Friction Stir Spot Welding of Dissimilar Materials: An Overview

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Abstract—**Friction Friction Stir Welding (FSW) process was invented and experimentally proven by The Welding Institute (TWI) in 1991 for joining Aluminium alloys. Friction Stir Spot Welding (FSSW) is a variant of the FSW which is found to be environmental friendly and an efficient process. FSSW technique has been gaining ground when compared to resistance spot welding (RSW) and could be used in various industries including, automobiles, ship building, aerospace, electrical and construction. FSSW has been successfully used to join several materials used in the above mentioned industries. In this review, FSSW studies are briefly summarised in terms of the evolving microstructure and mechanical properties between aluminium alloys and other materials such as copper, steel and magnesium.**

Index Terms— **Aluminium, Copper, Friction Stir Spot Welding, Magnesium, Steel.**

I. Introduction

FRICTION Stir Spot Welding (FSSW) is a variant of Friction Stir Welding (FSW) process for spot welding applications. A non-consumable rotating tool is plunged into the workpieces to be joined. Upon reaching the selected plunge depth, the rotating tool is held in that position for a pre-determined time sometimes referred to as dwell period. Subsequently, the rotating tool is retracted from the welded joint leaving behind a friction stir spot weld. During FSSW, tool penetration and the dwell period basically determine the heat generation, material plasticisation around the pin, weld geometry and therefore the mechanical properties of the welded joint [1]. A schematic illustration of the FSSW process is shown in Fig.1.

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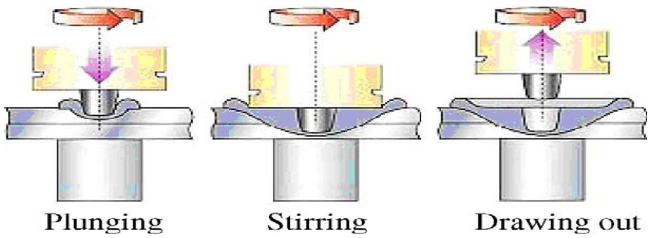

Fig.1 Schematic illustration of Friction Stir Spot Welding process [2]

FSSW process uses a tool, similar to the FSW tool [3]. The shoulder generates bulk of the frictional or deformational heat whereas; the pin assists in material flow between the work pieces [1]. Besides the tool, the other parameters involved in FSSW are, the tool rotation speed; tool plunge depth and the dwell period. These parameters determine the strength and the surface finish of the welded joints [1].
A nomenclature is required to accurately describe the different microstructural regions present after FSSW.
The cross section of the spot weld shows the five characteristics including the Parent Material (PM), the Heat Affected Zone (HAZ), Thermomechanically Affected Zone (TMAZ), The Stir Zone (SZ) and the Hook as shown in Fig. 2.

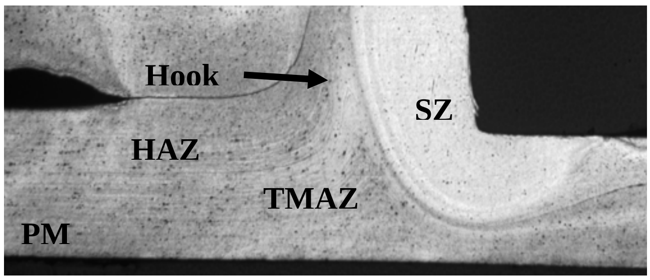

Fig.2 Cross-sectional appearance of a typical Friction Stir Spot Weld [1]

The Parent Material (PM) is the material that is remote from the welded region that has not been deformed; however it may have experienced thermal cycling from the weld. This is not affected by the heat in terms of the microstructure or the mechanical properties.
The Heat Affected Zone (HAZ) is the region which lies closer to the weld-center and has experienced a thermal cycle during welding which has modified the microstructure and/or the mechanical property, there is no plastic deformation in this region. Whereas, the Thermomechanically Affected Zone (TMAZ) is found in the region where the tool has plastically deformed the material. In some materials, it is possible to obtain significant plastic

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strain without recrystallization in this region. There is a distinct boundary between the recrystallized zone and the TMAZ.

The Stir Zone (SZ) is the fully recrystallized region that is, in the immediate vicinity of the tool pin. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material. Whereas, the Hook is a characteristic feature of Friction Stir Spot Welds in lap configuration where there is a formation of a geometrical defect originating at the interface of the two welded sheets [4].

There are many published reviews on Friction Stir Welding and processing [5]-[11] but so far there is no detailed review on Friction Stir Spot of similar and dissimilar materials. This review paper is focused on showing the current status of FSSW between similar and dissimilar materials and suggestions to fill the gaps to expand FSSW industrially.

II. CURRENT STATUS OF FRICTION STIR SPOT WELDING (FSSW) OF SIMILAR AND DISSIMILAR MATERIALS

A. FSSW between Aluminium Alloys

A number of studies have been conducted on Friction Stir Spot Welding between Aluminium alloys over the years. Uematsu *et al* [12], joined T4 treated 6061 using a double-acting tool consisting of outer flat shoulder and inner retractable probe, which could re-fill probe hole. The microstructures of the weld zone were classified into MZ (mixed zone) and SZ, where fine equiaxed grains were observed due to dynamic recrystallisation during FSSW process. They further found that the tensile strength of the joint was improved by a re-filling process because the effective cross sectional area of the nugget was increased [12].

Merzoug *et al* [2], conducted experiments on AA6060-T5 using a tool steel of the type X210 CR 12 and the rotational speed of the tool ranged from 1000 to 2000 rpm. The tensile tests made it possible to establish that the sample produced at 1000 rpm and 16 mm/min has a good quality of welding, which has 5 kN to 16 mm/min and 1000 rpm compared to 1.98 kN for 25 mm/min and 2000 rpm. The microhardness approached the maximum value as they moved away from the nugget zone.

Zhang *et al* [13], spot welded AA 5052-H112 of 1 mm thickness. They concluded that softening occurs in the welds. A minimum hardness of 19.2 HV, which equals to 45.7% of that of the PM, was measured in the HAZ. In addition, hardness in the TMAZ and SZ improved due to the recrystallisation which makes the hardness distribution exhibit a W-shaped appearance [13].The joints strength decreases with increasing tool rotational speed, while it is almost independent of the given tool dwell times [13].

Shen *et al* [14] used AA 7075-T6 plates of 2 mm thickness, the rotational speeds and the dwell time were varied, which were 1500, 1750 and 2000 rpm, and 3, 4 and 5 s, respectively. They investigated the microstructure and the mechanical properties of the refilled FSSW of AA7075-T6. The keyhole of the weld was refilled successfully, the microstructure of the weld exhibits variations in the grain sizes in the width and the thickness directions as depicted in Fig 3 [14].

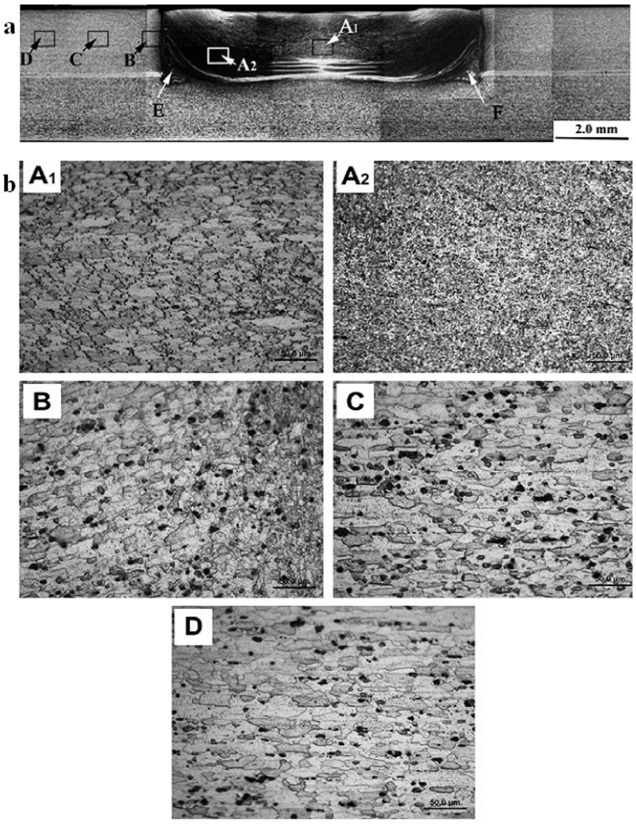

Fig.3 Microstructures on longitudinal section of RFSSW joint made at welding condition of the rotational speed of 1200 rpm and dwell time of 4 s: (a) cross section of weld zone, (b) magnified views of the regions A1-D marked in a, respectively [14].

Additionally, they observed, defects associated to the material flow, such as hook, voids, bonding ligament and incomplete refill [14].The hardness profile of the weld exhibited a W-shaped appearance in the macroscopic level. They attributed the change in the hardness to the comprehensive effects of several factors, in which the precipitation state plays a decisive role.

Shen *et al* [15], joined 6061-T4 aluminium alloy sheets with 2 mm thickness using high-speed steel tool (JIS,SKD61),whose shoulder diameter is 10 mm with a concave profile. A preferable appearance of the joint was obtained at higher rotational speed and longer duration time. The microstructures of the weld was divided into four regions, BM, HAZ, TMAZ and SZ, there exist dynamic recrystallisation and dissolution of precipitates in the weld. The hook geometries vary significantly depending on rotational speed and dwell time. The formation of hook was attributed to the insufficient pressure vertical to the tool, and the amount of material extruded upward and the effective weld width increases with the increase of the rotational speed and dwell time [15]. Furthermore, the Vickers hardness profile of the sheets showed a W-shaped or an upside down V-shaped appearance. The minimum hardness reaches 46.7 HV in the periphery of the HAZ and TMAZ and different variation of Vickers hardness in each region of the weld was attributed to the comprehensive effects of the strain-hardening, the dissolution of strengthening phase and

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the variation in the grain sizes. The tensile/shear strength increases with the increasing rotational speed at a given duration time. Though, under a given rotational speed, differences in tensile/shear strength among three dwell times are rather small. The tool rotational speed plays a determinant role in determining the tensile/shear strength [15].

Tozaki *et al* [16], joined AA6061-T4 sheets with 2 mm thickness using different probes lengths of 3.7, 3.1 and 2.4 mm with a shoulder diameter of 10 mm. The probes were made of high-speed steel (Japanese Industrial Standard (JIS), SKD61) and had a standard metric M3.5 left-hand thread. A constant tool plunge rate of 20 mm/min and a shoulder plunge depth of 0.2 mm below the upper plate surface were applied. Furthermore, the tool rotational speeds and the tool holding times were also varied, which were 2000, 2500 and 3000 rpm, and 0.2, 1 and 3 s, respectively. They observed that, the microstructures of the welds varied significantly depending on the probe length, tool rotational speed and tool holding time and the tensile shear strength increased with increasing probe length [16].

Badarinarayan *et al* [4] joined annealed AA 5083 sheets with two different thicknesses of 1.64 and 1.24 mm. The tool shoulder diameter was 12 mm with a concave profile, and the pin length was 1.6 mm. The two different pin geometries are conventional cylindrical and triangular pin. They concluded that the tool pin geometry significantly affects the hook. In the FSSW-C (cylindrical pin) weld, the hook runs gradually upward and then bypasses the stir zone and points downward towards the weld bottom. Whereas, in the FSSW-T (triangular pin) weld, the hook is directed upward towards the stir zone and ends with a very short plateau.

Wang *and* Lee [17], spot welded AA6061-T6 with a thickness of 1 mm. They found in their experimental results that under lap-shear loading conditions, the failure is initiated near the SZ in the middle part of the nugget and the failure propagates along the circumference of the nugget to final fracture. The location of the initial necking/shear failure is near the possible original notch tip and the failures of the Friction Stir Spot Welds were fractured through the TMAZ near the weld nuggets [17]. Furthermore, the hardness initially decreases upon approaching the boundary between the base metal and the HAZ, then drops sharply to a minimum in the TMAZ. After passing the TMAZ, the hardness gradually increases up to the SZ hardness [17].

Buffa *et al* [18], used AA6082-T6 aluminium alloy, 1.5 mm in thickness. They used an H13 tool steel quenched at 1020 ^{O}C, characterized by 52 HRC hardness. The shoulder was 15 mm in diameter and a 40^{o} conical pin was adopted, with a major diameter of 7 mm and a minor diameter of 2.2 mm; the pin height was 2.6 mm. They used a variation of FSSW process and successfully produced the welds.

Wang *et al* [19] joined commercially pure AA1050-H18 sheets with a 300μm thickness. The experiments results suggest that under lap-shear loading conditions, the failure is initiated near the SZ in the middle part of the nugget and the failure propagates along the circumference of the nugget to final fracture. The location of the initial necking/shear failure is near the possible original notch tip and the failures of the Friction Stir Spot microwelds were fractured through the TMAZ near the weld nuggets.

Yuan *et al* [20], spot welded 1 mm thick AA6016-T4 sheets using two tools. They used a conventional tool (CP) and an off-center tool (OC) to produce the welds. The CP tool with a center pin has a concave shoulder with 10 mm diameter and a 1.5 mm long step spiral pin with root diameter of 4.5 mm and tip diameter of 3 mm. Whereas, the OC tool was feature with the same concave shoulder shape and diameter, and three off-center 0.8 mm long hemispherical pin features. Both tools were machined from Densimet tungsten alloy. Results indicated that the tool rotation speed and the plunge depth profoundly influenced the lap-shear separation loads [20].

Furthermore, both tools exhibited maximum weld separation load, about 3.3 kN at 0.2 mm shoulder penetration depth; different tool rotation speeds, 1500 rpm for the CP tool and 2500 rpm for the OC tool [20].

Jeon *et al* [21], used Friction Stir Spot Welding process to join, 3mm thick 5052-H32 and 6061-T6 aluminium alloy sheets. The z-force and torque histories as a function of the tool displacement vary significantly during the FSSW process. The force and torque histories during the FSSW process can be distinguished by different stages based on the contact phenomena between the tool and joined sheets. The shapes of the z-force histories are somewhat different for the selected material combinations, while the torque histories have quite similar shapes. The differences in the z-force histories for the different material combinations may be explained based on the different mechanical behaviours of the aluminium alloys at various elevated temperatures [21].

Thoppul *and* Gibson [22], used AA6111-T4 to produced spot welds. From the microstructural studies, it is clear that increasing the processing time increases both the tool depth of penetration and the bonding area between the lap joints.

Su *et al* [23], investigated the Friction Stir Spot Welding of 5754 and Al 6111 sheets using a tool having a smooth pin with or without a dwell period and spot welds were made using a threaded tool without the application of a dwell period. They did not observe dissimilar intermixing in the spot welds made using a tool with a smooth pin with or without the application of a dwell period. They further proposed that dissimilar intermixing during the dwell period in spot welding results from the incorporation of upper (Al 5754) and lower (Al 6111) sheet materials at the top of the thread on the rotating pin [23].

Babu *et al* [24], welded 3 mm thick AA2014-T4 and T6 conditions with and without alclad layers to investigate the effects of tool geometry and welding process parameters on joint formation. A good correlation between process parameters, bond width, hook height, joint strength, and fracture mode was observed. They further found that the presence of the Alclad layers and the base metal temper condition have no major effect on the joint formation and joint strength [24].

Pathak *et al* [25], joined AA5754 sheets using tools with circular and tapered pin considering different tool rotational speeds, plunge depths, and dwell times. Symmetric temperature profiles have been observed near the sheet-tool interface during spot welding using tools with circular and tapered pin at different rotational speeds. The peak temperature increases with increase in tool rotational speed and dwell time. Tool geometry also affects the temperature distribution, as under similar condition, tool with circular pin generated more heat than tool with tapered pin. The lap shear test with welded samples shows influence of tool rotational speed, plunge depth, and dwell time. The common observation for both the tools is that lap shear load increases with the increase in the said parameters [25].

B. FSSW between Aluminium and Magnesium

FSSW process has been successfully used to Friction Stir Spot Weld aluminium to magnesium used especially in the automotive and the aerospace industry.

Suhddin *et al* [26] successfully joined Al alloy AA5754 to Mg alloy AZ31. Their microstructure analyses showed that the grain structure development in the stir zone was affected by grain boundary diffusion, interfacial diffusion and dynamic recrystallisation, which resulted in fine equiaxed grains of $Al_{12}Mg_{17}$ in the weld center. Whereas the hardness profile of the Mg/Mg similar weld exhibited a W-shaped appearance, the lower hardness values appeared in the TMAZ and HAZ of both Mg/Mg and Al/Al similar welds. In the Al/Mg dissimilar weld, a characteristic interfacial layer consisting of intermetallic compounds $Al_{12}Mg_{17}$ and Al_3Mg_2 was detected. Both the Mg/Mg and Al/Al similar welds had significantly higher lap shear strength, failure energy and fatigue life than the Al/Mg dissimilar weld. While the Al/Al weld displayed a slightly lower lap shear strength than the Mg/Mg weld, the Al/Al weld had higher failure energy and fatigue life [26].

Chowdhury *et al* [27], used FSSW process to spot weld commercial AZ31B-H24 Mg and AA5754 with a thickness of 2 mm. They used a tool made from H13 tool steel which had a diameter of 13 mm for the scrolled shoulder and 5 mm for the left-hand threaded pin. A pin length of 2.8 mm, tool rotational rate of 2000 rpm, tool plunge rate of 3 mm/s, tool removal rate of 15 mm/s, shoulder plunge depth of 0.2 mm and dwell time of 2 s was used. There was a presence of intermetallic compounds ($Al_{12}Mg_{17}$ and Al_3Mg_2). The microhardness profile of the Mg/Mg weld exhibited a W-shaped appearance, where the hardness gradually increased towards the keyhole direction [27].

Chowdhury *et al* [28] conducted a study on FSSW of Commercial AZ31B-H24 Mg and AA5754-O Al alloy sheets with a thickness of 2 mm were selected for FSSW. They observed a distinctive interfacial layer consisting of $Al_{12}Mg_{17}$ and Al_3Mg_2 intermetallic compounds in the Friction Stir Spot Welded dissimilar Al/Mg and Mg/Al adhesive joints. Furthermore, they stated that in comparison with the Al/Mg weld without adhesive, the extent of forming the intermetallic compounds decreased in the dissimilar adhesive joints. They also observed a much higher hardness with values in between HV90 and 125 in the stir zone of Al/Mg and Mg/Al adhesive welds due to the presence of intermetallic compound layer [30]. It was also observed that both Mg/Al and Al/Mg adhesive welds had significantly higher lap shear strength and failure energy than the Al/Mg dissimilar weld without adhesive [28].

Choi *et al* [29], Friction Stir Spot joined 6K21 Al alloy and AZ31 Mg alloy with a tool made of general tool steel (SKD11) and composed of a shank, a shoulder, and a pin. The shoulder diameter, pin diameter, pin height and weld tilt angle of the tool were 13.5 mm, 9.5 mm, 0.5 mm and 0^o, respectively. The obtained results demonstrated the formation of intermetallic compounds (IMCs) in the interface between the Al and Mg alloy joints. These intermetallic compounds were revealed as Al_3Mg_2, formed on the Al substrate, and $Al_{12}Mg_{17}$, formed on the Mg substrate. Additionally, the thickness of the IMCs layer increases with increasing tool rotation speed and duration time, and has a significant effect on the strengths of the joints. Substantial thicknesses of intermetallic compounds layer seriously deteriorates the mechanical properties of the joints. The maximum tensile shear fracture load of the Al and Mg alloy joint was about 1.6 kN, however, the load value decreased with increasing of tool rotation speed and duration time, owing to the cracks in the Intermetallic compounds (IMCs) [29].

C. FSSW between Aluminium and steel

Chen *et al* [30], welded 1 mm thick 6111-T4 Al and DC04 low carbon steel sheet. The tool had an 11 mm diameter steel shoulder, with a scroll profile to improve the flow of material, and a tapered 3 mm diameter WC 1 mm long probe. The radius of the probes orbital path was 2.5 mm which produced a swept area of 8 mm diameter on the steel surface. They produced high quality friction spot welds between thin Al and steel automotive sheet within a weld time of 1 second which is a desired target time by industries.

Sun *et al* [31], used a concave-shaped shoulder geometry tool with a diameter of 12 mm and a probe with a diameter of 4 mm to FSSW a 1 mm thick commercial 6061 Al alloy and a mild steel. They observed no obvious intermetallic compound (IMC) layer along the Al/Fe interface after producing the welds. Furthermore, they observed that the shear tensile failure load can reach a maximum value of 3607 N. The pin length has little effect on the weld properties, which indicates that the tool life can be significantly extended by this new spot welding technique [31].

Bozzi *et al* [32], joined AA 6016 (1, 2 mm thick) to a galvanized IF-steel sheet (2.0 mm thick) using a tool machined into tungsten rhenium alloy (W25Re). The intermetallic compounds layer thicknesses increases with the rotational speed and the penetration depth. They also noticed that the intermetallic compounds seems to be necessary to improve the weld strength, but if the intermetallic compound layer is too thick cracks initiate and propagate easily through the brittle intermetallic compounds layer [32].

Figner *et al* [33], Friction Stir Spot Welded HX340 LAD sheets of steel of 1 mm thickness and aluminium AA5754-H111 of 2 mm thickness. They observed by using proper selection of spindle speed and dwell time, the strength of the spot weld can be improved significantly. Thus, a maximum load in the shear tension test of 8.4 kN per spot can be achieved while by increasing the dwell time, the amount of intermetallic phases (IMP) increases and breaks off, causing a drop in the strength [33]. More research needs to be conducted to optimise the process in order to use FSSW between Aluminium and Steel industrially.

D. FSSW between Aluminium and Copper

Efforts have been made to produce Friction Stir Spot Welds between Aluminium and copper. This section summarise studies conducted and published. Ozdemir *et al* [34] and Heideman *et al* [35] have successfully Friction Stir Spot Welded a 3 mm thick AA1050 to pure copper and 1.5 mm thick AA6061 –T6 to oxygen free pure copper respectively. It was noticed while conducting an investigation on the existing literature on FSSW between Aluminium and Copper that not many published results are available, therefore, it is of importance that more research has to be conducted to optimise the process to enable it to be used as an alternative to riveting and Resistance Spot Welding.

Ozdemir *et al* [34] produced Friction Stir Spot welds using three different plunge depths namely 2.8, 4 and 5 mm, using a tool with a shoulder diameter of 20 mm and a pin with a diameter of 5 mm. Furthermore, the spot welds were produced using 1600 rpm rotation speed with 10 seconds hold time [34]. They produced spot welds with no macroscopic defects and the grains on the copper side close to the Al/Cu interface were finer than those of copper base metal. The difference in the grain sizes was attributed to the effect of the rotating pin which deformed the grains close to the interface and the recrystallization of grains in the stir zone of the copper metal due to heat input [34]. Furthermore, the EDS analyses conducted revealed the formation of hard and brittle intermetallic compounds AlCu, Al_2Cu and Al_4Cu_9 formed at the interface [34]. The tensile shear test results showed that 2.8 mm plunge depth produced poor results whereas 4 mm plunge depth showed the highest values of shear tensile test compared to the 5 mm, it was suspected to be due to the penetration of Cu into Al in a more diffused way [34]. They also indicated that the hardness increases at the bottom region of the pin hole (in the Cu material) due to heat input introduced by the rotating pin. Furthermore, they stated that as the plunge depth increases, the grain size decreases, which caused higher hardness at the Cu side for the 5 mm plunge depth and due to more diffuse and selective penetration of Cu into Al for 5mm plunge depth, higher hardness values were obtained on the Al side [34].

On the other hand, Heideman *et al* [35] conducted metallurgical analysis on AA 6061-T6 to oxygen free Cu using Friction Stir Spot Welding process. The tool used was a threaded pin design using a prehardned H13 tool steel with a shoulder of 10 mm, pin diameter of 4 mm and the thread pitch of 0.7 mm. Two different plunge depths were used: 0 and 0.13 mm and two different weld times of 3 and 6 seconds [35]. They used rotation speeds varying from 1000 to 2000 rpm. Furthermore, they indicated that, the plunge depth, rotation speed and tool length were the primary factors affecting the strength of the welds. There was no presence of an intermetallic interface in the strong welds; they were only in the form of small particles that do not connect along the bond line to become most detrimental to the weld quality [38]. Heideman *et al* [35] also showed a vertical cross section of the spot weld with a Cu ring appearing on each side of the keyhole. Cu rings images with their measurements using different process parameters are exhibited in Fig 4.

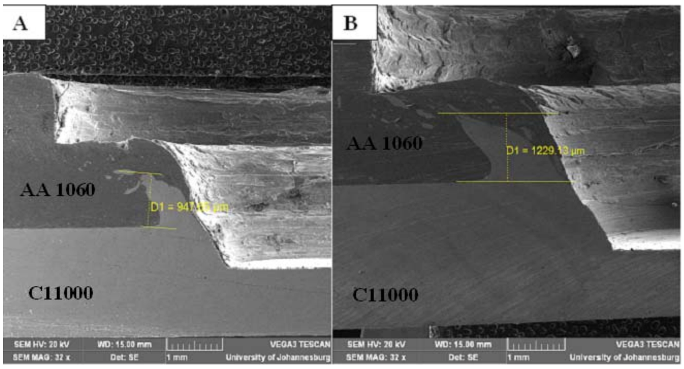

Fig.4 Copper ring size of weld produced using conical pin (3mm length) and a concave shoulder (15mm diameter) at welding conditions of 800 rpm and 0.5mm (A) and 1.0 mm (B) shoulder plunge depth.

So far, no published work is available on the optimisation of tool geometry and welding parameters to produce sound Friction Stir Spot Welds (Al/Cu). Therefore, it is of importance to successfully conduct studies on the optimisation of the tool geometry and process parameters to produce spot welds between Aluminium and copper using Friction Stir Spot Welding process in order to harness the commercialisation of the process.

III. Conclusion

A literature review has been conducted on the FSSW process of dissimilar materials. It shows that significant research and development of the FSSW process has been achieved worldwide and this process has established itself as a viable joining option for the automotive and aerospace industries. However, more researches need to be further conducted to fully understand and optimise the process. It was also noticed that not much importance has been shown on producing FSS welds between aluminium and copper which could be an alternative solution to riveting and Resistance Spot Welding (RSW) since spot welding between aluminium and copper could be useful in making electrical connections and components. Although, the ability of FSSW to join lightweight, high strength aluminium alloys to other materials such as magnesium, copper and steel is desirable, extending this process into high melting temperature materials has proven challenging due to tool cost and tool wear rates. It is expected that if the process is applied efficiently, it can be a technical and economical process compared to the traditional welding processes.

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