A Review on Friction Stir Welding of Aluminium Alloys

[1]Anton SavioLewise K, [2]Edwin Raja Dhas J

[1]Department of Aeronautical Engineering, Noorul Islam University, Thuckalay, 629180, Tamil Nadu
[2]Department of Automobile Engineering, Noorul Islam University, Thuckalay, 629180, Tamil Nadu
Email: kaslewise@gmail.com

[Received:1st Sept.2017; Accepted: 30th Sept.2017]

Abstract--The comprehensive body of knowledge that has built up with respect to the friction stir welding (FSW) of aluminium alloys since the technique was invented in 1990's, enables us to weld aluminum alloys and titanium alloys etc. The processing of FSW, the microstructure in FSW alloys and the factors influencing weld quality are introduced. Aluminium Alloy one of the major raw material used in these industries due to its high strength in low temperature, corrosion resistance etc. The complex factors affecting the properties are investigated. The basic principles of FSW are described, including effect of temperature and speed of the tool during friction stir welding. This paper gives a detailed review about Friction Stir welding of Aluminium alloys. A detailed review about Friction stir welding of Aluminium alloys has not been done before in this manner.

Keywords: friction stir welding, Aluminium Alloy, microstructure

I. INTRODUCTION

The friction stir welding (FSW) process is commonly accepted as a promising method for joining light metallic alloys. However, the extended application of this welding process in industry still requires accurate knowledge of the joining mechanism, and the metallurgical and mechanical transformations are induced in the base materials. This knowledge will then allow the establishment of suitable welding parameters for joining a large range of materials in varied weld configurations, such as different plate thicknesses or joint types. Another important aspect is to guarantee improved levels of welding productivity[1]. Since the welding speed has a direct influence on the process productivity, in any welding operation in an industrial context, the objective behind the selection of suitable welding parameters has to be to maximise the welding speed while ensuring acceptable welding quality.

Although FSW technology has attracted significant interest from the aerospace and transportation industries, there are few reported systematic studies on process parameter optimisation[2]. Though numerical modelling of plastic flow in FSW has provided guidelines concerning tool design and weld quality optimisation[3], there does not appear to have been an application of these models towards the prediction of practical processing maps. The only principle globally accepted is that, for each set of welding conditions (joint type, base material and plate thickness), a specific set of welding parameters must be used to ensure acceptable process behaviour [4-5].

Friction stir welding is one of the latest welding techniques that has found a major part in automotive sector. Friction stir welding is a solid state joining technique invented and developed by The Welding Institute (TWI), UK. Firstly, Friction stir welding was used for welding Aluminium alloys. Later it found application in welding Magnesium, Copper alloys etc. Some materials such as Aluminium 2xxx series to 7xxx series which were considered non weldable are now possible with Friction stir welding [6].

In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two plates. For proper welding, the plates must be clamped during the process. Friction Stir welding is a solid state joining process and the heat generated during the rotation of the tool will cause the materials to get joined without reaching melting point. The plasticized material is transferred to the trailing edge of the tool pin, and is forged with the tool shoulder and pin [7].

ALUMINIUM ALLOYS

The last decades have seen increased use of aluminium as a structural material for building and architecture for various reasons such as its light weight which allows for easier rectification of structures , its good inherent corrosion resistance and methods for protection such as anodising allow for durable outdoor exposure; the good strength-to-weight ratio that can be obtained[8].The rolled plates of the RDE-40 aluminium alloy (Al-Zn-Mg) were cut into the required size by power hacksaw cutting and milling. A single 'V'butt-joint configuration was prepared to fabricate GTAW and GMAW joints. Single-passwelding was used to fabricate the joints. An AA5356 (Al-5%Mg) grade filler rod and wire were used for the GTAW and GMAW joints, respectively. High-purity (99.9%) argon gas was the shielding gas. The square butt-joint configuration was prepared to fabricate the FSW joints. A non-consumable, rotating tool made of high-carbon steel was used to fabricate the FSW joints. The smooth tensile specimens were prepared to evaluate the yield strength, tensile strength, elongation and reduction in the cross-sectional area[9].

II. FRICTION STIR WELDING PROCESS

Friction Stir Welding (FSW) is a simple process in which a rotating cylindrical tool with a shoulder and a profiled pin is plunged into the abutting plates to be joined and traversed along the line of the joint. A schematic of the friction stir welding process is shown in Fig. 1.

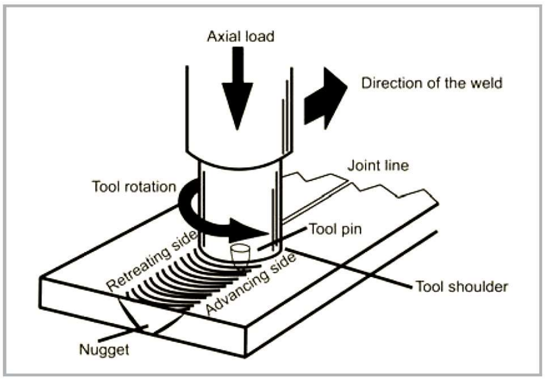

Fig 1. Schematic of the friction stir welding process

The plates are tightly clamped on to the bed of the FSW equipment to prevent them from coming apart during welding. A cylindrical tool rotating at high speed is slowly plunged into the plate material, until the shoulder of the tool touches the upper surface of the material. A downward force is applied to maintain the contact. Frictional heat, generated between the tool and the material, causes the plasticized material to get heated and softened, without reaching the melting point. The tool is then traversed along the joint line, until it reaches the end of the weld. As the tool is moved in the direction of welding, the leading edge of the tool forces the plasticized material, on either side of the butt line, to the back of the tool. In effect, the transferred material is forged by the intimate contact of the shoulder and the pin profile. It should be noted that, in order to achieve complete through-thickness welding, the length of the pin should be slightly less than the plate thickness, since only limited amount of deformation occurs below the pin. The tool is generally tilted by 2-4°, to facilitate better consolidation of the material in the weld. Upon reaching the end of the weld, the tool is withdrawn, while it is still being rotated. As the pin is withdrawn, it leaves a key hole at the end of the weld. This is the main disadvantage of FSW and few variants are being used to overcome this aspect[10].

DESIGN AND DEVELOPMENT OF TOOLS

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. It is desirable that the tool material is sufficiently strong, tough and hard wearing, at the welding temperature. Further, it should have good oxidation resistance and low thermal conductivity, to minimize heat loss and thermal damage to the machinery further up the drive train. Tool steels have been widely used for welding aluminium alloys within thickness ranges of 0.5 - 50 mm, but more advanced tool materials like Carbides, Polycrystalline Cubic Boron Nitride (PCBN) and tungsten rhenium (W-Re) alloys are necessary for more demanding applications such as highly abrasive metal matrix composites or higher melting point materials like steel or titanium. Improvements in tool design have been shown to bring about substantial improvements in productivity and quality [11]. Modifications in the design of the pins ensured, that the plastically deformed material is fully delivered around the pin, and from the upper parts of the joint to the lower parts. This results in efficient mixing and enables the use of higher speeds and results in better quality, void free welds. Tools with scrolled shoulders eliminated weld surface undercutting and the flash that extrudes under the tool shoulder.

MICROSTRUCTURE STUDIES

During friction stir welding, a variety of interactions occur amongst the tool, workpiece, backing plate and surrounding environment. These interactions affect the temperature distribution and material flow[12,13]. As a result of these complex interactions, the microstructure in and around the weld region are affected. This has resulted in the classification of friction stir welds, into four microstructurally distinct regions. According to Thread gill[14] the four regions are (i) Parent Material, (ii) Nugget, (iii) Heat Affected Zone (HAZ) and (iv) Thermomechanical Affected Zone. (TMAZ). All these regions are identified in Fig. 2, which shows the schematic of a typical cross-section of a friction stir weld. The parent material (or base material) is the region which does not undergo deformation and

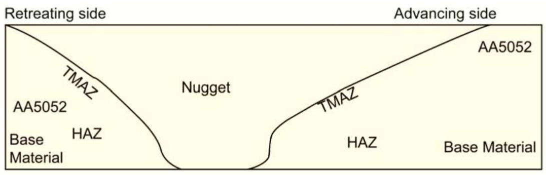

Fig 2. Schematic of the cross-section of the friction stir weld showing the various characteristic regions

The microstructure in this region is not affected by the heat produced during the process. No detectable changes are seen in the microstructure of this region. The nugget region is formed by the intense plastic deformation induced mainly by the tool pin and consists of fine recrystallized grains. Hence this zone is also referred to as ‘dynamically recrystallized zone’. The heat affected zone is the region which is affected only by heat and there is no plastic deformation. In this region, the microstructure and/or properties are modified by the thermal heat.

The thermomechanically affected zone surrounds the nugget and it experiences lower temperatures and less deformation, as compared to those in the nugget. In this region, the material is plastically deformed by the tool and is affected by the heat produced (both due to deformation and friction) during the process.Friction stir welding is regarded as an asymmetric process mainly due to the material flow being affected by the rotation and translational motions of the tool. This asymmetry is reflected in the shape of the nugget and to some extent on temperature distribution, on either side of the nugget. The side of the weld, where the local direction of the tool is the same as the traversing direction, is called the 'advancing side'. The other side, where the directions are opposite and the local movement of the shoulder is against the traversing direction, is called the 'retreating side' [15].

J. Adamowski and M. Szkodo investigated on the properties and microstructural changes in Friction StirWelds in the aluminum alloy 6082-T6 . As per their design and methodology, tensile strength of the produced joints was tested and the correlation with process parameter was assessed. They presented and analysed the Microstructures of various zones of FSW by means of optical microscopy and micro hardness measurements. Finally, they found Mechanical resistance of test welds increased with the increase of travel (welding) speed with constant rotational speed. They observed, softening of the material in weld nugget and heat affected zone of entity inferior than that of fusion welds and they found Origin of tunnel (worm hole) defects. Their test welds were produced with various combinations of process parameters without the possibility of controlling the downward force. They examined the further extension of applicable parameters in combinations [16]. Practically, the increase of mechanical resistance with increasing welding speed offers an immediate economic return, as the process efficiency is increased.

W. Gan et.al. tested and analysed the properties of friction stir welding of aluminium Alloys 6111 and 5083, such as joints with low porosity, fine microstructures, minimum phase transformation, and low oxidation compared with conventional welding techniques. They used certain combinations of FSW parameters to create FSWs of aluminium alloys 5083-H18 and 6111-T4, and they measured the physical weld defects. They used few of the friction stir welding behaviours like, tensile tests, hardness measurements and they correlated to the microstructures of the weld and base material. So they found, stir zones in the 5083 specimens were much softer than the strain-hardened base materials. SZs in the 6111 material are approximately as hard as the base material. From their analysis, they found, Natural aging of 6111 friction stir welding specimens occurred in some parts of the heat-affected zone and produced hardening for up to 12 weeks after welding[17]. Annealing of 5083 FSW specimens produced abnormal grain growth (AGG) for welds produced under certain welding conditions and in certain parts of the weld zone. And also they realised that AGG is more severe for low-heat conditions.

A. K. Lakshminarayanan et al. focused on the effect of welding processes on tensile properties of AA6061 aluminium alloy joints. Initially they investigated the effect of welding processes such as Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding(GMAW) and Friction Stir Welding (FSW) on mechanical properties of AA6061aluminium alloy. Then they found, GTAW and GMAW are the feasible welding methods for their requirements. Because of the prevailing thermal conditions during weld metal solidification, the weld fusion zones of AA6061 aluminium alloy typically exhibit coarse columnar grains. They have used rolled plates of 6 mm thickness as the base material for preparing single pass butt welded joints. Since the thickness of the plates is less and difficult to weld using more traditional fusion techniques. They have used filler metal for joining the plates of AA4043 [Al-5Si (wt%)] grade aluminium alloy [18]. In the present work, they have evaluated, tensile properties, micro hardness, microstructure and fracture surface morphology of the GMAW, GTAW and FSW joints and they compared the results. From this investigation, they found that FSW joints of AA6061 aluminium alloy showed superior mechanical properties compared with GTAW and GMAW joints, and this is mainly due to the formation of very fine, equiaxed microstructure in the weld zone.

D. M. Rodrigues et.al. have examined, the High speed friction stir welding of aluminium alloys. They have tested, the weldability of AA 5083-H111 (non-heat treatable) and AA 6082-T6 (heat treatable) aluminium alloys, which are widely used in welding fabrication, and are compared by analysing the welds obtained from both materials under a large range of welding conditions. That is, AA 5083-H111 supplied in plates of 4 and 6 mm thickness, and the AA 6082-T6 (heat treatable) aluminium alloy, supplied in plates of 3 and 6 mm thickness. They have evaluated the heterogeneity in mechanical properties across the welds with slight or no defects by performing hardness measurements transversely to the weld direction, using a Shimadzu micro hardness tester with 200 gf load for 15 s. Tensile tests were also performed, all of which were carried out at room temperature at a crosshead speed of 5 mm min^{-1} using an Instron computer controlled testing machine[2]. They found the differences in friction stir weldability, assessed by weld defect analysis and weld strength characterisation, will be related to the markedly different plastic behaviours of both base materials.

Indira Rani M. et al. experimented on process parameters of friction stir welded AA 6061 aluminium alloy in annealed and T6 condition. They used the latest technique in FSW, a non-consumable rotating welding tool to generate frictional heat and plastic deformation at the welding location while the material is in solid state. AA 6061 Aluminum Alloy plates (150mm X 75mm X 6.6mm) in the annealed and solutionized and aged conditions were chosen. Specially designed tool is used in the Friction stir welding. The material of the tool is H11 tool steel. A non-consumable high-speed steel tool is used for welding 6061 Al alloy having the shoulder diameter of 10 mm and the tool has a probe (tool pin). The tool has frustum shaped probe with threads. Probe diameter is varied from 5 mm to 3 mm. The diameter of the shoulder is 10 mm. So the tool design and material play a vital role in addition to the important parameters like tool rotational speed, welding speed and axial force. That is, the tool rotation speed 1000 rpm and welding speed 10 mm/min are the optimal parameters in ‘T6’ condition[19]. They focused on optimization of FSW parameters in different conditions of base material and the microstructures of the as-welded condition are compared with the post weld heat treated microstructures welded in annealed and T6 conditions.

H. Izadi et.al. investigated the tool geometry on material flow during friction stir welding of dissimilar aluminium alloys. Friction stir welding of dissimilar alloys Al 2024-T351 and Al 6061-T6 was conducted in both the lap weld and butt weld configurations. The tool rotation speed was maintained at 894 rev min-1, and both clockwise and counter clockwise directions were investigated while the travel speed was 88 mm min-1 during lap welding, and 33– 88 mm min-1 during butt welding. Lap welding was conducted with the Al 6061 material which was rolled to a 1 mm thickness and placed on top of the Al 2024 alloy plate. They utilised optical microscopy with serial sectioning to systematically study material flow when small variations are made to the tool pin. They used three flat features on the pin impose vertical material flow which can promote intermixing. When they used a threaded tool, the material flow and formation of the intermixed region depends on the orientation of the base materials, since the differences in viscosity of material on the advancing versus retreating side of the tool will inhibit intermixing [20]. Decreasing the travel speed will promote intermixing by increasing the residence time to compensate for the differences in material viscosity that otherwise limit intermixing. Finally, they found, the material flow imposed by the threads is heavily influenced by the position of the base materials. When the tool travel speed is decreased, the intermixing is enhanced by the residence time within the stir zone.

Ranjith. R and Senthil Kumar. B have joined two dissimilar aluminium alloys AA2014 T651 and AA6063 T651. This was carried out using friction stir welding[21]. They have made it in various tilt angles and varying pin dimensions. That is, the weld was obtained by varying its tilt angle (2◦-4◦), tool offset (0.5mm towards AS, centre line, 0.5mm towards Rs) and Pin diameter (5mm – 7mm). After welding, they have carried out tensile strength and % of Elongation to evaluate the strength of the weld. They also carried out the microstructure analysis by optical microscope. The results show that better interlocking and bonding of materials occur at 4-degree tilt angle. The pin diameter influences heat generation, which is affecting the tensile strength of the joint. And also, they have determined the effect of tool inclination on the tensile strength of the joint and the effect of tool offset on the tensile strength of the joint. Then they found that the tensile strength is better when the tool is offset towards AA2014 side because of complete fusion of harder material. When, it is offset towards AA6063 side results in insufficient heat generation on advancing side. This leads to incomplete fusion of AA2014. The 6 mm pin diameter, 4-degree tilt angle and 0.5 mm offset towards advancing side give the optimum tensile strength of 371 MPa.

S. K. Aditya and Abhijit Datta have analysed Friction Stir Welding using Aluminum Alloys and Optimized the Welding Parameters for Maximum Tensile Strength [22]. They implemented their friction Stir Welding technique in plastics. It is an innovative technique to join metals in the plastic state thus not reaching the liquid state as it happens in traditional welding processes.This feature of the FSW proved that a modification can be done on the fatigue behaviour and strength of the welding joints. Due to this, some of the leading companies adopted the process for the manufacturing of Automotive, Locomotive, Shipping and Aerospace products. Their FSW parameters, such as tool Rotational speed, Welding speed, Axial Force, Tool tilt angle, Welding Tool Shoulder Diameter, and Welded Plate thickness play a major role in determining the properties like Tensile strength, hardness, residual stress, HAZ etc. of the joints. Their objective is to optimize the welding parameters to achieve Maximum Tensile Strength of Aluminium Alloys (especially on AA-2xxx, AA-5xxx) under FSW. They only wish to optimize (by Taguchi and ANOVA method) with three variable input parameters (Rotational speed in rpm, Translation speed in mm/min and Axial force in KN) considering a cylindrical pin.

III. CONCLUSION

From various investigations, it is found that the friction stir welding (FSW) process didn’t produce gaseous emission, particulate emission and radiation during welding of above materials and hence it could be very much called as Eco-Friendly Welding process. Moreover, the joints fabricated by FSW process exhibited superior mechanical and metallurgical properties compared to other conventional welding processes.

REFERENCES

[1] J. Mononen, M. Sire´n and H. Ha¨nninen: ‘Cost comparison of FSW and MIG welded aluminium panels’, Weld. World, 2003, 47, 32–35.

[2] D. M. Rodrigues*1, C. Leita˜o1, R. Louro2, H. Gouveia2 and A. Loureiro1, ‘High speed friction stir welding of aluminiumalloys’ Science and Technology of Welding and Joining stw1709.3d.

[3] R. Nandan, T. DebRoy and H. K. D. H. Bhadeshia: ‘Recent advances in friction stir welding – process, weldment, structure andproperties’, Prog. Mater. Sci., 2008, 53, (6), 980–1023.

[4] A. Steuwer, M. J. Peel and P. J. Withers: ‘Dissimilar friction stir welds in AA5083–AA6082: the effect of process parameters on residual stress’, Mater. Sci. Eng. A, 2006, A441, 187–196.

[5] M. J. Peel, A. Steuwer, P. J. Withers, T. Dickerson, Q. Shi and H. Shercliff: ‘Dissimilar friction stir welds in AA5083–AA6082. Part I: Process parameter effects on thermal history and weld properties’, Metall. Mater. Trans. A, 2006, 37A, (7), 2183–2193.

[6] Prakashkumarsahu, Sukhomay pal (2015) Multi response optimization of process parameters in friction stir welded AM20 Mg alloy by taguchi grey relational analysis, Journal of Mg and alloys 3 36- 46.

[7] Prof. S. K. Aditya, 2 Mr. AbhijitDatta, ‘Analysis of Friction Stir Welding of Aluminum Alloys and Optimization of Welding Parameters for Maximum Tensile Strength’, Prof. S. K. Aditya Int. Journal of Engineering Research and ApplicationsISSN : 2248-9622, Vol. 5, Issue 5, (Part -5) May 2015, pp.36-43.

[8] Ramona GABOR1, Jorge F. dos SANTOS2, ‘Friction Stir Welding Development Of Aluminium Alloys For Structural Connections’. Proceedings Of The Romanian Academy, Series A,Volume 14, Number 1/2013, pp. 64–71.

[9] V. Balasubramanian, ‘Friction Stir Welding: An Environmentally Cleaner Welding Process’, Placid Rodriguez Memoial Lecture, 2010.

[10] N.T. Kumbhar and G.K. Dey and K. Bhanumurthy, ‘Friction Stir Welding of Aluminium Alloys’. Research Article, Issue No. 321July - Aug. 2011 pg. 11-17.

[11] M. Shtrikman, Weld Int, 22(10), Research Article,712-719 (2008).

[12] R. Nandan, T. DebRoy and H. Bhadeshia , Prog Mater Sci, 53(6), 980-1023 (2008).

[13] A. Gerlich, P. Su, M. Yamamoto, et al., SciTechnol Weld Joining, 13(3), 254-264 (2008).

[14] P. Threadgill, SciTechnol Weld Joining, 12(4), 357-360 (2007).

[15] R. Mishra and Z. Ma, Mater SciEng R Rep, 50(1-2), 1-78 (2005).

[16] J. Adamowski a,*, M. Szkodo b. ‘Friction Stir Welds (FSW) of aluminium alloy AW6082-T6’ Journal of of Achievements in Materials and Manufacturing Engineering. Volume 20 Issues 1-2 January-February 2007. Pg- 403-406.

[17] W. Gan, K. Okamoto, S. Hirano, K. Chung, C. Kim, R. H. Wagoner. ‘Properties of Friction-Stir Welded Aluminum Alloys 6111 and 5083’.

[18] A. K. Lakshminarayanan, V. Balasubramanian, K. Elangovan Effect of Welding Processes on Tensile Properties of AA6061 Aluminium Alloy Joints, International Journal Advanced manufacturing technology (Springerlink) ,2009 Vol.40, 286-296.

[19] Indira Rani M., Marpu R. N. and A. C. S. Kumar. ‘A Study Of Process Parameters Of Friction Stir Welded Aa 6061 Aluminum Alloy In O And T6 Conditions’. ARPN Journal of Engineering and Applied Sciences. Vol. 6, No. 2, February 2011. ISSN 1819-6608. Pg-61-66.

[20] H. Izadi, J. Fallu, A. Abdel-Gwad, T. Liyanage and A. P. Gerlich. ‘Analysis of tool geometry in dissimilar Al alloy friction stir welds using optical microscopyand serial sectioning’. Science and Technology of Welding and Joining2013. Vol.18, No. 4. Pg-307-313.

[21] Ranjith. R, Senthil Kumar. B. ‘Joining of dissimilar aluminium alloys AA2014 T651 and AA6063 T651 by friction stir welding process’. E-ISSN: 2224-3429. Vol. 9, 2014. Pg 179-186.

[22] Prof. S. K. Aditya, Mr. AbhijitDatta. ‘Analysis of Friction Stir Welding of Aluminum Alloys and Optimization of Welding Parameters for Maximum Tensile Strength’. Prof. S. K. Aditya Int. Journal of Engineering Research and ApplicationsISSN : 2248-9622, Vol. 5, Issue 5, (Part -5) May 2015, pp.36-43.

◈◈◈