International Journal of Innovation Engineering and Science Research
(ISSN: 2581-4591)

www.ijiesr.com

Effect of Tool Pin Profile of Underwater Friction Stir Welding of Dissimilar Materials Aa5083 and Aa6061-T6

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ABSTRACT

Underwater friction stir welding (FSW) is a primary joining process for welding aluminium, magnesium, and other metals in which no dissolving occurs and joining occurs below the material's melting point, resulting in a high-quality weld. This welding process was developed to be exceptionally effective, with no filler material used and no gas emitted, making the operation ecologically benign. This research aims to look at how shape and rotational speed relate to different materials during the joining process. It investigates the interaction between the tool pin profile and rotating speed underwater. In this context, the effect of underwater circumstances on tool pin profile and rotational speed concerning the mechanical properties and microstructure of the tool is discussed.This research aims to investigate the hypothesis that better mixing of dissimilar metals happens when the tool rotates faster throughout the weld path. AA5083 and AA6061-T6 were used to develop three different tool profiles. Several defects, such as voids in the weld zone, are apparent during welding. The study's findings indicated that changes in tool pin profile and welding conditions had a significant impact on determining the welded joints' mechanical properties. With ideal welding settings of 900 rpm, 60 mm/min, and tapered cylinder pin profile, the maximal hardness value attained was about 75 HV. These findings imply that different tool profiles have other impacts on the generation of faults during welding. As a result, the tool pin profiles should be considered while building an experimental underwater friction stir welded joint.

Keywords—underwater friction stir welding, aluminium alloy, tool pin, mechanical properties, microstructures

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state joint technology that produces high-quality, low-distortion, high-strength butt, or lap joints in a wide variety of industrial applications[1] [2]. The tool consists of a pin and tool shoulder, which have a relevant influence on heat generation. Heat is generated when the shoulder contacts the base material[3]. Numerous pin tools are available, including straight-cylinder, threaded cylinders, tapered cylinders, and enclosed cylindrical threads. Due to plastic's severe deformation, these are the most efficient elements for metallic grain refinement in significant microstructure development [4]. Excessive material softening promoted sliding conditionsdue to a reduction in frictional force induced by precipitate dissolving or coarsening, resulting in defects in weld nugget and poor welded joint quality [5]. It was discovered that by using water cooling conditions in various solid-state joining processes, the mechanical properties could be improved the joint performance [6]. Due to its fast circulation and high heat absorption, the method applied water-cooling has a cooling effect on the samples during the friction stir process.As the pin rotation speed increases, the speed of the shoulder increases, creating tremendous heat in the stir zone, which produces approximately 95% of heat input underneath the tool shoulder[7]. In the water environment, the dynamic heat was influenced by the action of tool pinstodissimilarweldment joints and impacted the heat dissipation of an underwater weld [8].Furthermore, water cooling can give a more refined grain than air cooling [9].

It was proved that there is a correct combination of the weldment formed by strength and hardness in metallurgical bonding at varying rotational speeds (700 to 900 rpm) and transverse speeds (40 to 80 mm/min) on the FSW of Al-alloy [10]. The rotating tool speed and tool pin shape significantly impacted the strength and microstructure of dissimilar weldments [11]. The effect of process elements on weldment quality was influenced by tool design, material flow, and welding conditions. Through these qualities of alloying element addition on their samples, heat extraction rate may also improve the thermal stability of joints [12].Structural metallic alloys' quality and microstructure properties exhibit different cooling rate techniques [13]. Mechanical properties demonstrated that the alloy had the same strength as the welded zone AA6111 alloy's base material [14].Because of porosity, the softening zone is related to the heat generated by the FSW process, and the onion ring was formed when the welding speed increased [15].Mechanical testing was performed on several tool pin profiles to determine the micro-hardness distribution of the FSW. It was validated in the association between temperature and hardness. Furthermore, frictional forces and material flow stirring produced heat production had a notable augmenting influence on the hardness value for varied tool pin profiles during FSW [16].

A tool shoulder analysis considers numerous profiles with crucial features for given material and welding parameters. Due to a better dynamical-static volume ratio [17], the suitable probe was built from the design triangular pin. The tool flat shoulder design is straightforward; however,interrupted materialflowing beneath the surface must be avoided. The welding parameter modification employed a concave 10 mm diameter shoulder produces higher heat resulting in homogenous stirring flow[18].The conical probe on the concave shoulder tool agitated with three grooves had considerable results compared to other tools [19]. Theprocess parameter combinationwas proposed to represent the attributes between material output and input parameters during the FSW process [20]. The high friction input supplied additional heat during the welding across the recrystallisation temperatureto form the welds, resulting in the optimal mechanical properties [21]. The influence of tool pin profiles on FSW of AA6061-AA5086 joints was studied. The threaded cylindrical shape resulted in good flowability and a free sound weld [22]. The strong combination resulted in the behaviour of tool pin threaded with surface mixing flow[23]. Furthermore, research on FSW keeps on studying how to increase the quality of joints and eliminate defects created for better weldment joints and strength.

II. MATERIALS AND METHODS

A. Experimental Procedure

The material for the workpiece are AA5083 and AA6061-T6aluminium alloys.The AA6061-T6 is widely used in various applications due to its favourable characteristics, such as high resistance towards corrosion due to seawater and atmospheric condition. AA5083 also shows good corrosion resistance towards seawater. The plates to be joined were in the dimension of 150 mmx 65 mm x 6 mm. Table 1 shows the chemical composition of both AA5083 and AA60661-T6.

Table 1. The chemical composition of aluminum alloy, reproduced from [24,25].

Weight (%)	Si	Fe	Cu	Mn	Mg	Zn	Ti
AA6061-T6	0.6	0.34	0.26	0.07	0.8	0.01	0.01
AA5083	0.40	0.40	0.1	0.2	0.4	0.1	0.15

B. Design of Experiment Setup

Taguchi L9 factorial design was used to investigate the experiment. In this work, dissimilar joints, Taguchi technique was adopted to optimise process parameters in quality control, Taguchi L9 optimisation method was utilised in this experimental study that the component has pointed out the quality of viewing it as the setup of three internal display elements (speed, feed, and type of tool pin profile). Table 2 shows the experimental level with a variety of parameters. In addition, several trial tests were carried out by adjusting the trail experiments' rotational tool speed (600rpm to 1200rpm) and welding speed (30 mm/min to 90 mm/min). The specimens utilised in this investigation were AA5083 and AA6061-T6 plates.

The FSW procedure was carried out on a vertical milling machine. The tool was made of H13 steel and was designed for single-pass butt welding. Strap clamps were used to secure the plates to the machine table. Four clamps were utilised to secure the plates at the edges. Two extra strap clamps were added to the sidewalls of the plates to guarantee that the plates did not separate during the FSW process. Figure 1 shows the experimental setup of FSW whereas Figure 2 shows variation of the tool pin profiles. The tool is manually inserted into the materials to a depth of 4 mm. Once the pin is fully inserted, and the shoulder is in contact to the plates. The spinning tool is rotated at 30 mm/min, 60 mm/min, and 90 mm/min speeds. The machine table is moved alongthe welding line at 100 mm per run to make a weld of the same length. Once the tool travel distance of 100 mm was reached, the tool was rotated and drawn out of the welded plating. The machine was only turned off after the tool had been entirely removed. For this investigation, there are nine weld joints built from dissimilar AA6061-T6 and AA5083.

Table 2. The level process of parameters.

Parameters	Notation	Levels of factors		
		1	2	3
Speed	**RPM**	600	900	1200
Feed	**Mm/min**	30	60	90
Type of tool pin profile	**TTPP**	CS	CT	TC

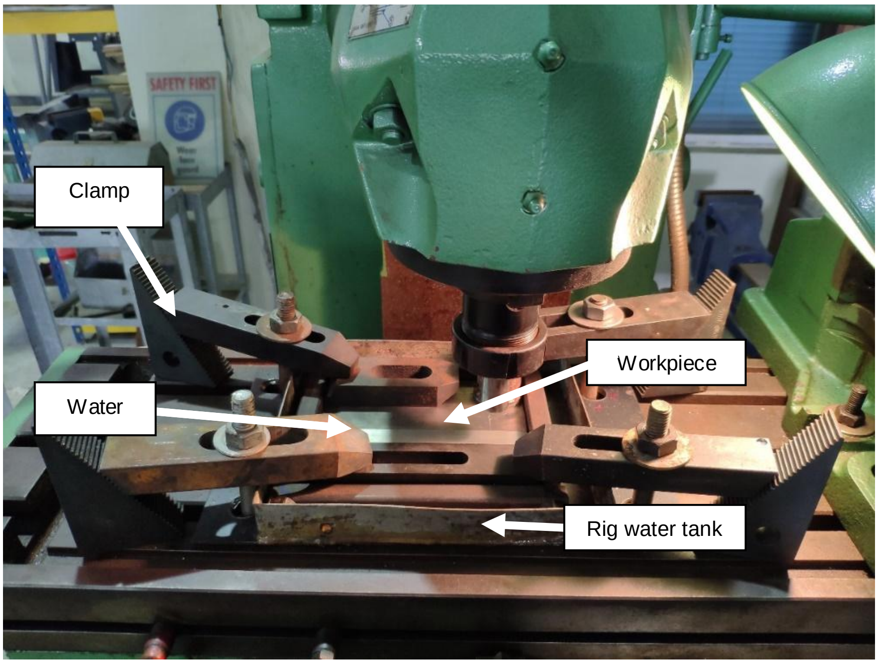

Figure 1. Experimental setup of FSW of butt joint between AA5083 and AA6061-T6 in the water environment.

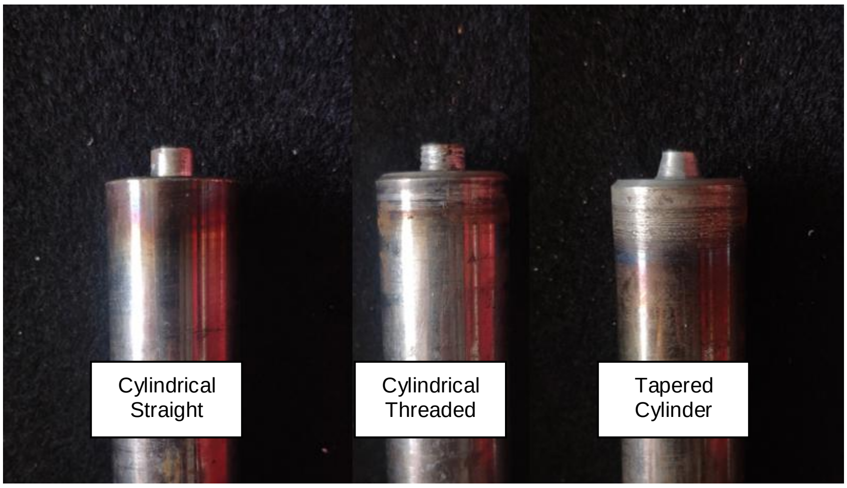

Figure 2. Different experimental tools pin profile.

After welding, the weld was placed on examining the cross-section of each sample. The macrostructure profile assessed the joints; the welding state was polished and etched in 10 to 30 seconds using a reagent containing methanol (25ml), nitric acid (25ml), hydrochloric acid (25ml), and hydrofluoric acid (1 Drop) and inspected under an optical microscope. Vickers hardness testing was also performed on welded joints using a hardness machine with a force of 10kgf and a dwell period of 15s along the perpendicular to the cross-section.

III. RESULTS AND DISCUSSIONS

3.1 Effect of tool pin profiles

The findings include a visual evaluation of the weld surface and a distribution of hardness. Table 3 shows the top view of the welded junction for three distinct tool pin profiles. The stirring behaviour on the top surface exhibits ripples and flashes on the welding line. Welded specimens were visually evaluated for any faults developed at the welded surface of different materials. Under these conditions, the pin produced noticeable onion rings in the cross-sectional region. Three distinct specimens have an unpleasant appearance keyhole surface on the welded surface with flashes. This defect demonstrates that the insufficient heat input in the stir zone caused by the tools resulted in low material flow in the base material.Excessive flashes developed on the surface of both the advancing and retreating sides at 1200 rpm while utilising a threaded tapered cylinder and a cylindrical threaded tool. Tunnel flaws arise when the area of all tool pin profiles is impacted by a greater 600 rpm. This was caused by the FSW tool's low heat input.

Table 3. Macrograph of joint cross-section.

Rotational Speed (rpm)	Tool pin profile	Welding line	The cross-sectional joint of welded joint	Observation
600	Cylindrical Straight			Tunnel defect at the mid thickness and insufficient heat input
900	Cylindrical Threaded			Tunnel defect at the mid thickness and insufficient heat input
1200	Tapered Cylinder			Tunnel defect at the mid thickness and insufficient heat input

The study chooses an experimental sample run for a tapered cylinder pin profile with 900 rpm rotational speeds and 60 mm/min welding speed. This is because the growth of onion rings in the stir zone was not seen in the flow of materials in the mid thickness area. Figure 3 shows the cross-sectional area subjected to macrostructure examination. Microscopy photographs show the stir zone and the characteristics of the aluminium joints and an optical lens to explain the grain structure at surface cross-sections. The material's transfer behaviour controls the significant effect of tool pin profile and welding speed in the welding joint underwater environment and grain refinement process.Underwater FSW was used on various pin profiles, and more excellent thermal dissipation reduces welding temperature. These advantages for process cooling rate produce fine microstructure, which increases weld durability and strength. Figure 4 shows a 5X, and 20X magnification picture of the stir zone and TMAZ region welded of tapered cylinder pin profile on AA5083 and AA6061-T6 joints, respectively. Strong plastic deformations are caused by the mechanical combination of manufacture from the stirring tool pin to the stir zone. Significant product diffusion occurs because of the cumulative impact of higher temperatures and plastic solid deformation, contributing to the homogenisation of elementary components between the specimens. Furthermore, the water environment has a cooling effect on the samples due to its heat absorption capability.

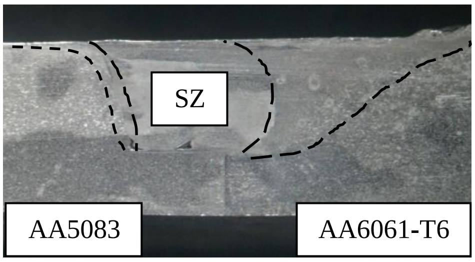

Figure 3. The cross-sectional area of sample 5 (900rpm and 60 mm/min).

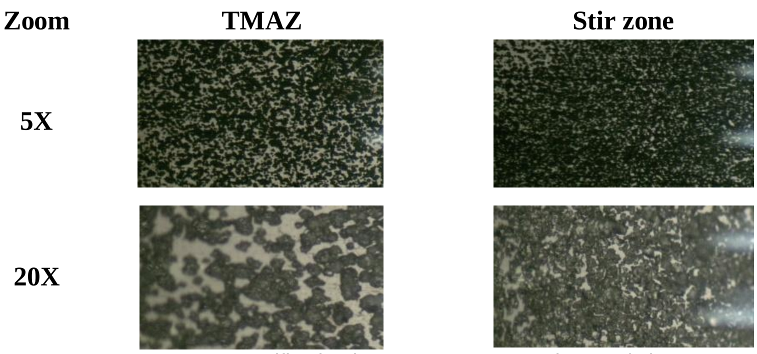

Figure 4. Magnification image at 900 rpm and 60mm/min.

Figure 5 a) shows an onion ring layering formed when the components in the weld nugget are well combined. The material flow starts to develop the banded structure (white circle). The onion ring generated illustrates that the stirring action of the pin profiles is homogenous in the stir zone while welding at a consistent speed of 60 mm/min. Changes in water temperature influence the production of dissimilar weldment junctions in the weld nugget zone. Figure 5 b) shows the dwell time wassignificantly impacted temperature variations; insufficient heat was generated due to slower welding rates and poor material consolidation, resulting in void defects on the advancing side.

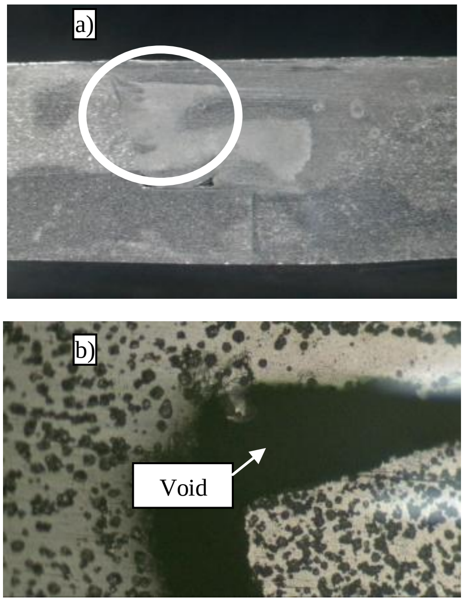

Figure 5. Cross-section of the joint created at a) material flow at advancing side and b) void defect at advancing side.

3.2 Effect On Hardness Value.

The current study found that quick cooling rate was connected to grain size, which was impacted by the water environment. This might be because the grains did not have enough time to germinate in the softened zone. Even though fast cooling reduced the HAZ in the softened area, it enhanced the hardness value reached on both sides of the dissimilar weldments. This significantly influences joint strength and hardness, which is tightly linked to the strengthening stages. Therefore, the water environment enhances hardness variation and keeps the excellent welded joint samples above room temperature. Figure 6 shows both hardness profiles, with no discernible symmetrical trend due to physical and mechanical properties differences, particularly in the stir zone, which consists of dissimilar joints on opposing advancing and retreating sides. The resulting hardness profile is shown over distance in 6 mm thick dissimilar weldment joints. When the feed rate increase to a higher rotational speed, the minimum hardness value in the dissimilar joint increases. It exhibits softening behaviour when the rotation speed increases due to heat generated during FSW.

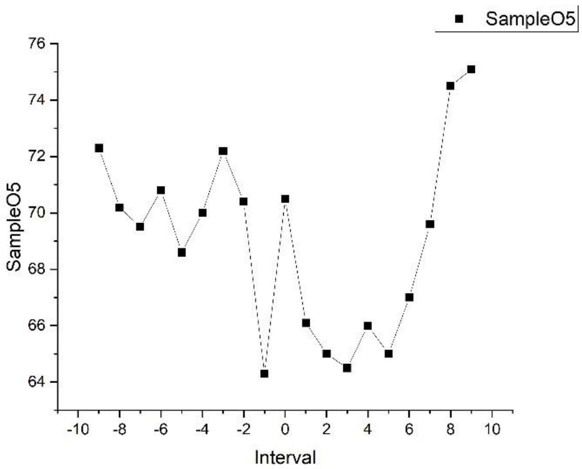

Figure 6. Microhardness for tapered cylinder (900rpm and 60 mm/min).

The minimum hardness value of all places in the relevant weldment AA5083 joint. The advancing side of AA5083, on the other hand, has a rising hardness value since it is close to the centre of the welds. Tool rotation triggered the rising hardness values, while a tapered cylinder pin supplied adequate stirring at all feed rates. At 30mm/min, the maximum hardness was 75Hv. Because the material mixes with another well and proper heat generation during the welding process, the lowest feed speed corresponds to the highest hardness.

Table 4 shows the summary for hardness value; both cylindrical straight and tapered cylinder pin profiles have a higher hardness value than cylindrical threaded in the stir zone. Figure 6 shows a microhardness plot of a tapered cylinder pin profiled at the weld nugget zone at 900 rpm and 60 mm/min feed rate. The hardness profiles of AA5083 and AA6061-T6 show a sharp drop at the weld nugget zone. The primary concern in the welding zone is the hardness distribution, which is heavily influenced by water cooling changes in the microstructure. A softening region identified the lowest hardness under the pin throughout the stir zone, which was more profound in the TMAZ sections where the production process of observed tunnel flaws was discovered. When the rotation speed is increased, the material transfer distribution of the advancing side (AA5083) in TMAZ is smaller than the material deformation ability of the retreating side (AA6061-T6).

Table 4. Summary data for hardness value.

Experimental Run	Speed	Feed	Pin	Hardness
1	600	30	CS	75
2	600	60	CT	70
3	600	90	TC	73
4	900	30	CT	68
5	900	60	TC	72
6	900	90	CS	65
7	1200	30	TC	75
8	1200	60	CS	74
9	1200	90	CT	63
Average				71

IV. CONCLUSIONS

Different tool profiles influence differently on the formation of defects at welds. For threaded straight cylindrical, the tunnel defect formed at the mid-bottom part of the stir zone, and the size is relatively more significant, while for tapered cylindrical tool, the void formed at the stir zone AA5083, and the size is smaller. The onion ring can also be observed with less dissimilar materials in the welded zone. For tapered cylindrical tools, the size of the tunnel defect is much smaller at 900 rpm and 30 mm/min. It was due to the lack of heat generated at the tool.

All in all, threaded tools provide lower material flow as there is adecrease in hardness at the advancing side of welds. On the other hand, cylindrical straight and tapered cylinder produced joints have the highest hardness value and better mixing based on the hardness distribution. In addition, the higher tool rotational speed producesunderwaterwelded joints with higher hardness value and less defect formation.

ACKNOWLEDGEMENT

This material is based upon work supported by the Ministry of Higher Education (MOHE), Malaysia and Research Management Centre of UniversitiTeknologiMalaysia for the financial support through the RUG funding R.J130000.7851.5F382.

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