The square pin profile generates more effective material mixing due to its broader contact area with the workpiece. This enhanced mixing promotes a more uniform distribution of material properties, resulting in a stronger weld joint. The square pin's continuous contact with the material also leads to more significant plastic deformation within the weld zone. This deformation aids in breaking down material barriers and homogenising microstructures, contributing to higher tensile strength. A greater contact area indirectly promotes improved metallurgical bonding between adjacent material layers. This intimate bonding reduces the likelihood of interface weaknesses, bolstering the weld's overall strength. These results indicate that the tool with a higher shoulder angle minimizes the heat passing through the connector area, thereby reducing the effect of heat supply, as shown in Figure 6. It revealed that pulsating stirring produced a higher sweep volume, thus increasing the material flow due to the lower shoulder angle, as shown in the illustration in Figure 6. Furthermore, the increased swept volume resulting from the pulsating motion of the threaded tool pin profile and hexagonal pins, in comparison to square tool pins, suggests that the material undergoes more significant strain during usage. Higher tension can improve the mechanical properties in the thermomechanically affected zone [25]. The heat input from the higher strain of the pulsating action element contributes to more significant deformation and plastic material flowing around the tool pin profile. It is supported by Ashu et al. [38] that the stirring and mixing motion due to the pulsating action by the round tool shoulder of the square tool pin profile sweeps the high-viscosity material from the plasticised zone. In conclusion, the square tool pin profile is suitable for obtaining high tensile strength through higher spindle speed and feed rate.

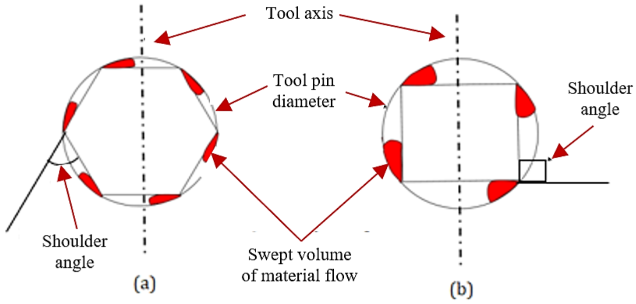

Figure 6. Comparison illustration of material flow by shoulder angle: (a) hexagonal tool pin profile and (b) square tool pin profile based on clockwise rotation

3.2 Surface Appearance

Figure 7 shows the surface appearances and defects when processing parameter 6061 –T6 aluminium Alloy at 1750 rpm, 30mm/min feed rate. FSW generally produces a smooth surface finish along the weld line. This is due to the process's solid-state nature, which avoids forming a molten weld pool that can result in surface irregularities, as shown in Figure 7. The tool pin is in asymmetrical geometries that lead to material flow [39]. There is an effect from the simultaneous motion of material flow and an effect from the geometrical asymmetry of the tool pin rotation and tool shoulder, respectively. Observing proper material flow formation during FSW is a meaningful indicator that the processing parameters are appropriate, leading to smooth and efficient material flow within the weld. Material flow is a critical aspect of FSW as it directly influences the quality and integrity of the resulting weld joint. Proper material flow formation indicates that the heat input from the FSW tool is sufficient. Adequate heat input ensures that the material becomes sufficiently softened, allowing for plastic deformation and proper mixing of the material between the plates being joined [40].

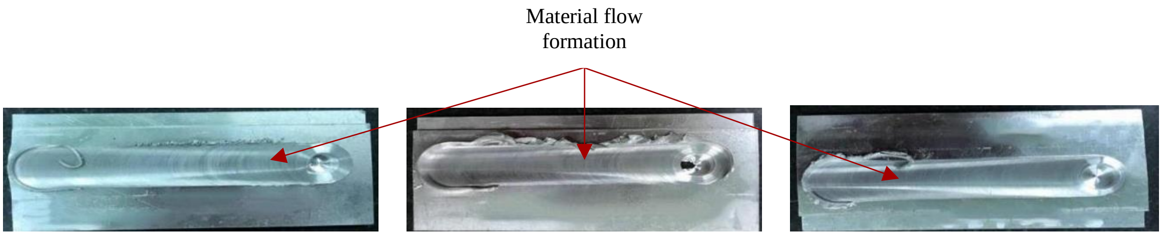

Figure 7. Surface appearances and defects when process parameter at 1750 rpm, 30mm/min feed rate: (a) squared tool pin profile, (b) thread tool pin and (c) hexagonal tool pin profile

However, this study found tunnel defect formation inside the cavity close when cut in the middle of the thread tool pin specimen, as shown in Figure 8, by using 1400 rpm and 20 mm/min. Tunneling refers to a specific defect where a void or cavity is formed below the weld surface. The shape and geometry of the FSW tool, especially the pin profile, can affect the material flow and cause tunneling. In this study, threading tool pins produce uneven material movement and lead to tunnel defects. The tunnel defect is due to the low spindle speed effect, which produces insufficient heat generation that restricts material flow, which allows improper plasticisation mixing of the material due to unsuitable feed rate and improper tool pin profile [41]. Feed rate is one of the main factors to ensure the material has enough heating input generated from the friction motion due to softening the material under and surrounding the tool pin profile. Hence, a combination of a slower feed rate at constant spindle speed will increase frictional heating input during the joining process. In other words, the lower feed rate during the joining process is better to ensure sufficient heat generated than the fast feed rates [42] . It is supported by Kah et al. [43] that the reduced feed rate speed will improve material flow ability. Optimising the machining parameters is essential to eliminate tunneling defects due to heat losses during the joining of the overlap process.

Figure 8. Tunnel defect in the middle of the overlapped welded piece

In addition, the other cause of the tunneling defect comes from an improper tool pin profile [44] . This may be due to the lower pulsating stirring action from the hexagonal tool pin profile than the square tool pin, as depicted in Figure 7. It is found that the lower stirring due to less shear stress around the hexagonal tool pin profile is the main reason for lower plastic deformation. The study by Hussain et al. [45] indicates that lower stirring action in FSW leads to decreased frictional heat generation and inadequate material mixing. Consequently, a higher stirring action facilitated by a flat-surfaced tool pin profile is crucial. This enhanced stirring improves material flow, ensuring even distribution across the joint area. The continuous supply of deposited and intermixed material results in successful material flow, as demonstrated in the absence of tunneling defects when using the square tool pin profile (see Figure 8(a)). Terra et al. [46] also corroborate that using a square tool pin profile prevents defects due to its polygonal shape. The flat face of the square profile contributes to this phenomenon [47]. Adopting the square tool pin profile enhances stirring action, material mixing, and consistent material flow, thereby reducing defects and promoting successful FSW outcomes.

3.3 Surface Roughness

The surface roughness value is considered one of the most critical parameters because of the reliability of the surface of the part being joined before evaluating the profile of the joint in more detail. From another perspective, surface roughness is significant because most graft failures start at the surface, either due to surface quality degradation or discontinuity [48-50]. Therefore, the minimum surface roughness is one of the essential criteria to improve and extend the service life of the overlapped join for AA6061–T6. The main roughness parameter used in this study is the arithmetic mean roughness height, R_a which describes the contour height characteristics of the texture. Figure 9 shows that the most consistent and significantly reduced Ra is from square and hexagonal tool pin profiles. The thread profile has a significant rate of fluctuation due to the tapered pin profile of this thread producing a slightly larger stir zone width at the root of the weld [50]. Therefore, the correct process parameters and selecting the appropriate tool pin profile are essential to ensure optimal surface roughness [51]. Furthermore, the fluctuating surface roughness, R_a observed because of the taper tool's tip can be attributed to the dynamic interaction of the heating zone area during the joining process. This phenomenon arises because the tool used has a tapered shape (thread tool pin) with a gradually changing geometry along its length [52]. This study refers to the end portion of this tapered tool that comes into contact with the workpiece during welding. During FSW, the heat generated by the rotating tool's friction and pressure softens the material in a localized region known as the heating or thermo-mechanical affected zone [53,54]. The statement suggests that the interaction between the heated zone and the tool's taper tip leads to changes in surface roughness. Besides, irregularities or texture on a material's surface. Fluctuating R_a indicates that the surface is not consistently smooth but experiences roughness variations.

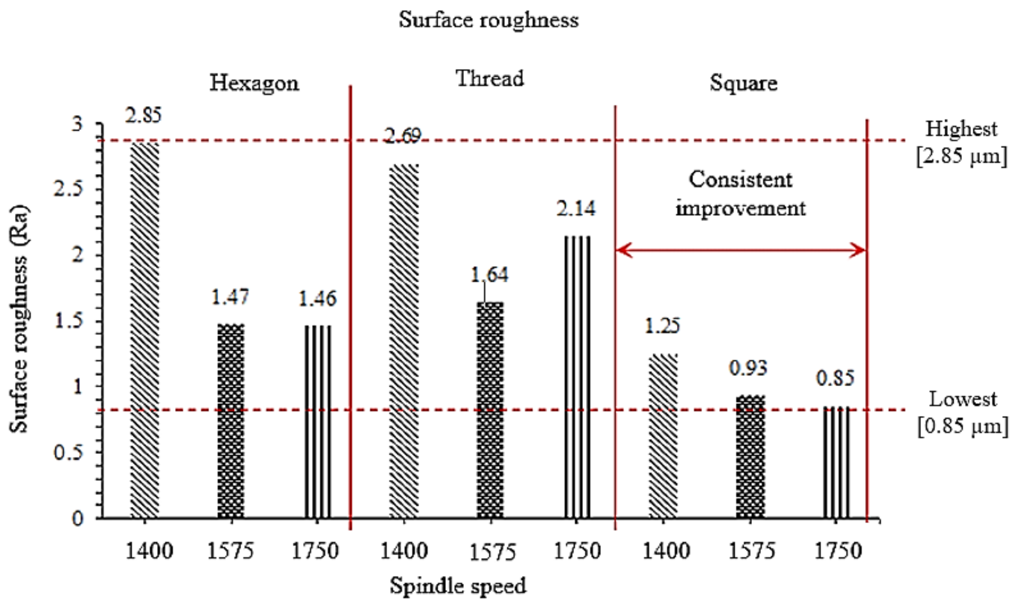

Figure 9. Spindle speed versus average of surface roughness

4.0 CONCLUSION

In the present work, AA6061 –T6 aluminium alloy was welded by FSW to investigate the effect of various variables and tool geometry profiles on the yield strength, surface appearances and surface roughness of the joining part. Derived on the result obtained in this investigation, conclusions that can be made are as follows:

1) The higher spindle speed of 1750 rpm and 30 mm/min feed rate on all three types of tool pins dominate the best results compared to other processing parameters.
2) The higher heat generated under the tool shoulder and joint area influences the tensile strength.

3) Insufficient heat generation leads to tunnel defects in the overlap joint.
4) The lower pulsating stirring action results in poor material homogeneity under the tool pin shoulder.
5) When a square tool pin is used, it is found that the surface roughness decreases as the revolutionary pitch decreases compared to other tool pin shapes.

5.0 ACKNOWLEDGEMENTS

The authors would like to thank grant Tier 1 Q169, Universiti Tun Hussien Onn Malaysia (UTHM), Industrial Machining Focus Group (IM Tech) and Faculty of Technical and Vocational Education (FPTV) for the research facilities provided during the project.

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