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Projection Friction Stir Spot Welding: A New Welding Technique for Creating Safe and Reliable Aluminum Welds

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Highlights

- A novel friction stir welding method called projection friction stir spot welding is introduced to produce safe and reliable welds.
- The projection geometry along with the tool rotation speed plays an important role in having a reliable joint with excellent mechanical properties and good surface appearance.
- This new welding technique can be a good alternative to conventional welding techniques that have major welding defects.
- This welding technique can be widely developed in oil and gas, automotive, aerospace, and transportation industry.

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Abstract

A novel friction stir welding method called projection friction stir spot welding (PFSSW) was introduced to produce safe and reliable welds by using a pinless tool and a specially-designed projection on the surface of a backing anvil. This projection along with the tool rotation speed plays an important role in having a reliable joint with excellent mechanical properties and good surface appearance. This welding technique can be widely developed in oil and gas, as well as in automotive, aerospace, and transportation, industry. The effect of tool rotation speed (1000, 1600, 2000 rpm) on the hardness, microstructure, and mechanical properties of 2024 aluminum alloy sheets was investigated. The surface appearance of the welding zone showed that the keyhole was not formed, and the appearance of the weld was almost smooth. Fracture surfaces of the failed specimens present the interfacial fracture at the tool rotation speed of 1000 rpm and circumferential fracture at tool rotation speed of 1600 and 2000 rpm.

Keywords: Friction Stir Spot Welding, Mechanical Properties, Microstructure, Oil and Gas Industry

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1. Introduction

One of the most important factors which all industries face is saving the energy without losing the quality of their products. On the other hand, using various techniques of welding and joining is an essential and inseparable part in different stages of manufacturing products (Mousavizade and Pouranvari, 2019). For this reason, as an easy and quick technique for welding, resistance spot welding is widely used in the transportation industry (Pouranvari and Marashi, 2013). Although the speed of welding, automation ability, and flexibility of resistance spot welding have made it popular in manufacturing industries (Mishra et al., 2014), this process has some weaknesses. Welding defects during solidification and melting processes, having difficulties in joining some light metals like aluminum, being an inappropriate method for joining steels owing to martensite creation, rather expensive equipment, tearing of copper electrodes, and high energy utilization are some of the disadvantages of this welding technique (Goodarzi et al., 2009; Pouranvari et al., 2010; Tavasolizadeh et al., 2011; Sun et al. 2013). Using light-weight alloys such as aluminum (Al) and/or magnesium (Mg) instead of steel has been noticed as a right policy to achieve this target. Thus, welding structures produced by lightweight metals is really important under this scenario (Zarghani et al., 2018). Using fusion welding of light metals faces some difficulties. Liquation and solidification cracking, distortion, and hydrogen porosity are some of these problems (Yamamoto et al., 2013). Between other common joining methods, friction stir welding (FSW) has a high quality in joint efficiency related to a fine recrystallized grain structure in the weld region (Badarinarayan et al., 2009). Lately, friction stir spot welding (FSSW) was proposed as a novel joining technique for developing the FSW process (Sun et al., 2013). Furthermore, application of FSSW in some different Al alloys such as 5083 (Badarinarayan et al. 2009), 2024-T3 (Paidar et al., 2015), 6111 (Bakavos and Prangnell, 2009), 6061-T6 (Venukumar et al., 2014), 5754/2024-T3 (Bozkurt et al., 2013), 2198 (Chu et al. 2016), and 6061 (Fujimoto et al., 2008) usually in sheets with a thickness between 1 and 2 mm has been studied. Hence, friction stir spot welding is evaluated as an energy-saving solid-state technique in the automotive industry (Mishra and Ma, 2005; Hovanski et al., 2007; Nadan et al., 2008).

FSSW which was suggested in 2000 based on linear friction stir welding is a comparatively new welding method (Kano, 2004; Gerlich et al., 2006; Yuan et al., 2011). Lately, several industries, especially the automobile industry, have expressed considerable concern about the application of this technique, and it has been accepted in transportation industries (Khan et al., 2007; Baek et al., 2010). However, although the FSSW is based on the FSW, they have main differences. In the FSSW technique, welding is done in a particular area by piercing and pulling out the special tool on the surface of the plates (Figure 1). The FSSW has some certain benefits. For example, it can be useful for welding high thermal conductive metals, and since it is known as a solid-state technique, it essentially hinders solidification defects. The maximum temperature in this technique is extremely lower compared to other fusion welding methods (Dourandish et al., 2018).

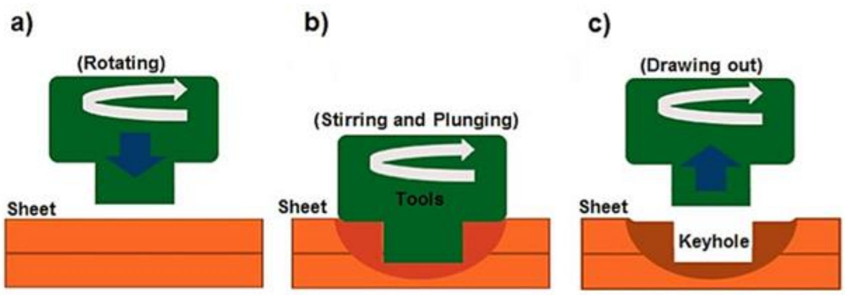

Figure 1

The illustration of different steps in conventional friction stir spot welding (CFSSW) (Shahrabadi et al., 2018).

Despite the plentiful significant advantages, the FSSW has disadvantages like higher process time than resistant welding and a remarkable indentation (keyhole) which remains at the middle of the weld nugget (see Figure 1), thereby generating stress concentration, increasing corrosion rate (remaining rainwater in the hole), and decreasing mechanical properties (Mishra et al., 2014; Shahrabadi et al., 2018).

Various methods have been developed to decrease/remove the keyhole in the FSSW technique, as follows:

1- Double-sided FSSW (Cox et al., 2014);
2- Refill friction stir spot welding (RFSSW) (Yang et al., 2014);
3- Pinless FSSW (Shahrabadi et al. 2018), which is just a simple tool with no probe, but with a scroll channel on the shoulder surface. This welding is a complex, costly, and time-consuming method.
4- Flat FSSW (Sun et al., 2013) which is a two-step technique;
5- In the walking process (Venukumar et al., 2014), pin tool motion in the length direction is carried out partially, while in the FSSW technique, the movement of pin tool is longer and the welds have a more joint surface;
6- FSSW technique with a tool designed as an assembly-embedded rod (AER) tool (Hieh et al., 2015).

The double-sided FSSW, RFSSW, flat FSSW, WFSSW, and FSSW using AER tool are time-consuming and expensive processes (Shahrabadi et al., 2018).

In this paper, a simple novel method which eliminates the keyhole in FSSW is proposed. This technique is a pinless process based on the utilization of a specially-designed protrusion on the surface of the backing anvil. This new technique is called projection friction stir spot welding (PFSSW) (see Figure2). This method possesses some key different specifications such as an increase in material flow, improved bonding length, and deletion of keyhole owing to the absence of a tool pin that contribute to the improved joint strength (Mousavizade and Pouranvari, 2019).

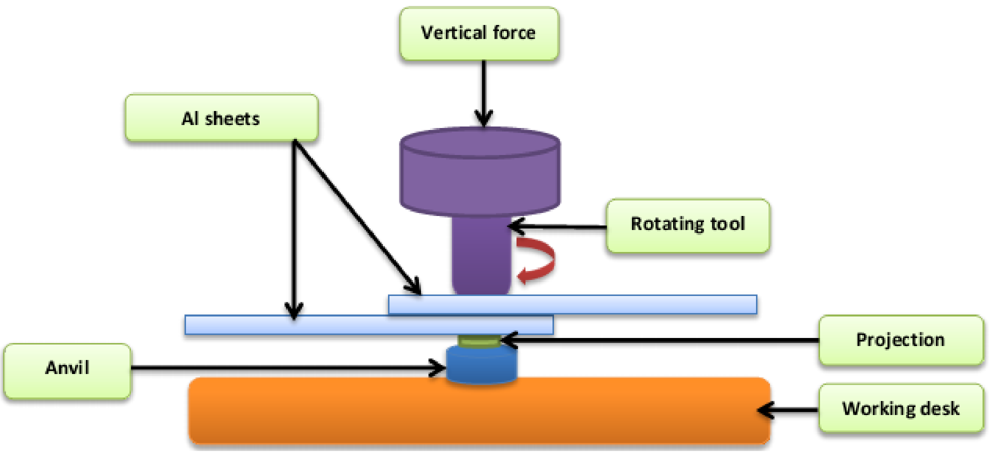

Figure 2

A schematic illustration of the novel projection friction stir spot welding (PFSSW).

In this new method of welding, the effect of tool rotational speed on microstructure, hardness, and mechanical properties of the PFSSW of aluminum alloy sheets grade 2024 is investigated to examine the logical relationship between these parameters.

2. Experimental procedure

2.1. Materials and methods

In this work, the novel PFSSW method shown in Figure 2 was used for the similar joining of 1 mm thick AA2024 aluminum sheets.

Table 1

Chemical composition and mechanical properties of 2024 aluminum alloy.

Chemical composition (wt %)					Mechanical properties		
Al	Cu	Mg	Mn	Fe	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
Remained	4.9	1.28	0.629	0.239	322	441	18

Table 1 tabulates the mechanical properties and chemical composition of the base metal. According to standard AWS D8.2M (AWS D8.2M 2017) for resistance spot welds, samples with the dimensions 105 mm × 45 mm were used for friction stir welding. According to this standard, these dimensions are suitable for tensile-shear sample tests when sheet thickness is equal to or lower than 1.29 mm. As displayed in Figure 3, for the dimensions of the tensile shear sample, the overlapped area was 45 mm × 30 mm (AWS D8.2M 2017).

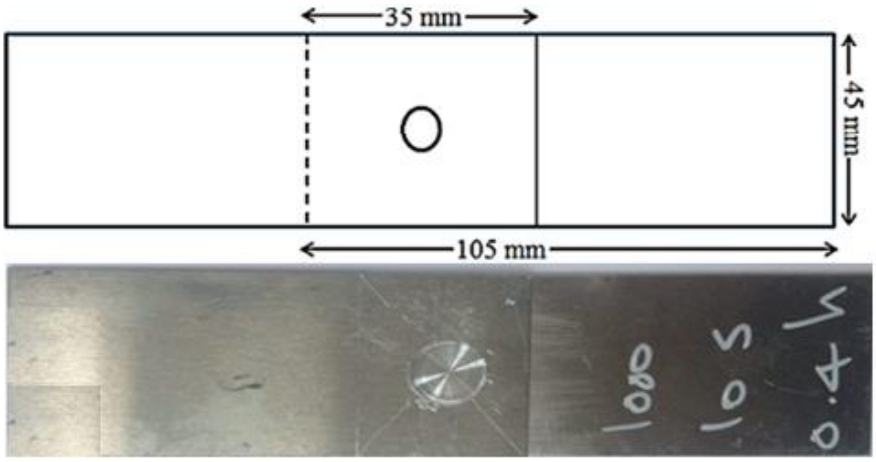

Figure 3

The dimensions of the tensile shear sample.

Before welding, all the aluminum sheets were cleaned with acetone to remove any surface contamination and ensure the consistent cleanness of the base metal. A pressed projection was created on the surface of the backing plate (anvil). The projection is a solid cylinder with a diameter of 10 mm and a height of 0.4 mm made of H13 hardened tool steel to resist high wear at elevated temperatures. A pinless tool made of an alloy based on tungsten carbide (WC) with a shoulder diameter of 16 mm and with zero inclination tool angle was used in all the experiments. This tool, which is named the rotating tool, is shown in Figure 2. Welding process was performed at a rotation speed of 1000, 1600, and 2000 rpm. The dwell and plunge depth were 10 s and 0.1 mm respectively. To control the plunge depth, the position of the tool with respect to the work-piece surface is held constant. To protect the rotating tool against oxidation, a protective atmosphere of Argon gas was flown around the FSW tool. Table 2 lists the welding parameters used for joining the investigated 2024 aluminum alloy.

Table 2

Welding parameters and conditions for the investigated 2024 aluminum alloy.

Welding parameters			Welding conditions (mm)		
Rotational speed (rpm)	Plunging depth (mm)	Dwell (s)	Projection diameter	Projection height	Shoulder diameter
1000, 1200, 1600	0.1	10	10	0.4	16

2.2. Hardness and microstructural examination

Like all FSW processes, the projection friction stir spot welding contains three different zones, namely the nugget zone (NZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ). As illustrated in Figure 4, the area after the HAZ is the base metal which is not affected by the welding heat. Microstructure examinations of welding cross-sections were performed by optical microscopy (Olympus GX51). The specimens were cut from the joint center and then polished and etched by a 2% nital solution. Vickers microhardness test was performed using Vickers microhardness tester (Qv-1000DM) under an indenter load of 0.5 kgf for a dwell of 10 s.

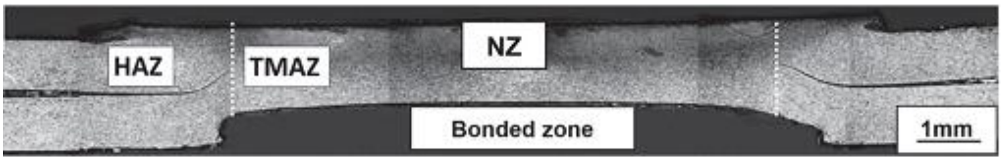

Figure 4

A schematic of the different zones in the PFSSW.

3. Results and discussion

3.1. Surface appearance of the weld

Considering the types of metal function in various industries, the surface quality of joints can be considered as one of the denoting factors of spot welds (Framanbar et al., 2019). Figure 5 displays the appearance of the welds produced by the PFSSW method. After welding, an excellent appearance is observed in the welded spots under all the welding conditions.

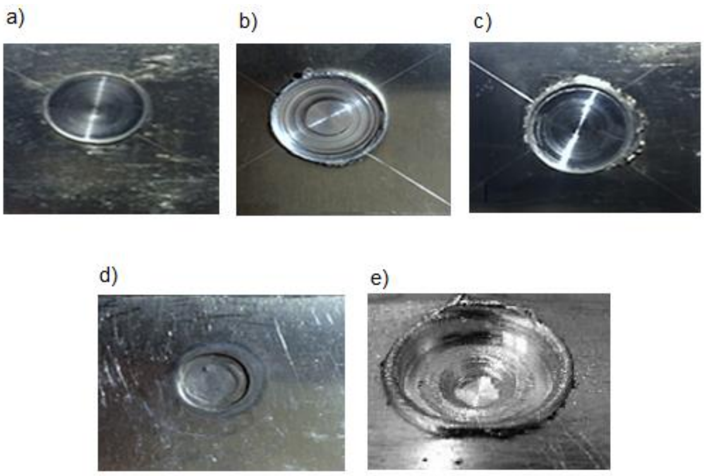

Figure 5

Surface appearance of the top and bottom view of the weld at a tool rotation speed of a) 1000 rpm, b) 1600 rpm, and c) 2000 rpm; d) bottom surface; e) the bottom surface reported by Paidar et al. (2014).

The PFSSW technique does not make large distortion in the upper and lower sheets. The top surface of the weld is quite smooth, and, on the back surface of the lower sheet, a dent is created owing to the anvil protrusion (on the backing sheet). Regardless of the various tool rotational speeds used, the appearances of the all the welds are similar. It is notable that in comparison with the usual FSSW (Figure 5(e)) (Paidar et al., 2014), no keyhole is created, and the appearance of the weld is smooth.

3.2. The effect of tool rotation speed on stir zone depth

The distance from the top surface of the joint to the end of the fine-grained region is supposed as the depth of the stirring zone (SZ depth). Since the stirring of the materials among the two sheets removes the interface and appearance of the joint, the SZ depth is a significant factor in specifying the strength of the welds (Framanbar et al., 2019). Figure 6 reveals that increasing the tool rotation speed raises the maximum temperature. An increase in the temperature causes more frictional heat which leads to an increase in the volume of the dough material produced by the process of recrystallization in the larger stir zone. In fact, it means that the increase in the heat input justifies raising the depth of the mixing zone by increasing the tool rotation speed. Accordingly, the material will be softer under the tool and smoothed by means of the tool. In other words, the softness of the material under the tool increases the capability to put strain on the material at a greater depth. As a result, the depth of the mixing zone increases by raising the tool rotation speed.

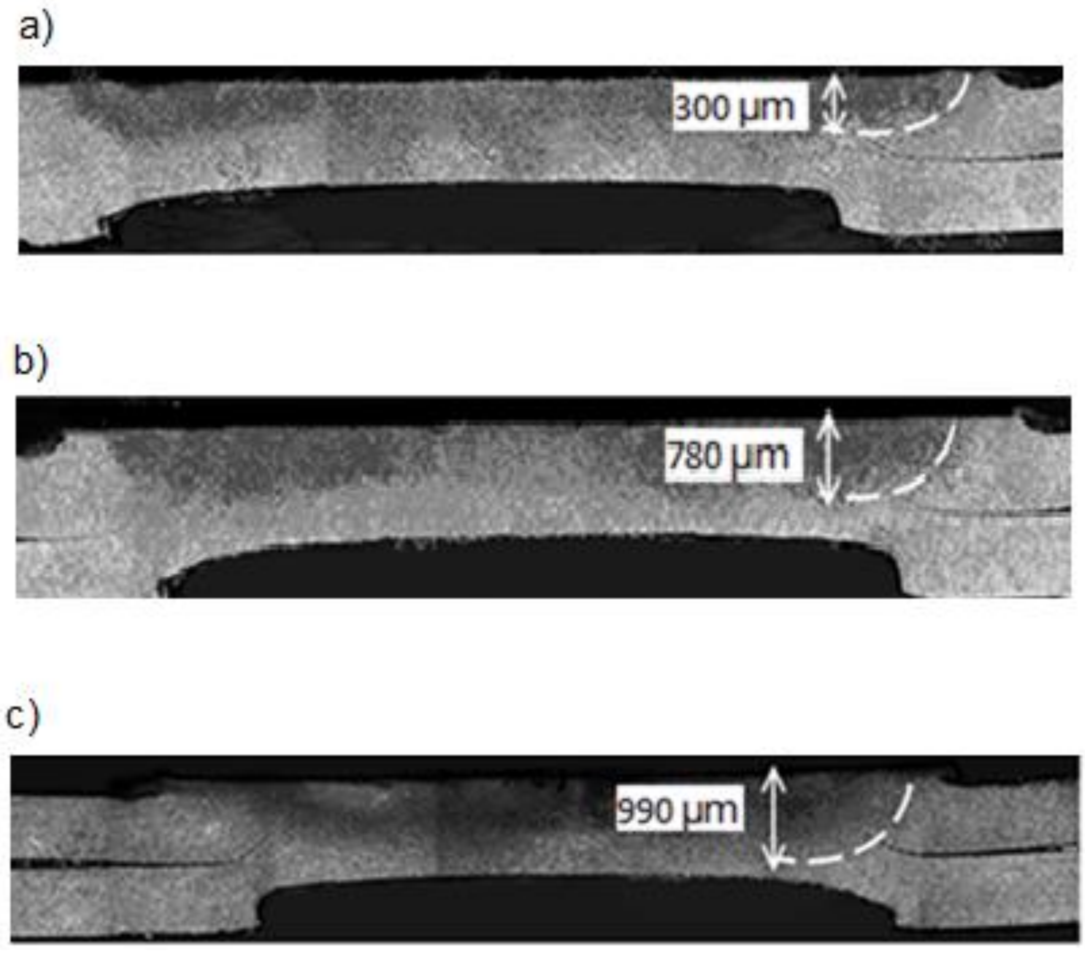

Figure 6

Macrostructure of the welding samples at a rotational speed of a) 1000 rpm, b) 1600 rpm, and c) 2000 rpm.

3.3. Microstructure and grain size

Two main metallurgical phenomena in the grain size of the stir zone in the friction stir spot welding are recrystallization and grain growth. Some factors affecting these two phenomena are the maximum temperature, the time remaining at a high temperature, strain, and strain rate. Increasing the strain and strain rate decreases the size of the crystallization grain, but increasing the temperature raises it. Also, by an increase in the temperature and in the time during which the welding is performed at this temperature, the size of the grain also increases because of crystallization and the growing process.

An indicating aluminum alloy property is its very high heat transfer capability, which makes it possible to quickly transfer heat from the stir zone to the base metal in the friction stir spot welding technique; also, there is little opportunity for the growth of the grains in this process. The microstructure of the stir zone at different rotational speeds is illustrated in Figure 7. Increasing the tool rotational speed raises the strain and strain rate, which reduces the recrystallizing grain size. On the other side, raising the tool rotation speed causes a rise in the heat produced by the friction and thus increases the temperature of the stirring zone, which enlarges the crystallized grain size. At a projection height of 0.4 mm, the grain size is dropped at higher tool rotational speeds.

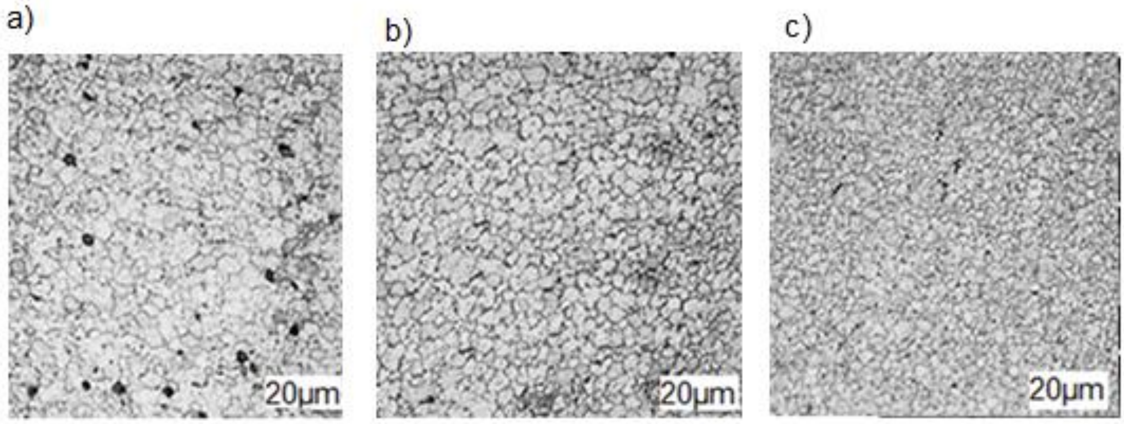

Figure 7

Microstructure of the stir zone at a rotational speed of a) 1000 rpm, b) 1600 rpm, and c) 2000 rpm.

The optical microscopy images of the heat-affected zone are presented in Figure 8. The grain size in this region and stir zone was specified by using microscopic imaging and is listed in Table 3. When the rotational speed rises, the grain size is reduced. Also, the rapid aluminum heat transfer causes the grain size to be close to each other and do not differ significantly from the base metal.

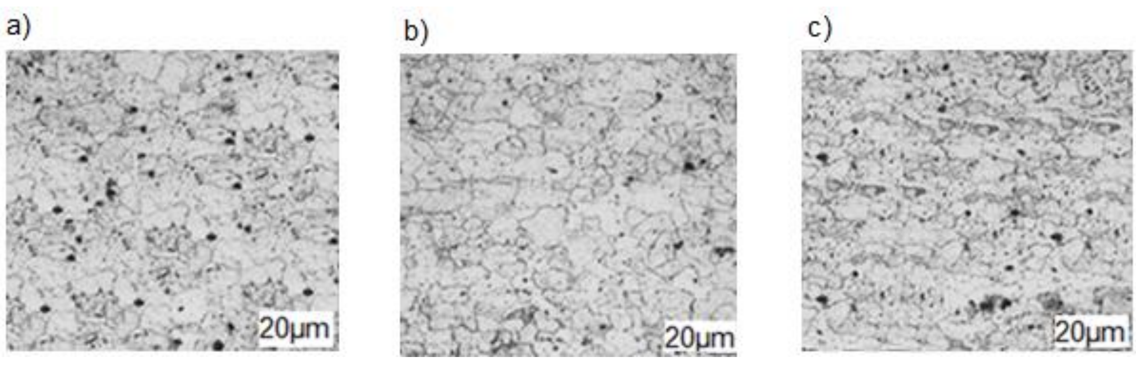

Figure 8

Microstructure of the HAZ at a rotational speed of a) 1000 rpm, b) 1600 rpm, and c) 2000 rpm.

With regard to the microstructure of the heat-affected zone, which is placed just under welding conditions, and the material in this region, which is not directly exposed to the strain of the tool, it may be expected that the change in the welding parameters will only be owing to the variation in the welding temperature that can change the microstructure of the heat-affected zone. Increasing the tool rotation speed enlarges the welding heat input. In conclusion, by increasing the tool rotation speed, the grain size drops.

Table 3

Grain size in the SZ, HAZ, and base metal at different tool rotational speeds.

Tool rotational speed (rpm)	Grain size (μm)		
	SZ	**HAZ**	**Base metal**
1000	10	13.7	
1600	7.8	14.3	21
2000	5.5	15.9	

3.4. Hardness examination

Microhardness examinations were conducted to assess the microstructure of the weld zones. Figure 9 illustrates the hardness values of the upper and lower sheets which are marked as lines a and b respectively versus the distance from the weld center. The center of the stir zone of the upper sheet has the highest hardness value because it is located in the middle of the rotating tool. The linear velocity of this special tool is less than the weld edge. Hence, the strain approaches zero, and the temperature decreases in the HAZ that is located away from the corner of the tool. Consequently, the grain size of the HAZ is greater than that of the SZ which has lower hardness. The hardness of the base metal is higher than that of the SZ owing to the severe deformation by rolling operation and the high density of the dislocations. Farmanbar et al. (Framanbar et al., 2019) exhibited the same trend for hardness value. On the other hand, it is seen that the hardness of the SZ in the top sheet is more than that in the lower sheet owing to the more deformation in this area. In addition, the TMAZ has lower hardness than the SZ. Compared to the lower sheet, the upper sheet presents less hardness in the HAZ since the lower sheet experiences a lower temperature and a higher cooling rate.

Based on the results, the hardness profile is divided into different parts. In one part, the hardness increases by enlarging the distance from the center and reaching the joint edges. In another part, the hardness drops by increasing the distance from the SZ. The changes in the hardness of the welding area can be relevant to the variations in the grain size and precipitation size. The difference between the grain size in the edge of the SZ and HAZ leads to the formation of a hardness peak. In the first part, the existence of grain size gradient from the center to the joint edges causes an increase in the hardness according to Hall-Petch theory (Piccini and Svoboda, 2015; Zarghani et al., 2018).

Fine precipitations, such as $CuAl_2$ or Al_2CuMg precipitations, which exist in the matrix of aluminum alloys affect the hardness value (Dourandish et al., 2018). The precipitations in the nugget zone are much finer with a more uniform distribution comparing with the base metal just because of plastic deformation and heat input, while the precipitations are coarser in the HAZ just owing to heat input. Therefore, precipitates can affect mechanical properties based on their size and distribution. Consequently, the hardness of the NZ and HAZ changes differently. In the NZ, the hardness is noticeably increased, while in the HAZ, it is decreased; this change in the hardness in the different zones are related to the role of precipitations, grain size, and plastic deformation.

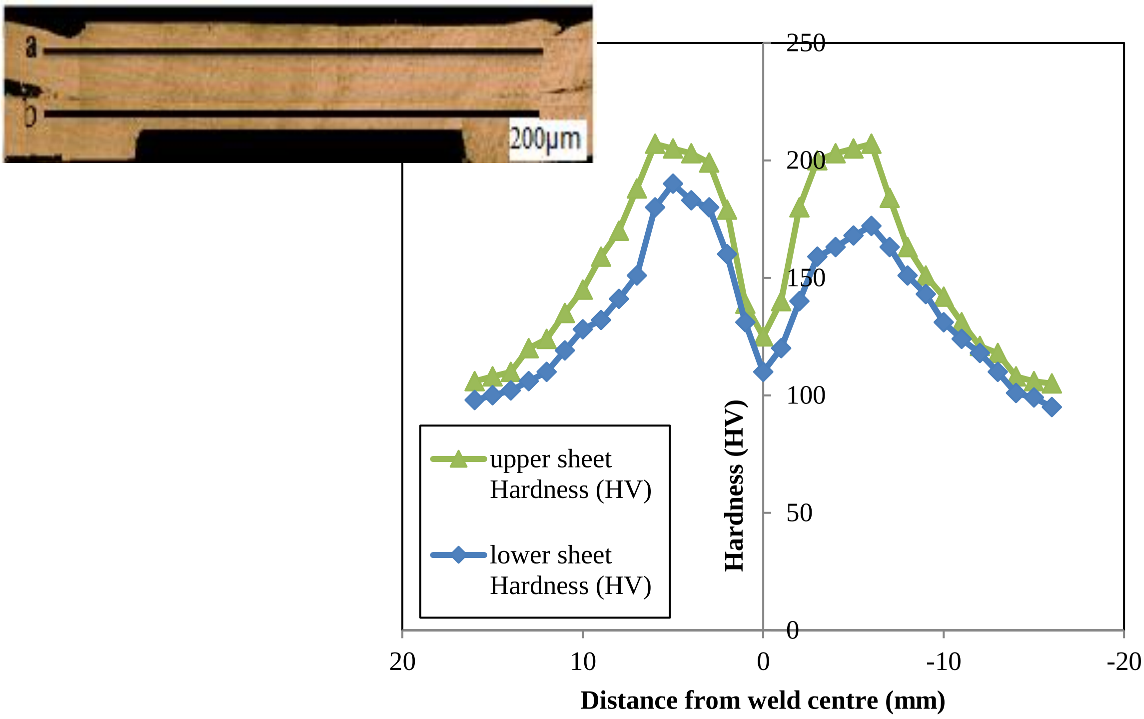

Figure 9

Microhardness profile along lines a and b (upper and lower sheets respectively) versus the distance from the weld center.

3.5. Tensile shear test and fracture mode

Interfacial and circumferential fractures are two common failure modes in spot welding (Pouranvari and Marashi, 2010; Zarghani et al., 2018; Dourandish et al., 2018). Shear plastic deformation at the interface between the sheets and the necking in the base metal play essential roles in these two types of fracture modes (Framanbar et al., 2019). The joints generated by the PFSSW in this study failed due to interfacial fracture at a tool rotation speed of 1000 rpm but owing to circumferential fracture at a tool rotation speed of 1600 and 2000 rpm.

The investigation data on the failure mode of the PFSSW samples under various conditions are summarized in Table 4. The corresponding macrostructure of each of the failure modes is also shown in Figure 10.

Table 4

Effect of the tool rotation speed on welding fracture mode.

Tool rotation speed (rpm)	**1000**	**1600**	**2000**
Fracture mode	Interfacial	Circumferential	Circumferential

In mechanical analyses such as a tensile shear test, the position of the welded specimen is deformed to the side of the tensile force, but a little distortion is visible. Failure mode generally has an indicative effect on the maximum failure force and failure energy of the weld (Khodabakhshi e al., 2011). Interfacial failure happens when piercing and joining are not rightly achieved, that is, the weld interface is poor. In this case, the force is reduced to zero automatically, and there is less deformation (Sun et al., 2013). In circumferential failure mode, fracture happens across the weld (in the HAZ). In this case, the crack is formed and grown around the weld owing to necking. At that point, the weld nugget is separated from one sheet and stayed on the other sheet; these joints are generally strong. This failure mode may be due to various reasons such as softening in the HAZ, the presence of deficiency in the sheet, or in the best situation, the greater strength of the joint with respect to the base metal (Pouranvari and Marashi, 2010; Sun et al., 2013). According to the study of the FSSW of aluminum alloys, if the depth of the nugget zone is low and not enough to reach the interface sheets and stirring materials in the welding zone, creating a continuous structure is not possible (Tozaki et al., 2007). As a result, in the tensile shear test, the shear stress applied to the weld center reaches the ultimate tensile strength of weld center before the weld circumference undergoes necking and fracturing; thus, the fracture happens along the interface.

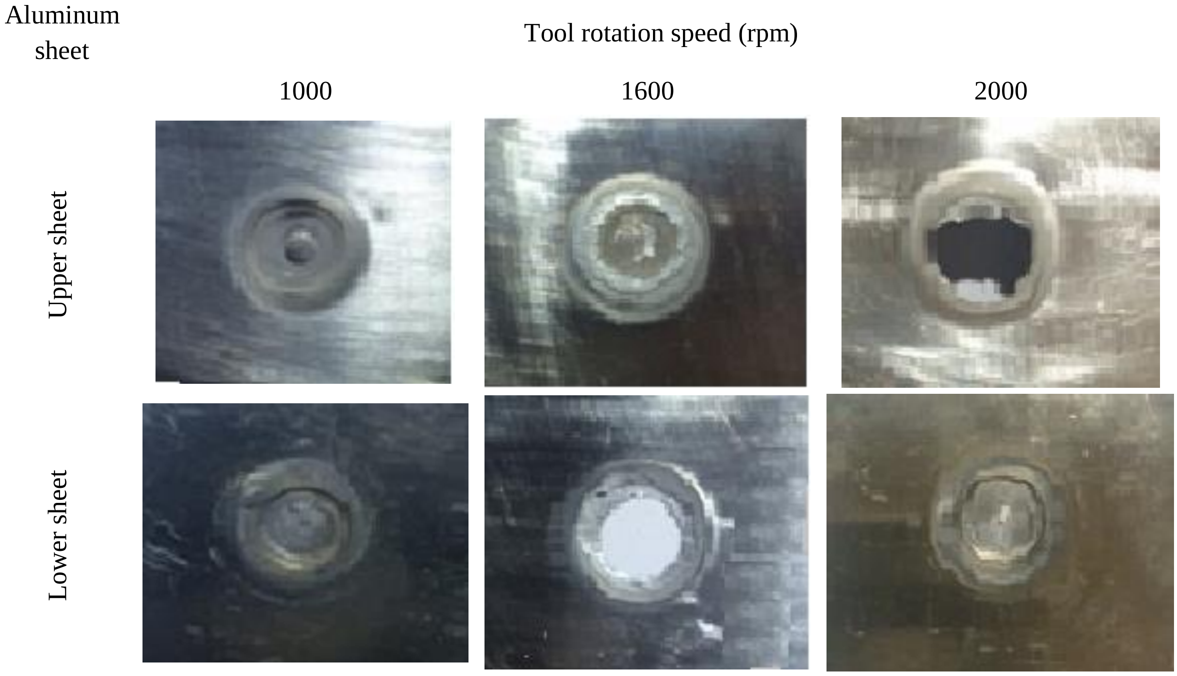

Figure 10

Macrostructure of the fracture modes at different tool rotation speeds: Interfacial (at a tool rotation speed of 1000 rpm) and circumferential (at a tool rotation speed of 1600 and 2000 rpm).

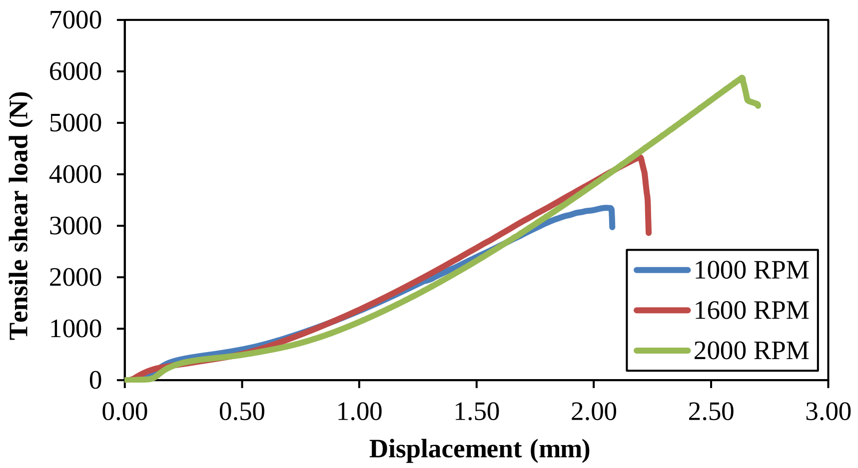

Figure 11

Force–displacement diagram of the welds produced by the PFSSW at different rotation speeds.

Figure 11 delineates the displacement diagram of the welds produced by the PFSSW, and the influence of the tool rotation speed on the shear load of this welding technique is compared. According to this figure, by increasing the tool rotation speed, the maximum load enlarges. The same relation between the tool dwell and the maximum load values during the friction stir spot welding of Al6061-T6 is also reported (Song et al., 2014). The cause of this behavior can depend on the increase of the SZ depth and bonding area since frictional heat and the plastic flow of the material are intensified by increasing the temperature because of an increase in the dwell or tool rotation speed. At a tool rotation speed of 2000 rpm, the maximum failure load is observed.

In this study, the maximum load of the produced welding is compared to the other welding methods, such as Refill FSSW (Sergio et al., 2011; Zhengwei et al., 2016; Zhiwu et al., 2018) and conventional FSSW (Karthikeyan and Balasubramanian, 2009; Wenya et al., 2014; Mahmoud and Khalifa, 2014), for welding different aluminum alloys.

Table 5 lists a summary of the maximum achievable peak load obtained by various techniques of friction stir spot welding for different aluminum alloy sheets. To consider the differences in the sheet thickness (t) and in the tensile strength of the base metal (σ_{BM}), the values of the peak load and failure energy were normalized by dividing them to $t \times \sigma_{BM}$.

In Table 5, t is the sheet thickness, σ_{BM} is the tensile strength of the base metal, and P_{max} is the peak load.

Table 5

Peak load of the aluminum sheets fabricated by using different welding techniques.

Aluminum alloy	***t* (mm)**	**σ_{BM} (MPa)**	**Welding technique**	**P_{max} (kN)**	**Reference**
2024-T3	1	441	PFSSW	6	Present work
5083-0	2	300	Refill FSSW	7.72	(Zhiwu et al., 2018)
2024-T3	1.75	441	Refill FSSW	9.36	(Zhengwei et al., 2016)
2024-T3	2	441	Refill FSSW	10	(Sergio et al., 2011)
2024-T3	1.5	441	Conventional FSSW	6.95	(Wenya et al., 2014)
5754-0	3	215	Conventional FSSW	5.14	(Mahmoud and Khalifa, 2014)
2024-T3	2.7	441	Conventional FSSW	9.39	(Karthikeyan and Balasubramanian, 2009)

Based on Figure 12, the joints produced using the PFSSW process presented superior load-bearing capacity in comparison with the other FSSW methods. Based on the findings of the current work, the PFSSW can be considered to be a simple single-stage technique for creating high-quality keyhole-free welds with no need to use costly equipment such as preheating equipment, specially-designed tools, etc.

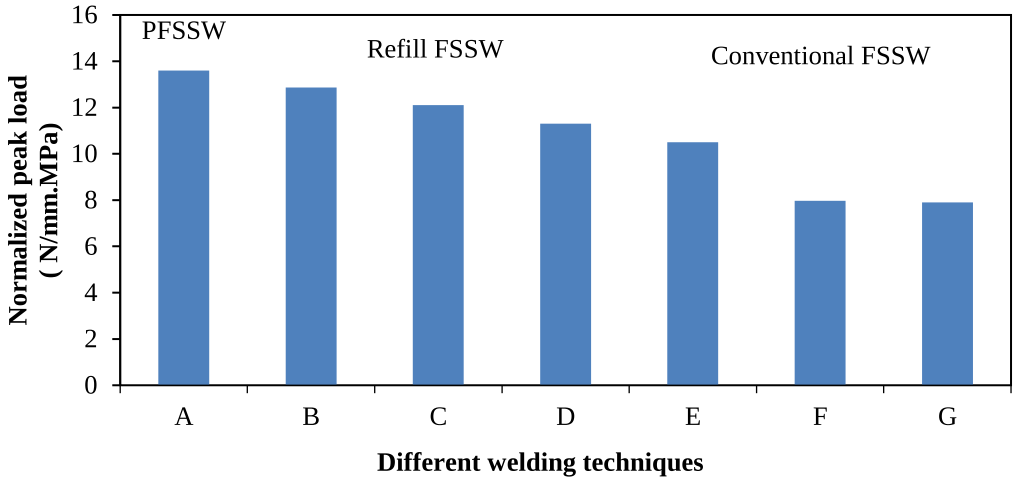

Figure 12

Normalized peak load of the aluminum sheets fabricated by using different welding techniques: A: PFSSW of AA2024-T3, present work; B: Refill FSSW of AA5083-0 (Zhiwu et al., 2018); C: Refill FSSW of AA2024-T3 (Zhengwei et al., 2016); D: Refill AA2024-T3 (Sergio et al., 2011); E: Conventional FSSW of AA2024-T3 (Wenya et al., 2014); F: Conventional FSSW of AA5754-0 (Mahmoud and Khalifa, 2014); G: Conventional FSSW of AA2024-T3 (Karthikeyan and Balasubramanian, 2009).

4. Conclusions

From the findings of this work, the following conclusions can be drawn:

- The projection accelerates the material flow from the lower sheet upward perpendicular to the joint interface, which improves material mixing and eliminates the need for the penetration of the rotating tool into the lower sheet.
- This method removes the keyhole at the top side of the upper sheet and produces a reasonable interface, while in the conventional FSSW method, the keyhole is a weak point.
- By using a projection under the sheets, we achieve superior metal bonding and higher mechanical properties in comparison with the usual friction stir spot welding.
- The maximum load and fracture energy were obtained at a tool rotation speed of 2000 rpm, a plunging depth of 0.1 mm, and a projection height of 0.4 mm.
- The specimens produced at a tool rotation speed of 1000 rpm failed due to the interfacial fracture, while the specimens produced at a tool rotation speed of 1600 and 2000 rpm failed owing to the circumferential fracture.
- This new welding technique can be a good alternative to conventional welding techniques that have major welding defects, and, as an electrical energy-saving method, can be widely developed in the oil and gas, automotive, aerospace, and transportation industry.

Nomenclature

AER	Assembly-embedded rod
AWS	American Welding Standard
BM	Base metal
CF	Circumferential fracture

FSSW	Friction stir spot welding
FSW	Friction stir welding
HAZ	Heat affected zone
IF	Interfacial fracture
NZ	Nugget zone
PFSSW	Projection friction stir spot welding
rpm	Rotation per minute
SZ	Stir zone
TMAZ	Thermo-mechanically affected zone
WC	Tungsten carbide
P_{max}	Peak load
σ_{BM}	Tensile strength of the base metal

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