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A Review on Friction Stir Spot Welding Joints of Dissimilar Aluminium Alloys

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Abstract--- ***The continuous advancement of lightweight resources for the application in the automotive industry is due to the lower absolute strength of aluminum alloys. From these alloys, several components are produced by casting, stamping, forging and extrusion manufacturing processes. General technique for joining the steel sheets is Resistance spot welding. When compared to other fusing based welding technologies FSSW has some advantages that are high tolerance to poor part fit-up, ease of maintenance and low capital cost. Present review explains briefly about mechanical properties and microstructure between aluminum alloys and other materials like steel, magnesium, and copper.***

I. INTRODUCTION

The rapid development of lightweight metals like aluminium alloys in automotive industries to reduce fuel consumption and CO_2 exhaust gas. Due to the higher material expense and lower absolute strength of aluminium alloys, steels are used as structural components widely. Formation of breakable intermetallic compound with interface results make steel and aluminium alloy not reliable for fusion welding, which leads to welds with minimum amount of strengths. Currently, friction stir welding is the only solid state technique to achieve high strength welds between steels and aluminium. A new kind of a friction stir spot welding enable the spot welding process and is developed by Kawasaki heavy industry and Mazda Motor Corporation. It is used for body parts of transportation systems which are made of aluminium sheets. FSSW has application for joining dissimilar metals such as steel and aluminium alloys.

For spot welding based application, FSSW is an alternative of the FSW process. A non-consumable rotary tool is plunged into the work pieces to be joined for a predicted time (dwell period). Then the rotating tool is tack back from the weld joint forms the FSSW (friction stir spot weld). At the time of FSSW dwell period and tool penetration, the mechanical properties of weld joint material such as plasticization around the pin and heat generation is figure out fundamentally [1]. A schematic of the FSSW technique is shown in figure.1.

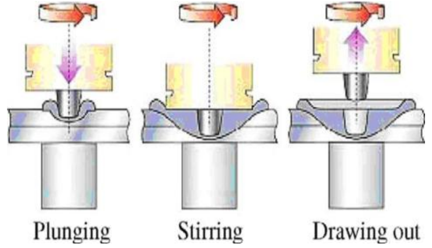

Fig. 1: Schematic of Friction Stir Spot Welding process

Both FSW and FSSW tools are similar one [3]. Inthe figure, the shoulder produces bulk of the deformational or frictional heat and pin helps for material course between the work piece [2]. The dwell period decides the tool rotation speed and tool plunge depth parameters involved in the FSSW. These parameters figure out the surface finish and strength of the welded joints. Various microstructural regions existing after the FSSW is mandatory to define exactly. The parent material is not been deformed and remote from the welded region. The weld parent materials experience some thermal cycling in mechanical properties or microstructure. Heat affected zone (HAZ) is the region nearer to the weld center influenced by the thermal cycle, after that this region will be modified as a mechanical property or microstructure without plastic deformation. But in thermo mechanically affected zone (TMAZ), the tool plastically deforms the material without crystallization. There is a specific boundary between the TMAZ and crystalline zone. The stir zone is an entirely recrystallized region in the instantaneous vicinity of the tool pin. Inside the stir zone, the grains are approximately equal-axed and frequently smaller magnitude than parent materials contains grains. In a lap configuration, hook is a characteristic feature of FSSW. In the interface of the two weld sheets, the generation of a geometrical defect can be identified. The present review paper targets on explaining the ongoing works of dissimilar materials of FSSW and recommends developing FSSW industrially.

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

A. FSSW between Aluminium Alloys

Over the years a lot of researches on friction stir spot welding are ongoing among the alloys based on aluminium. Uematsu et. al implemented double acting tool to join the T4 treated 6061 [5]. The double acting tool contain an inner retractable probe and outer flat shoulder which can be able to refill the probe hole. The weld zones microstructure were divided into sinle zone (SZ) and mixed zone (MZ). Because of the dynamic recrystallization, fine equiaxed grains were observed at the time of the FSSW process. The effective cross-sectional area increases by the refilling process and improved the target tensile strength of the joint.

Merzoug et. al studied AA6060-T5 by the rotational speed of the tool in the range of 1000-2000 rpm and tool steel of the type X210 CR 12 [2].

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Good quality welding was obtained by the tensile test to produce the sample at 1000 rpm and 16 mm/min comparing to 1.98KN for 2000 rpm and 25 mm/min and has 5kN to 16 mm/min. The micro hardness proceeds to the highest value based on the position from the nugget zone.

Zhang et. al experimented welds in the range of 1mm thickness spot welded between 5052-H1112 alloys. After the welding process, softening exists finally in the welds. In HAZ, a minimum amount of hardness was 19.2 HV. Because of the recrystallization, SZ and TMAZ hardness developed which results in the hardness distribution in the W shaped appearance. If tool rotational speed increases, joint strength will decreases which are independent of tool dwell time [6].

Shen et. al investigated on 2 mm thickness of AA 7075-T6 plates with different dwell time and rotational speed, that is 2000, 1750, 1500 rpm and 5, 4, 3 seconds. In this analysis, mechanical properties and microstructure were studied and refilled welds keyhole. The weld microstructure provides grain size variation in the direction of thickness and width. The defects combined with the material flow like voids, incomplete refill, hook and bonding ligament were noticed [7]. In the microscopic level, hardness of the weld and comprehensive effects in the W-shaped appearance make the changes in hardness. In this work, high-speed steel tool ((JIS, SKD61) were used to join 2mm thickness of 6061-T4 aluminium alloy sheets with 10 mm shoulder diameter combined with the concave profile. A required joint formation was attained at the longer duration and higher temperature.

The microstructures of the weld have four regions such as TMAZ, SZ, HAZ and BM. In weld dissolution, precipitates and dynamic recrystallization exist. Hook geometry will differ significantly on the dwell time and rotational speed. Effect of the weld is based on the increase of the dwell time and rotational speed [8]. The appearance of the hook was associated with the insufficient pressure vertical tool. Vickers hardness of the sheet represents an inverted V-shaped form. The least amount of hardness reaches 46.7 HV in the periphery of the TMAZ and HAZ. The various changes of Vickers hardness in every section of weld were associated with the wide-ranging effect of changes in grain sizes, dissolution of strengthening phases, strain-hardening. The shear strength increases with the increasing rotational speed. The tool rotational speed is used to determine the shear strength.

Tozaki, et. al used various probe lengths of 2.4, 3.1and 3.7 mm with a shoulder diameter of 10 mm to join the AA6061-T4 sheets with the thickness of 2 mm [9]. The probes were made of standard metric M3.5 left-hand thread and high-speed steel. A fixed tool plunge speed of 20mm/min and a 0.2mm shoulder plunge depth was applied below the upper plate surface. Then tool holding times and tool rotational speeds were speckled to 3000, 2500and 2000 rpm with 3, 1 and 0.2s. The weld microstructures were changed based on the tool rotational speed, probe length as the tensile shear strength improved on increasing tool holding time and probe length.

Badarinarayan, et. al joined two different thickness of 1.24 and 1.64mm of annealed AA 5083 sheets [5]. Pin length was 1.6mm and with a concave profile tool and shoulder diameter was 12mm. The two various pin geometries used are triangular pin and conventional cylindrical. The tool pin geometry automatically influenced the hook and hook runs constantly upward and points downwards towards the welded bottom and bypasses the stir zone in the FSSW. The hook is assisted upward towards the stir zone and concludes with a very short plateau.

Wang and Lee joined the 1mm thickness of AA6061-T6 sheets [10]. The experimental observation was that the failure propagates through the circumference of the nugget to final fracture and the failure started near the center part of the nugget SZ under lap shear loading condition. The position of the creation of shear failure is closer to the achievable unique notch tip and failure of the FSSW was cracked through the TMAZ closer to weld nugget. Also the hardness primarily decreases on processing the boundary among the HAZ and base metal, then drops sharply to a minimum in TMAZ. After passing the TMAZ, the hardness gradually increases regularly to SZ.

Buffa, et. al joined the 1.5mm thickness of the AA6082-T6 aluminium alloy with H13 tool steel quench at OC characterized by 52 HRC hardness with shoulder diameter 15 mm, 400 conical pin with minor diameter of 2.2mm,7mm as major diameter and pin height 2.6mm [11]. The different FSSW approach create welds successfully.

Wang, et. al welded thickness in 300μm of commercially pure AA1050-H18 sheets [12]. The experimental results show that the failures propagate through the boundary of the nugget to final fracture and when applying lap shear loading condition, the nugget failure started in the middle part near the SZ. The position of beginning shear failure was closer to the achievable original notch tip along with the failure of the friction stir spot welds closer to the weld nugget through the TMAZ.

Yuan, et. al, used two tools machined from Densimet tungsten alloy, OC (off center tools) and CP (conventional tool) to produce welds to join the AA6016-T4 sheets in the thickness of 1mm [13]. The CP tool was with long step spiral pin with 1.5mm, 3mm tip diameter, 4.5mm root diameter and 10mm center pin with concave shoulder. The OC tool was equipped with the same diameter and concave shoulder. Hemispherical pin features have 0.8mm long. The lap shear separation tools were influenced by plunge depth and rotation speed. Each tool maximum weld separation load was around 3.3KN at a shoulder penetration depth of 0.2mm with rotational speeds of 2500 rpm for OC tool and 1500 rpm for CP tool.

Jeon, et. al , joined 6061-T6 and 5052-H32 aluminium sheets with the thickness of 3mm [14]. At the time of the FSSW approach, the torque hysteresis and Z-force hysteresis as a function of the tool displacement vary significantly. Based on the influencing phenomena among the joined sheets and tool, the torque hysteresis and force at the time of the FSSW approach differentiate by various stages.

Depend upon a combination of selected materials z- force hysteresis shapes vary but torque-force shape doesn't change. The various mechanical behavior of aluminium alloys at different high temperatures explain the changes in Z force hysteresis for the various material combination.

Gibson and Thoppul produced spot welds through the AA6111-T4 sheets [15]. The microstructural studies reveal that increasing the processing time increases the bonding area between the lap joints and tool depth of penetration. Su, et. al analyzed the FSSW of 5754 and 6111 sheets with and without dwell period of the smooth pin to spot welds using a threaded tool [16]. The threaded tool is not influenced by the dwell period. There was no dissimilar intermixing on spot welds using a tool with a smooth pin irrespective of dwell period. The dissimilar intermixing at the time of the dwell period in spot welding results from the incorporation of lower and higher sheet materials on the rotating pin.

Babu, et. al, joined thickness in 3mm, thickness of AA2014 and T6 conditions without Alclad and with layers to analyze the welding process parameters of joint formation and effects of tool geometry [17]. A good correlation between bond width, joint strength, process parameters and hook height were studied. The base metal temper state has no key consequence on the joint strength, joint formation and appearance of Alclad layers.

Pathak, et. al, welded AA5754 sheets with a tapered and circular pin tool recognizing plunge depths, dwell time and various tool rotational speeds. The systematic profile has been observed closer to the sheet tool interface at the time of spot welding tools by means of tapered and circular pin on various rotational speeds. The temperature increases and reaches peak with an increased dwell time and tool rotational speed. Also, the tool structure influences the temperature allocation under similar condition as circular pin tool produced further amount of heat than a tapered pin tool. The lap shear test with welded samples represents dwell time, plunge depth and influence of tool rotational speed. Investigation of both tools reveals that the increase in parameters increases with increase in lap shear load [18].

B. FSSW between Aluminium and Magnesium

In aerospace and automotive industry magnesium and aluminium welded by FSSW are used widely. Suhddin, et. al, welded the aluminium alloy AA5754 to magnesium alloy AZ31. The grain structure growth in stir zone was influenced with dynamic recrystallization, internal diffusion and grain boundary diffusion, that leads to $Al_{12}Mg_{17}$ equiaxed grains in weld center and the hardness contour exhibited W-shaped presence of the Mg/Mg similar weld. Lesser hardness value was reported in the HAZ of both Al/Al similar welds, Mg/Mg and TMAZ. A distinctive interfacing coating consists of intermetallic compounds Al_3Mg_2 and $Al_{12}Mg_{17}$ was detected in the dissimilar weld of Mg/Al. Both the Al/Al and Mg/Mg similar welds had significantly higher fatigue life, failure energy and lap shear strength [19]. The Al/Al welds have lower lap shear strength than Mg/Mg weld.

Chowdhury, et. al welded 2mm depth of commercial AA5754 and AZ31B-H24 Mg using FSSW method. The tool made from the scrolled shoulder with 13mm of diameter and H13 steel and 5mm of left hand threaded pin, tool plunge rate of 3mm/s, the tool removal rate of 15mm/s, shoulder plunge depth of 0.2mm, the rotational rate of 2000 rpm and dwell time of 2s was continued on intermetallic compounds like Al3Mg2 and Al12Mg17. Micro hardness of weld exhibit w shape and hardness slowly augmented towards the keyhole track [20].

Chowdhury, et. al Analyzed 2mm thickness of commercial AA5754-O Al and AZ31B-H24 Mg alloy sheets and identified the particular interfacial layer of Al3Mg2 and Al12Mg17 intermetallic compounds in the FSSW of Mg/Al and Al/Mg dissimilar adhesive joints. In dissimilar adhesive joints, the degree of formation of intermetallic compounds reduced. Higher hardness inside the range of HV90 and mg/al and 125 of Al/Mg adhesive welds at stir zone is by the intermetallic compound layer. The Al/Mg and Mg/Al adhesive welds had higher failure energy and lap hear the strength than the al/mg without adhesive dissimilar welds[21].

Choi, et. al, welded AZ31 Mg alloy and 6k21 Al alloy with an FSSW tool with a shank and pin and shoulder made of common tool steel (SKD11), pin height, the shoulder diameter, weld tilt angle were 0, 0.5mm, 9.5mm, and 13.5 mm respectively. The generation of intermetallic compounds was seen at the boundary between Mg and Al alloy joints. The width of intermetallic compounds coating increases duration time results and tool rotational speed in major effect on joints strength. Significant width of IMCs coating at joints deteriorate the mechanical properties. Mg and Al alloy's maximum shear fracture load was around 1.6KN, increasing of tool rotation time and speed with a decrease in the load value which leads to cracks of intermetallic compounds [20].

C. FSSW between Aluminium and steel

Chen, et. al, Joined 1mm in thickness of DC04 and 6111-T4 low carbon steel sheet with steel shoulder in diameter of 11mm, 3mm diameter WC 1mm long probe, a scroll profile to improve the tapered and material flow[23]. The radius of the probes orbital path was 2.5 mm with a swept area of 8 mm diameter on the steel surface. Within a weld time of 1-second high-quality FSW between steel and thin Al automotive sheet was produced, the target time is preferred by industries.

Sun, et. al, applied concave - shaped shoulder geometry tool with a diameter of 12 mm, 4mm diameter of the probe,1mm thick commercial 6061 Al alloy and mild steel for an Fssw, results from no IMC coating on the Al/Fe boundary. The shear tensile failure load attained at a maximum of 3607N. The pin length has a minimum amount of effect on the weld properties and FSSW technique to tool life can be extended.

Bozzi, et. al, joined 1.2mm thickness of AA6016 to a thickness in 2.0mm of galvanized IF-steel sheet with a tool of W25Re(tungsten rhenium alloy).

The IMC layers with increase with penetration depth and rotational speed. Figner, et. al, joined thickness in 1mm of HX340 LAD sheets of steel and 2mm thickness of AA5754-H111 by FSSW method. By increasing the IMC phases, dwell time and breaks off in turns of reduces the strength to the maximum load of 8.4 kN per spot was experienced in the shear tension test [26]. Upcoming study needed to optimize the progression of FSSW involving steel and aluminium commercially.

D. FSSW between Aluminium and Copper

Nowadays a lot of researches are going on in the FSSW between copper and aluminium. Heideman, et. al and Ozdemir, et. al did FSSW on thickness in 3mm of AA1050 to pure copper and thickness in 1.5mm of AA6061-T6 oxygen-free copper correspondingly [27,28]. More analysis has to be conducted to optimize the approach to facilitate FSSW as a substitute to RSW and riveting.

Ozdemir, et. al created FSSW with three dissimilar plunge pits of 5mm,4mm and 2.8mm, 5mm in diameter of pin, with a tool 20mm in shoulder diameter. The spot weld was produced using 10 seconds as hold time and 1600 rpm as rotation speed [27]. No macroscopic imperfection in the spot welds and the grain were exceptional on the copper side closer to the Cu/Al interface than copper base metal. The difference in grain size credited to the effect of the heat results and rotating pin in recrystallization of grains within the stir zone of the copper metal. The EDS evaluation uncovered the improvement of brittle and hard intermetallic compounds of Al4Cu9, Al2Cu, AlCu at the boundary. By the heat input of the rotating pin, Cu material hardness increased at pinholes lower section. Since the enhance of plunge depth decreases the grain size, Which leads to higher hardness at the Cu surface for the plunge depth of 5mm and selective penetration of Cu into Al for plunge depth of 5mm and more diffuse and Al side hardness values are improved.

Heideman, et. al, performed metallurgical investigation with FSSW on AA 6061-T6 to oxygen-free Cu [28]. The tool had a threaded pin with a pre hardened H13 tool steel with 10mm shoulder, pin diameter of 4mm, 0.7 mm thread pitch on plunge depths 0.13 and 0 mm with 6 and 3 seconds of weld period. The rotation speeds diverse from 1000 to 2000 rpm provides Cu ring with a vertical cross-section of the spot weld. The important factors disturbing the strength of the welds are tool length, rotation speed, plunge depth.

For strong friction stir spot welds, welding parameters and device geometry optimization are needed. consequently, it is important to carry out researches on the process parameter and optimization of the tool geometry for producing spot welds between the copper and aluminum by the way of Stir Spot Welding process to exploit commercialization of the technique.

III. CONCLUSION

Major studies and development of the FSSW procedure has been carried out worldwide and this procedure is viable as joining alternative for the aerospace industries. Further studies are suited to absolutely recognize and optimize the technique. It is observed that not much significance has been given on producing FSS welds among aluminium and copper which will be an alternative method to riveting and Resistance Spot Welding (RSW), considering that spot welding among aluminium and copper might be useful in making electric connections and machinery. Even though, the capability of FSSW to join light-weight, high power aluminium alloys to other substances include magnesium, copper and steel is applicable, extending this technique into high melting temperature substances showed difficulty because of tool value and device wear rates. It is predicted that if this method is carried out efficaciously, it can be a technical and economical development compared to the traditional welding tactics.

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