Journal of Current Research in Engineering and Science
Bi-Annual Online Journal (ISSN : 2581 - 611X)

Volume 5- Issue 1, Paper 37 January 2022

FRICTION STIR WELDING OF ALUMINIUM ALLOY PLATES USING CYLINDRICAL TOOL: A REVIEW

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ABSTRACT- **Aluminium alloys have significantly contributed to the lightweight and long-lasting constructions seen in high-precision applications (marine industry, aircraft industries). The most often used aluminium alloys in these industries are from 2000, 7000, and 6000 series. In aerospace, automotive, and other industrial sites Friction stir welding is used. The mechanical and metallurgical features of FSW aluminium alloys are promising. In the FSW process, rotational speed, welding speed, and tilt angle are most important parameters.FSW is a solid-state technique in which metal is not melted, and it is welded together using a cylindrical shouldered tool with a profiled pin that is rotated and progressively plunged into the weld joint between two metal plates or sheet sections. Frictional heat is created between the tool and the material, causing the work pieces to soften below the melting point and then intermix both metals at the joint. Due to the high temperature, further softened metal is joined by mechanical pressure applied by the tool. A high-quality weld is produced since the temperature is below the melting point and the joining is below the material's melting temperature.**

Keywords: **Friction stir welding, aluminium alloys, tool types**

I. INTRODUCTION

W Thomas and his colleagues at the Welding Institute (T.W.I.) discovered friction stir welding (FSW) in 1991 [1]. It is a solid-state joining process. There are no toxic gases or flames formed during the welding process, making it a sort of green welding. The revolving spindle, moving bed, and control system are the three primary components of the FSW machine. This is the most energy-efficient welding method for welding aluminium alloys and other ferrous and nonferrous metals. FSW is a type of friction welding that involves bonding metals without the need for fusion or filler materials. **Figure 1** shows a layout of the friction stir welding process. However, FSW technology has caught the interest of the aerospace and transportation sectors. Few systematic research on process parameter optimization has been published [2]. Ravindra and Surya [3] studied the effect of pin profiles and the process parameters on AA5083 weld joints. Here they use five different tool pin profiles such as straight cylindrical, tapered cylindrical, triangular, square and cone. FSW involves rotating and plunging a cylindrical shouldered tool with a profiled pin into the joint region between two plates. Friction Stir welding is a solid-state joining procedure in which the materials are bonded without reaching the melting point due to the heat created by the tool's rotation. Plasticized material is applied to the tool pin's trailing edge and forged along with the tool shoulder and pin [4]. Aluminium is used in various applications, from food packaging foil to aerospace and shipbuilding [5].

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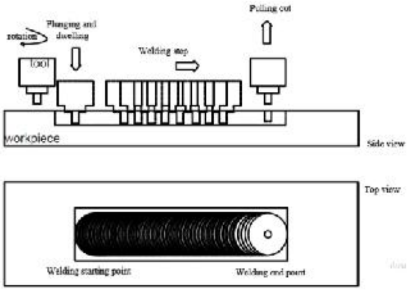

Fig 1: schematic of these three zones

Aluminium and its alloys have several benefits, including a high strength-to-weight ratio and superior corrosion resistance [6]. The tool is made up of a pin, and a shoulder rotates at a high rpm and is designed to plunge into the work piece and move at a set rate to complete the welding process. Tool rotational speed, welding speed, axial force, and pin-free weld connection in FSW are explained in [7] [8]. Flaws such as voids, hooks, onion rings, and tunnel defects may develop if these parameters are not properly selected and maintained. In addition, the tool may be damaged if the speed range, welding speed, and axial force are improper. During the FSW process, three distinct zones emerge, according to Russell (Russell, 2000) [9]: a Heat Affected Zone (H.A.Z.), a Thermo-mechanically Affected Zone (TMAZ), and a Weld Nugget Zone (W.N.Z.).The TMAZ has the less plastic strain and is a tiny area with a deformed grain structure around the W.N.Z. In the FSW process, the H.A.Z. is the weakest zone. These three zones are shown in Figure 2.

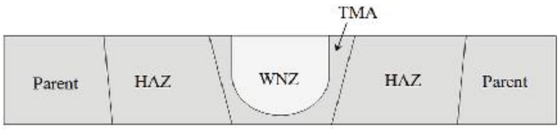

Fig 2: schematic of these three zones

II. METHODOLOGY OF FSW PROCESS

A cylindrical-shouldered tool with a profiled threaded/unthreaded pin is rotated at a constant speed and fed into the joint line between two pieces of plate material that are butted together in this process. The pieces must be secured tightly to a backing bar so that the abutting joint faces are not driven apart. The pin should be shorter than the desired weld depth, and the tool shoulder should have close contact with the work piece surface. After that, the pin is pushed against the work piece or vice versa. Frictional heat is created between the work piece material and the wear-resistant welding tool shoulder and pin. The weld joints will be cut with a power hacksaw and then machined to the desired dimensions. The test specimens should be prepared according to the American Society for Testing of Materials (ASTM E8M04) criteria.

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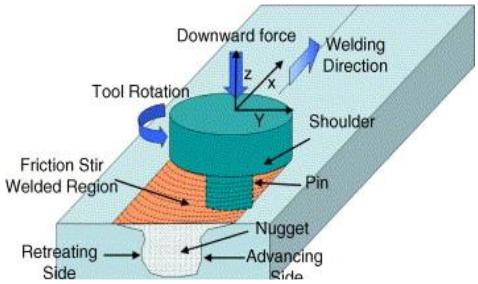

Fig 3: schematic of friction stir welding process

III. TYPES OF ALUMINIUM ALLOYS FOR THE FSW PROCESS

International standards are used to classify aluminium alloys. A four-digit number, followed by a temper designation code, distinguishes these alloys. The first digit represents the primary alloying ingredient. The seconddigit represents variations of the primary alloy. The third and fourth numbers represent individual alloy differences. Finally, the temper identification code relates to various methods of strengthening.The high alloy 2xxx, 6xxx, and 7xxx series are wide use of welding for joining aerospace structures.Thomas et al. [10] investigated the microstructure, hardness and tensile strength of aluminium alloys Al Mg4.5Mn0.7 (AA5083) and AlZn6Mg2Cu (AA7075). During hot working process microstructures of aluminium alloys are similar and the hardness is varied in alloy AA5083. The mechanical properties of welded AA5083 and AA7075 6.0 mm alloys are as high as 100% and 72% respectively compared with base material.Benavides et al. [11] investigated a study on low temperature FSW of aluminium 2024 and studied super plastic impairment using active reformation of superfine equiaxed grains. At low temperature, the hardness and the equiaxed grains are developed after the solidification process. The effect of heat affected zone is recorded during the welding process. Priya et al. [12] studied the microstructure and metallurgical properties of AA6061 and it is observed that hardness is increased in weld nugget and the hardness is not improved in HAZ (Heat Affected Zone).Because of the poor solidification microstructure and fusion welding processes difficulties such as distortion, porosity, solidification, liquation, cracking, these aluminium alloys are precipitation hardenable and categorized as non-weldable. Simultaneously, they were using the FSW to avoid these types of problems. The 3XXX, 5XXX families of non-precipitation-hardenable A.L. alloys are the most widely employed in aerospace applications.

A) 2XXX series Al alloy

M Milcic et al. [13] studied the results of structural and mechanical testing of the alloyed aluminum alloys AA 2024 welded by the FSW process. The main two parameters such as rotational speed and welding speed influence the fsw of EN AW-2024 T351 a aluminium alloy. From the experiment they concluded that the relation between the number of revolutions of tools n velocity of welding v directly influences the value of the fracture toughness and energy which is required for initiation and propagation of the crack.Three samples are welded that are A-I, B-II, C-III. This investigation points out that weld joint B-II (welded by 750/116 rpm/(mm/min)) achieves better properties and microstructure than weld joint A-I and C-III (welded by 750/73 and 750/150 rpm/(mm/min)).

B) 6xxx series Al alloy

Ch Mohana Rao and Dr. K Mallikarjuna Rao carried out the experiment on aluminium 6061 alloy plate. The plate size of Al 6061 having 100mm length, 70mm width and 4mm thicknessand H13 tool is used. The tool is having cylindrical tapered shoulder and pin. The parameter used were Rotational Speed 710, 900, 1000, 1120 Rpm; Transverse speed 28, 35, 40, 60 mm/min; Offset 2, 2, 2, 2 Mm; Plunge depth 3, 3, 3, 3Mm.the result points that Friction Stir Welding is most suitable joining

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technique for similar aluminium alloy. Compared to the traditional fusion welding, FSW exhibits a considerable improvement in strength and ductility.

C) 7xxx series Al alloys

According to Andrzej Kubit et al. [14], the experiments in this study aim to identify the effect of welding settings on joint load capacity and analyse flaws in welded single-lap joints obtained by their fill friction stir spot welding method. The influence of welding settings on the tensile strength and fracture mechanism of joints subjected to tensile/pure shear loading is also investigated. Two 7075-T6 aluminium alloy sheets with varying thicknesses are used to make the overlapping friction stir spot welded joints (1.6 and 0.8 mm). Optical microscopy and scanning electron microscopy were used to assess joint quality. Tensile/pure shear loading tests are used to measure the load capability of joints. Microstructural research revealed that the length of welding and tool plunge depth is the most critical factors impacting the quality of the joints. Three forms of joint injury were identified depending on the tool plunge depth. The tests show that poor welding process parameter selection leads to defects such as voids, hooks, onion rings, and bonding ligaments.

D) Dissimilar alloys

S Ravikumar and colleagues [15] Al alloys are widely used to construct lightweight constructions with a high strength-to-weight ratio and superior corrosion resistance. T.W.I. invented FSW, a new solid-state joining technique in which the welded material does not melt and is recast. Various process factors such as tool rotating speed, tool welding speed, and tool pin profile were used to explore the dissimilar friction stir weldability of 7075-T651 and 6061-T651 aluminium alloys. The investigation included micro and macrostructure analysis, scanning electron microscopy (S.E.M.), and energy dispersive spectroscopy. Both materials have been stretched and artificially aged using a solution heat-treatment process. The workpiece's dimensions are 100mm*50mm*6.35mm, and the rotating speed, welding speed, axial force parameters were chosen for the experiment. According to the optical and S.E.M. images, the tensile strength increases at first reaches a maximum value and subsequently drops as the rotating speed increases. When it relates to welding speed, a higher welding speed enhances tensile strength to a certain point, but a higher welding speed results in a lower tensile strength. The tensile strength of the dissimilar joint created using the T.C.T. tool is maximal. In taper profile, speed 900, and welding speed 100mm/min, the maximum is 205.23MPa. Because of the poor integration of the two plates, the taper drops to 178.01MPa. The elements of 7075 and 6061 are present at the nugget zone for three combinations that give better strength, according to the EDAX research. Compared to other tools, the taper tool exhibits an excellent tensile strength of 205.23MPa.

IV. DIFFERENT ALUMINIUM ALLOYS WITH CYLINDRICAL TOOL

A) A6005-T5

Weon-Kyong Kim et al.[16] investigated how aluminium 6005-T5 alloy plates, which are used to make the floor, roof, and wall panels of railway carriages, were welded in FSW using a cylindrical tool. The tensile strength of the welded junction increased as the welding speed increased. However, the fatigue strength of the welded joint dropped.

B) 7075-T6 aluminium alloy

Andrzej Kubit et al.[17] The weld quality of the 7075-T6aluminium alloy plates of different thicknesses (1.6 mm and 0.8 mm) was assessed using an optical microscope and a scanning electron microscope as alap joint. The welding procedure was tested for various parameters, including rotational tool speed, welding duration, and tool plunge depth. The spindle speed n was changed between 2000 and 2800 rpm, the welding time t between 1.5and 3.5 seconds, and the tool plunge depth g between 1.5 and 1.9 mm. Zwick/Roell Z100 tensile machine was used to conduct the testing. The N.Z.produced a defect-free and fine-grained microstructure, and the finer MgZn2particles in the N.Z. contributed to the joint's strength.

C) AA7075-T6 aluminium alloy

S. Rajakumar et al. [18] found that tensile/pure shear loading tests calculated the strength capacity of the weld joint. The microstructural study clearly showed the quality of joint-related to the tool plunge depth. Also, the alloy was welded as a square butt joint using the 15 shoulder diameter, 5 mm pin diameter, and 45 H.R.C. tools. The best results were obtained at the rotational tool speed of 1400 rpm, welding speed of 60 mm/min, and an axial force of 8 K.N., and they were yield strength of 315 MPa, the tensile strength of 373 MPa, hardness of 203 HV and a joint efficiency of 77%.

D) 6061 Al sheet

Yufeng Sun et al. [19] investigated the microstructure and mechanical properties of three 6061-T6 Al sheets with a flat FSSW dimension of100mml30mmw1mmt. The pre-drilled spherical dent on the backplates measured 8 mmin diameter and 1.5 mm in depth. In step 1, a cylinder rotating tool with a shoulder diameter of 12 mm, a probe diameter of 4 mm, and a probe length of 1.8 mm was employed. Due to the retraction of the spinning tool after step 1, a keyhole formed on the top sheet, which is a common feature of the FSSW joint. Step 2 involved filling the keyhole and removing the swell with a flat rotating tool with a diameter of 15 mm and a standard backplate with a smooth surface. Both step 1 and step 2 of the welding processes used an applied load of 500 to1000 kg, a rotating speed of 500 to 700 rpm, and a constant welding time of 2seconds. For the flat FSSW of three sheets of 6061-T6 Al alloy, the optimal welding parameters were 700kg/550rpm/2 S in step 1 and 1000kg/600rpm/2s in step 2. Compared to the FSSW of the two sheets, the cross-sectional after step 2 revealed that a different interface was inserted into the joints. The keyhole and bump in the first junction were successfully eliminated, and the top and bottom surfaces of the remaining three sheet FSWjoints were smooth. Different test settings revealed different failure scenarios for the joints. The joints ruptured through plug-type failure modes in type I and typed III, respectively, with 6438 N and 4450 N fracture loads. The joints fractured in type II mode due to middle sheet necking, with a fracture load of roughly 6307 N.

E) AA7075-T651and AA6061

The influence of FSW tool parameters on the tensile qualities of the friction stir welded AA7075-T651, and K.P. reports AA 6061 butt joint.Yuvaraj et al. [20]. For welding the plate with a thickness of 6 mm, the FSWtool was built of high-speed steel (H.S.S.) and had a pin profile of a straight cylindrical (S.C.) without a draught, a shoulder diameter of 20, and a pin length of 6 mm. Based on the literature survey results, many trial runs were conducted utilizing varying parameters. As a result, many junctions with good bonding between incompatible materials were achieved (Elatharasan and Senthil Kumar,2012) [21]. Based on preliminary studies, tool pin diameter, tilt angle, and offset were identified as independent process parameters impacting ultimate tensile strength (U.T.S.). Using data from the literature survey, the tool spin speed and welding speed are kept constant in this study. After they evaluated the FSW process parameters, the best values of the process parameters were 6 mm for the tool pin diameter, 0.9 mm for tool offset, and 3 degrees for tool tilt angle. The tensile fractured surface with ductile failure can be seen in the S.E.M. analysis thanks to the dimples accumulated in that area. At the ideal level, the average tensile strength was 241.566 N/mm2.

TABLE 1. Summary of major findings from FSW of different aluminium alloys using a cylindrical tool

No	Material	Tool pin profile	Major findings
1	AA 6005-T5	Cylindrical [16]	The tensile strength of the weld joint increases and its fatigue strength decreases with an increase in welding speed [16]
2	AA 6061-T6	Cylindrical [19]	Square pin gives finer grains in the nugget zone; the nugget/stirred zone has higher strength compared with HAZ and TMAZ because of the formation of smaller grain size at this zone due to stirring of the tool;
1	AA 7055	Cylindrical [22]	Water assisted cooling gives better strength [29]
2	AA 7075-T6 and AA 6061-T6 (Dissimilar weld)	Cylindrical [17] [23]; tapered cylindrical [24]	Tool offset increases the tensile strength due to a good flow of AA7075-T651 material on the retreating side to AA6061 on the advancing side; good mixing of material in the weld nugget zone; The material mixing is much more effective when AA6061alloy is located on the advancing side [17]; dynamic recrystallization and grain size in both alloys decrease significantly with the increase of welding speed [23]; taper cylindrical tool exhibits good tensile strength [24];
3	AA 7075-T6	Cylindrical [25][26]	Defects like a tunnel, kissing bond, zig-zag occur [25]; important parameters affecting the quality of the joint are the duration of welding time and tool plunge depth [26]
4	AA 6082-T6 and AA 7075-T6 (Dissimilar weld)	Cylindrical [28]	AA7075 alloy being placed on the advancing side increases welding heat generation, peak temperature and degree of material mixing [28]
5	AA 7050 and AA6061 (Dissimilar weld)	cylindrical [27]	Material intermixing and joint strength increase with the increase in tool rotational speed [27]
6	AA 7075 and AA 2024 (Dissimilar weld)	Cylindrical [29]	UTS, YS and percentage elongation increase with the increase in velocity ratio (tool rotational speed/tool traverse speed) [29]

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7	AA 5052	Cylindrical tapered [30];	Tool tilt angle has a significant role in determining the tensile strength of the weld joint [30]
8	AA 7050 and AA 7075 (Dissimilar weld)	Cylindrical tool [31]	Tensile and yield strengths of weld joint increased with a decrease in plate thickness due to faster work piece cooling rate and higher tool travel speed [31]

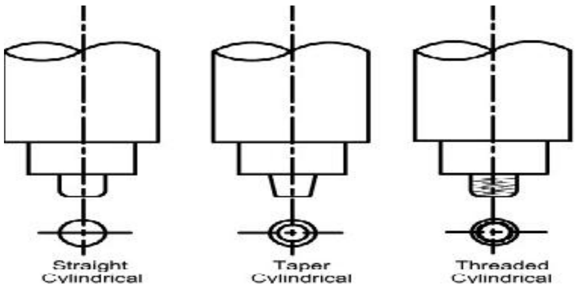

Fig 4: Different cylindrical tool profiles used (a) straight cylindrical (b) tapered cylindrical (c) threaded cylindrical [33]

V. MICROSTRUCTUREAND TENSILE PROPERTIES OF ALUMINIUM ALLOY PLATES WITH CYLINDRICAL PIN TOOL

V. Balasubramanian et al. [32] studied the microstructure and tensile properties of friction stir welded dissimilar AA6061-AA5086 by three different tool pin profiles are straight, taper, and threaded cylindrical. Using the optical and scanning electron microscope, they analysed the various regions of microstructures. This study found that the threaded pin profile gives a better flow of materials between two alloys, generation of defect-free stir zone (S.Z.), higher hardness value, and higher tensile strength than using the other two cylindrical tool pin profiles. However, the heat generation is almost the same for the three tool pin profile. It is well known that 2/3 of heat generation is caused by mechanical friction between tool shoulder and plate to be joined, and 1/3 of heat generation is caused by pin profile using deformation, including heat generation. Under this condition, the straight cylindrical pin yielded a defective joint, but the tapered and threaded cylindrical pins yielded defect-free joints. This may be due to the improper flow of plasticized material around the tool pin during stirring. This suggests that the deformation included heat generation (by the pin) is marginally insufficient compared to other pin profiles. This investigation found that the straight cylindrical pin is not preferable to welding the different grades of aluminium alloys, especially AA6061with AA5086. Formation of finer and uniformly distributed precipitates, circular onion rings, and smaller grain are the reasons for superior performance of joints fabricated by threaded pin profiled tool compared to tapered pin profiled tool—the threaded pin tool's interface microstructures of advancing side mild thickness region and pin influenced region.

VI. CONCLUSION

Friction stir welding is a new metal joining process manufacturing technique, particularly for aluminium alloys. Many research projects on aluminium alloys have been discovered. Furthermore, not only will aluminium and aluminium-based alloys be valued by many engineering industries, but so will mild steel and its alloys. This study emphasizes the fundamentals of FSW and critical elements that influence weld quality and the essential function of cylindrical tools.

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