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Investigation of microstructures and mechanical properties of the joints which welded by the pinless tool and the designed tool to reduce the keyhole in the friction stir spot welding

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ABSTRACT

To eliminate or minimize the keyhole in the friction stir spot welded (FSSW) joints, a new FSSW tool was designed for minimum notch effect in the thick AA6063-T6 sheets. The designed FSSW tool and the pinless tool were manufactured AISI H13 hot work tool steel and then were heat-treated. The hardness of the hardened tools were 54–56 HRC. Lap joint welding was made with a dwell time of 3s and with a different rotational speed for every spot weld. After the welding procedures, microstructure and mechanical properties of welded with the pinless tool and designed tool were investigated. Characteristic fine grain in the stirring zone has formed in the welded samples with the designed tool as a result of the deformation, unlike the pinless tool. The amount of material flow out in the contact zone increased with increasing the rotational speed in both of the tool geometries. The highest shear/tensile strength are obtained at the lap welded samples with 1200 rpm in the designed tool. The increase in welding rotational speed causes welding distortion. The distortion of the welded joints with the designed tool is more apparent.

1. Introduction

Friction stir spot welding (FSSW) is a solid state welding process that operates below the melting point of the workpieces. FSSW is a new spot welding technique to join overlapping workpieces and intends to replace existing techniques like resistance spot welding (Mishra et al., 2014). The concept was first developed at Mazda Motor Corporation and Kawasaki Heavy Industry as an extension of FSW for joining Al alloys (Sakano et al., 2001).

Traditional friction stir spot welding tool consists of a tool shoulder and a pin. Shoulder produces a majority of the deformational and frictional heat to the surface and subsurface regions and applies a forging pressure to welds, while the pin produces a majority of the heat in the thick workpieces and transports the material around it (Yuan, 2008).

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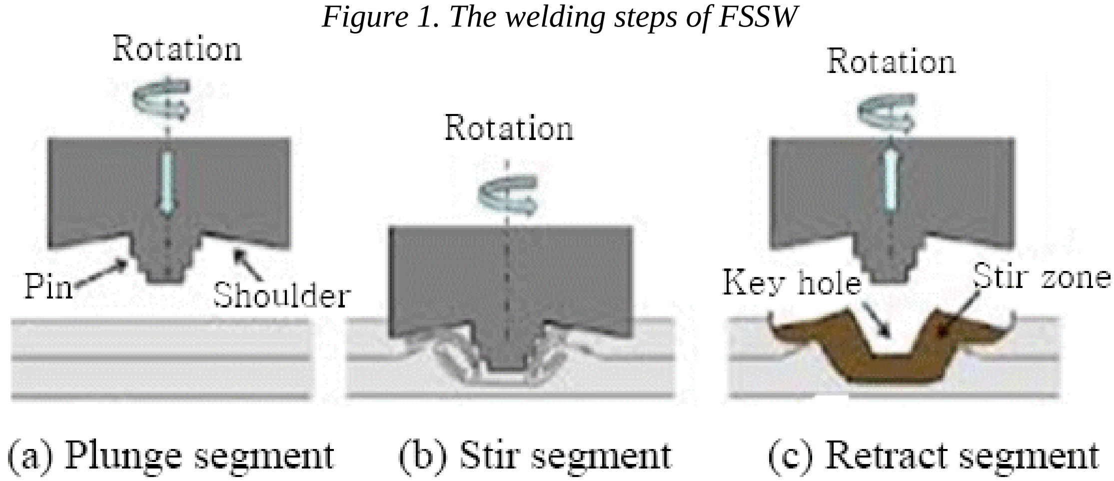
FSSW technique has three main steps, as it may be appreciated in Fig. 1. In first step, a rotating non consumable tool is plunged into the two sheets that are going to be welded in a lap configuration (Fig. 1.a). At the same time, a backing plate, contacts the lower sheet from the bottom and supports the axial load made by the welding tool during the welding cycle. Also, in this step, the tools shoulder gives compressive force to the materials. When the tool penetration depth is reached, the downward movement stops and the welding tool is held in that place for a certain period of time, known as dwell time (Fig. 1.b). In this step, heated and softened material due to the welding action causes plastic flow. Finally, the welding tool is retracted from the sheets while a solid-state joint has been made between the upper and lower sheet (Fig. 1.c) (Piccini & Svoboda, 2017).

Figure 1. The welding steps of FSSW



Source: (Manickam & Balasubramanian, 2016)

The properties of friction stir spot welds depend on tool design, welding process parameters, and base material. Especially tool design plays an important role in achieving high strength spot welds. Su et al. (Su et al., 2006, A; Su et al., 2006, B) studied three different tool designs: a tool with threaded pin and shoulder, a tool with smooth pin and shoulder, and a pinless tool. They reported that very small amount of the energy of FSSW was used to form the stir zone and thread on the pin had negligible influence on the energy generated during FSSW when compared to smooth pin. Tozaki et al. (Tozaki et al., 2007) used tools with three different pin lengths to study their effects on static strength. They reported tensile shear strength increased with increasing pin length when keeping the shoulder penetration depth same. But, usage of the pin in the FSSW form an undesirable characteristic keyhole in the middle, which significantly decreases the mechanical properties of the joints (Yang et al., 2014; Nguyen et al., 2011; Bilici, 2012; Rodrigues et al.,2009). In order to eliminate the keyhole inherent to FSSWed joints, refill FSSW (RFSSW) and pinless (probeless) FSSW (P-FSSW) have been proposed. Due to equipment complexity, the application of RFSSW is limited, while P-FSSW is a more simple process (Xu et al., 2016; Chu et al., 2018). Therefore, especially weld quality comparison of the conventional threaded pin and pinless tool has been studied in the literature (Bakavos et al., 2011; Bakavos & Prangnell, 2009).
But, with a pinless tool, the deformation zone of the sheet remains limited at a certain penetration depth due to the lower temperature in thick sheet metal (Chiou et al., 2013). Although surface features of the pinless tool can increase the interface temperature, it is still difficult to weld sheets with a thickness of more than 2 mm using a pinless tool (Chu et al., (2018).

The aim of this study was to design a FSSW tool for eliminate or minimize the keyhole in the friction stir spot welded (FSSW) joints. Moreover, microstructure and mechanical properties of AA6063-T6 aluminum alloy joints, welded with the pinless tool and designed tool were investigated.

2. Experimental Works

2.1. FSSW tool design

The FSSW tool was designed from AISI H13 hot work tool steel. This steel was selected due to its hot-hardness property, better hardenability and its excellent combination of high toughness and resistance to thermal fatigue (Adesina, 2018). The molybdenum and vanadium in the H13 steel act as strengthening agents. The chromium content assists H13 to resist softening when used at high temperatures (Sucharitha & Rain, 2017). Chemical composition of AISI H13 hot work tool steel was given in the Table 1.

Table 1. Chemical composition of AISI 2344 (H13) hot work tool steel (%w)

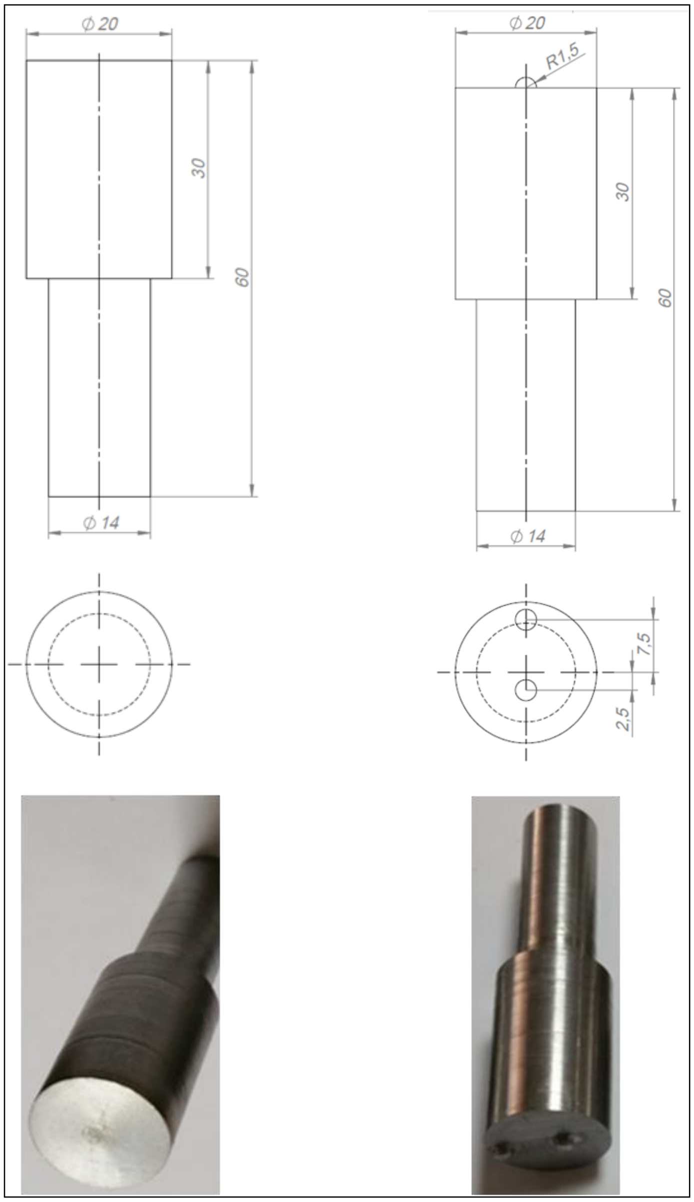
C	Si	Mn	P	S	Cr	Mo	V
0.40	0.1	0.40	0.030	0.020	5.0	1.30	1.0

A stir weld tool is used for frictional heating, plasticizing, and mixing in the two metal pieces for welding. The tool shoulder heats the metal parts with friction by rotating at high speed and the pin mixes the softening metal. Therefore, tool geometry is very important in FSSW and FSW. The criteria considered when designing the FSSW tool is;

- not to create as few or no keyholes as possible after welding,
- the possibility of friction and stirring as many regions as possible at the base material.

The effect of the pin on stirring, friction and heat generation in FSSW and FSW is high. However, it creates a pinhole after the welding process and thus reduces the strength of the welded joints because of the notch effect. In the notch effect, sharp changing the direction of the force lines causes a stress concentration in that area. For this reason, in this study, the pin designs tried to be made to reduce the notch effect that the keyholes would create. In the designed tool, a two spherical pin is designed to not create a sudden cross-section change and to make the cross-section change softer or in radial form. In addition, the pins is placed on the shoulder surface at the distance from the center so that larger friction and stirring area. Because, as previously mentioned, with a pinless tool, the deformation zone of the sheet remains limited at a certain penetration depth due to the lower temperature in thick sheet metal (Chiou et al., 2013). The designed tool with the two off center spherical pins and pinless tool are shown in Fig. 2.

Figure 2. Pinless and designed tool with two off center spherical pin



After the design and manufacturing stage, the designed tools and pinless tool were heat-treated. The AISI H13 FSSW tools were hardened in oil from 1050 °C in argon atmosphere and immediately tempered at 450 °C for about 1hr in a tempering process. The hardness of the hardened tools were 54–56 HRC.

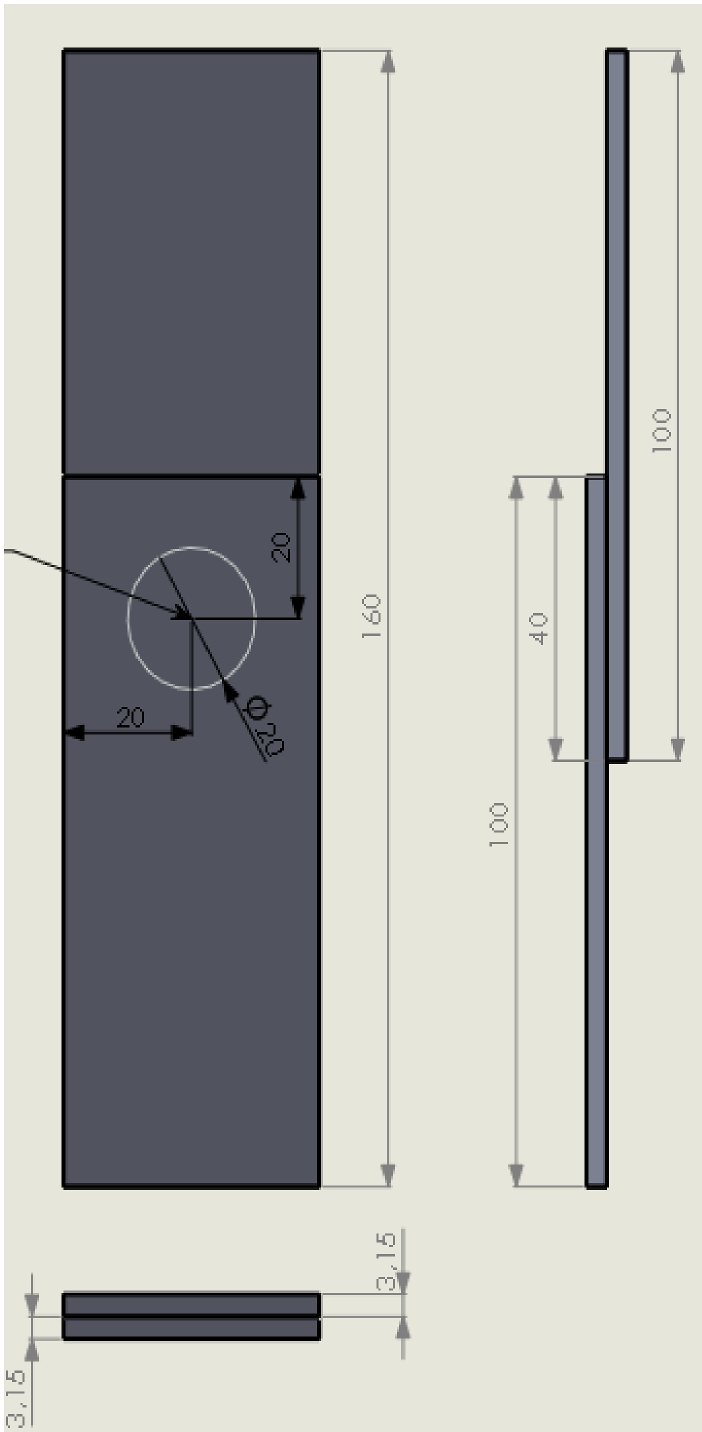
2.2. Base material and FSSW samples

In the experimental study, the rolled sheets of 3.15 mm thickness, AA6063-T6 aluminum alloy was used to make the joints. The chemical composition of the materials used is given in Table 2. AA6063-T6 aluminum alloy sheet was cut to required size (Fig. 3.). Lap joint configuration was used to fabricate the friction stir spot welds.

Table 2. Chemical composition of the AA6063-T6 alloy (wt%)

Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ni	Ti	Pb	Sn
98.8	0.424	0.22	0.0104	0.0001	0.48	0.0023	0.0024	0.001	0.0087	0.005	0.004

Figure 3. Schematic illustration and dimensions of the samples



In order to develop the FSSW tests, a properly designed clamping device was utilized to fix the specimens (Fig. 4).

Figure 4. Friction Stir Spot welding system and clamping device

Friction stir spot weld experiments were made for different tool rotational speed from 800 rpm to 1200 rpm with the pinless and designed tool. Welding parameters are given in Table 3. For each welding condition, four specimens were produced and tested.

Table 3. Welding Parameters for pinless and designed tool

Tool Geometry	Rotational Speed (RPM)	Penetration depth (mm)	Dwell time (s)
pinless (flat) tool	800	0.6	3
	1000	0.6	3
	1200	0.6	3
Designed tool	800	1.1	3
	1000	1.1	3
	1200	1.1	3

2.3. Metallographic characterization and mechanical properties

After metallographic preparation the specimens were etched with a reagent of 25ml CH3OH, 25ml HCl, 25ml HNO3 and one drop HF for 10 seconds to reveal the micro and macro structures. Metallographic inspections were done using a Nikon Epiphot 200 optical microscope.

Welded lap-shear specimens were tested on SHIMADZU UH-F500kNI universal testing machine at a constant crosshead speed of 2 mm/s. The lap-shear fracture load was obtained by averaging the strengths of 3 individual specimens, which were welded with identical welding parameters.

3. Results and Discussion

The appearance of FSSW samples can be seen in Fig. 5. The material amount that flows out of the contact zone increased with the rotational speed in both of the tool geometries. Higher rotational speeds generate higher heat and increase the temperature. As the temperature increase, base material softens and the amount of material flow out increases. But in the welded samples with the pinless tool, the amount of the material flow out is very low. Because, heat formation at the welding with the designed tool is higher than pinless tool due to the stirring and friction.

Fig. 5. Welds surface appearance of FSSW lap joints

Rotational Speed (rpm)	Pinless tool	Designed tool
800		
1000		
1200		

Macroscopic observations along the cross sections of the spot welds are shown in Fig. 6. Since there is no stirring in the pinless tool samples, characteristic stirring zone was not formed. Whereas it was formed in the all designed tool samples. In the areas where the spherical pins contact, stirring have occurred in the two large circular areas. Especially welding with the designed tool, heat formation is very high due to the stirring and friction. Therefore this high heat formation generates welding distortion.

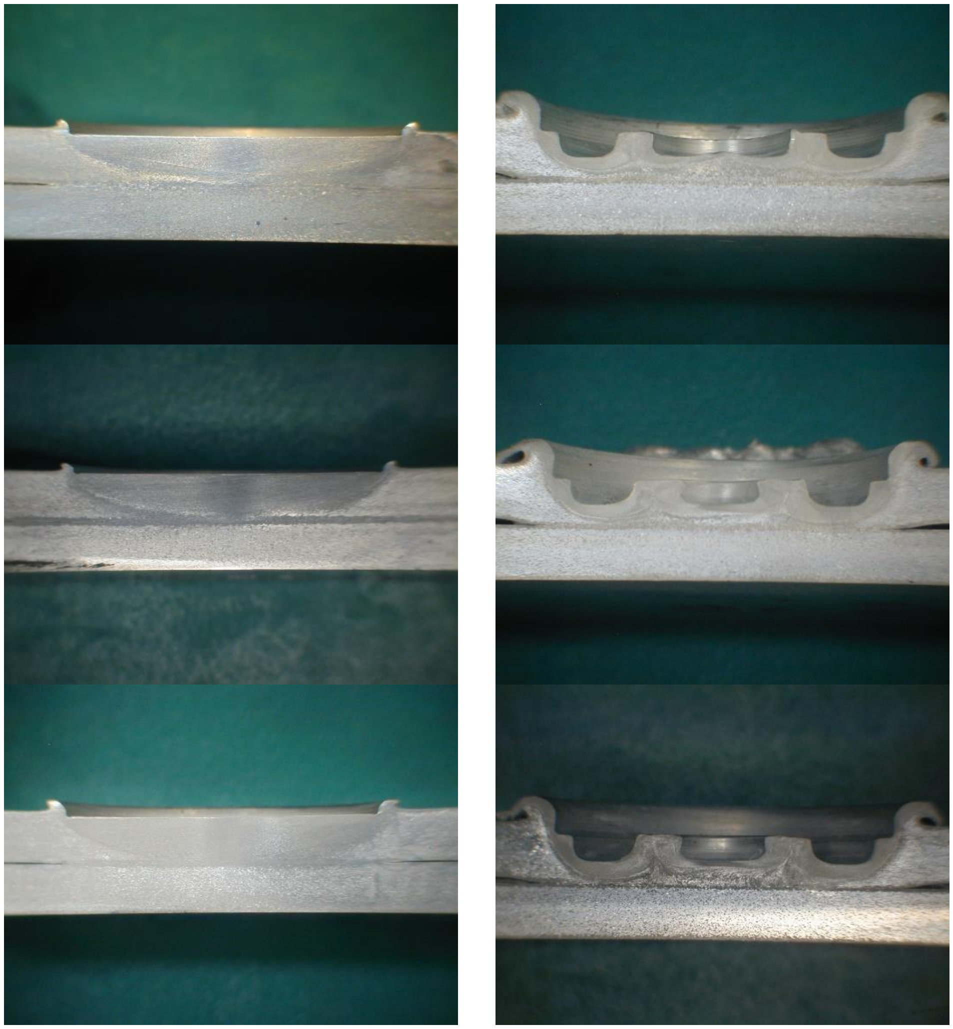
Figure. 6. Optical macrographs of spot welds made using pinless and the designed tools

Rotational Speed (rpm) | Pinless Tool | Designed Tool

800

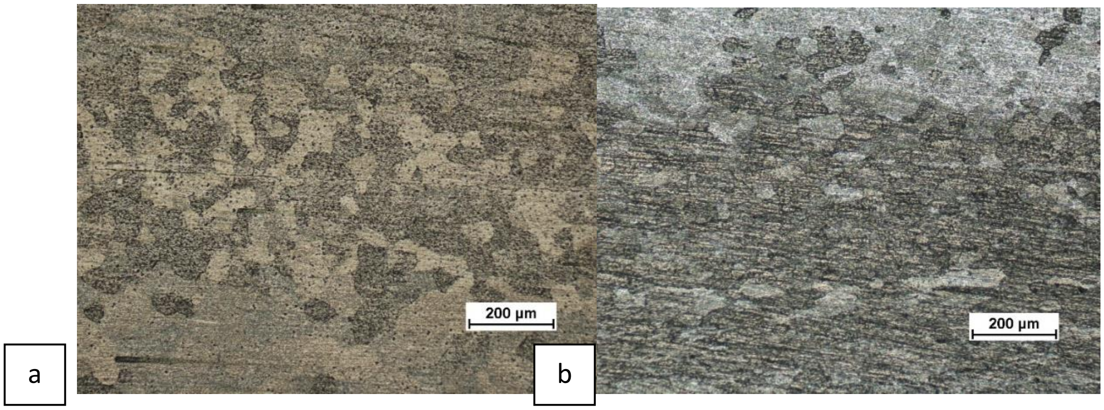
1000

1200



In the all welded samples with pinless tool, there is a discontinuous line in the bonded area (Fig. 7a). In addition, there is no stirring zone and therefore grain refinement in these welded samples. In the designed tool samples there is a good bonding in the spot weld area and no line. The designed tools samples has stirring zone and this zone has characteristic fine grains because of the deformation (Fig. 8b).

Figure 7. Spot weld bonding area of a) pinless tool at 1000 rpm b) designed tool at 1200 rpm



Higher tool rotation speed generates more friction heat, which is beneficial for larger bonded area formation. Therefore, strength of the welded samples has increased with increasing the rotational speed. The strength of the welds depends on the extent and quality of the bonded area, the thickness of the top sheet at the shoulder indentation in FSSW. Especially at the higher tool rotation speed in the designed tool, high quality and larger bonded weld area made the joints stronger than pinless tool.

Table 5. Lap shear fracture loads of different pin profiles

Tools	Rotational Speed (rpm)	Fructure Loads (N)
	800	3194
Pinless tool	1000	3842
	1200	3899
	800	3569
Designed Tool	1000	4036
	1200	5774

4. Conclusion

In this work, 3.15 mm thick AA6063-T6 alloy sheets were joined by using FSSW with the pinless tool and the designed tool. The effect of welding parameters on the microstructure and the mechanical properties of the joints were investigated.

The following conclusions can be drawn:

- Material flow out amount during friction stir spot welding increased with increasing the rotational speed in both of the tool geometries. As the temperature increase, base material softens and the amount of material flow out increases. High heat formation at the higher rotational speed tends to weld distortion. Welding distortion is more apparent at the designed tool joints.
- The designed tools samples has stirring zone and this zone has characteristic fine grains because of the deformation. In the designed tool samples there is a good bonding in the spot weld area and no line. In the welded samples with pinless tool, there is a discontinuous line at the bonded area
- Higher tensile/shear strength as obtained the designed tool samples because of the stirring and good bonding. Strength of the all welded joints has increased with increasing the

rotational speed. Especially at the higher tool rotation speed in the designed tool, high qulity and larger bonded area made the welds stronger than pinless tool.

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