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A REVIEW OF FRICTION STIR WELDING OF ALUMINIUM ALLOYS-IJAERD

Darpan K Patel [1], Rajnikant C. Bidajwala [2], Kishan J Patel [3], Navaj Malek [4]

1 PG Student, Dept. of Mechanical engineering, Ipcowala Institute of Engineering & Technology, Dharmaj-388430 Gujarat, India
2 Assistant Professor, Dept. of Mechanical engineering, Ipcowala Institute of Engineering & Technology, Dharmaj-388430 Gujarat, India
3 UG Student, Dept. of Mechanical engineering, Ipcowala Institute of Engineering & Technology, Dharmaj-388430 Gujarat, India
4 UG Student, Dept. of Mechanical engineering, Ipcowala Institute of Engineering & Technology, Dharmaj-388430 Gujarat, India

Abstract: *Friction stir welding is a solid state joining process. High strength aluminium alloys are widely used in aircraft and marine industries. Generally, the mechanical properties of fusion welded aluminium joints are poor. As friction stir welding occurs in solid state, no solidification structures are created thereby eliminating the brittle and eutectic phases common in fusion welding of high strength aluminium alloys. In this review the process parameters & its effects on mechanical properties & microstructure and macrostructure, specific to aluminium alloys have been discussed.*

1. INTRODUCTION

Advanced materials like aluminium matrix composites (AMCs) have attracted considerable attention due to their appealing mechanical properties and a clear potential for aerospace applications. They are thus viewed as an ideal candidate as a new generation of light weight and high strength materials [1–3]. However, the implementation of AMCs is restricted and they are not widely used in the aviation industry, in part because of the difficulties that are related to the joining of these metals by conventional welding processes [2,4]. Efficient joints in terms of strength of AMC materials cannot be achieved by fusion based welding methods due to the reaction between reinforcements and matrices leading to the formation of brittle secondary phases in the weld pool or decomposition of reinforcements in molten metal [4,5].With respect to welding processes, it has been proven by several studies that more efficient joints with much reduced porosity, cracking, distortion, and reinforcement dissolution can be achieved when friction stir welding (FSW) is adopted. However, as a result of the presence of reinforcement particles, a major difficulty of welding AMCs by FSW is the narrow welding window (the range of welding parameters by which successful welding can be accomplished without defects) in comparison with a monolithic aluminium alloy. In recent years, several review papers have been published on various aspects of FSW. Thomas et al. [6], Rai et al. [7], and Zhang et al. [8] comprehensively reviewed FSW tools and development. Threadgill et al. [9] gave a critical overview of FSW of aluminium alloys.

However, there is little information related to FSW of AMCs. The present review paper firstly gives a brief description on the FSW process and the weldability of aluminium alloys and AMCs. This is followed by a detailed evaluation of a number of critical issues in FSW of similar AMCs focusing on the microstructure and macrostructure and mechanical properties of AMC joints. Finally, conclusions are drawn with a particular view on future challenges and research directions.

2. BRIEF INTRODUCTION TO FSW

Friction Stir Welding was invented at The Welding Institute (TWI) of UK in 1991 as a solid–state joining technique and was initially applied to aluminium alloys [10]. In essence, FSW is very simple, although a brief consideration of the process reveals many subtleties. The principal features are shown in Fig. 1. A rotating tool is pressed against the surface of two abutting or overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the advancing side and the other side, where tool rotation opposes the traversing direction, is known as the retreating side. An important feature of the tool is a probe (pin) which protrudes from the base of the tool (the shoulder) and is of a length only marginally less than the thickness of the plate. Frictional heat is generated, principally due to the high normal pressure and shearing action of the shoulder. Friction stir welding can be thought of as a process of constrained extrusion under the action of the tool [11]. The frictional heating causes a softened zone of material to form around the probe. This softened material cannot escape as it is constrained by the tool shoulder. As the tool is traversed along the joint line, material is swept around the tool probe between the retreating side of the tool (where the local motion due to rotation opposes the forward motion) and the surrounding undeformed material. The extruded material is deposited to form a solid phase joint behind the tool. The process is by definition asymmetrical, as most of the deformed material is extruded past the retreating side of the tool. Friction stir welding is therefore both a deformation and a thermal process, even though there is no bulk fusion [11]. Thermocouple measurements during FSW of aluminum alloys suggest that, in general, the temperature stays below 500°C [12]-[14]. To date, the prime focus of FSW has been for welding aluminum alloys, although the process has been well developed for both copper alloys [15], [16] and magnesium alloys [17], [18]. The welding process in these materials takes place at considerably higher temperatures, although the feasibility of the process has been demonstrated, further work is needed to improve the performance and longevity of tool materials. In addition, considerable work has focused on using FSW to join dissimilar aluminium alloys [19], [20]. Coverage of the present review is confined to the FSW of aluminium alloys.

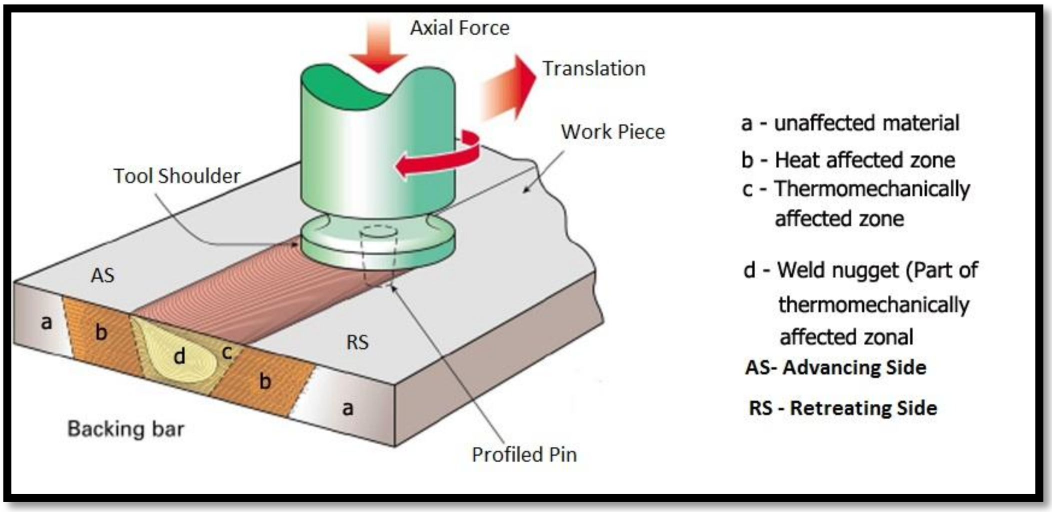

Figure 1 Schematic diagram of FSW

Moreover, FSW is considered as a green and environmentally friendly welding technology because of low energy consumption, no gas emission, and no need for consumable material such as electrodes, filler metals, and shielding gases (normally present in fusion welding processes). A survey carried out by the American Welding Society (AWS) in 2002 showed that $34.4 billion per year is spent on arc welding including the use of consumables, repair, and energy consumption in the USA. The adoption of FSW has increased rapidly and 10% of joining processes have reportedly been replaced by FSW.

3. ALUMINIUM ALLOYS AND THEIR WELDABILITY

As a versatile material, AMCs may be selected as an alternative to high strength aluminium alloys in aero engines and aerospace structures like fins, wings, and fuselage. In 2001 NASA used composite aluminium Al–Li 2195 rather than aluminium alloy Al 2219 for the external fuel tank of space shuttles leading to a reduction of weight by 3400 kg. This saving in weight increases the cargo capacity of space shuttles and enables it to transport more than one components in a single flight to the International Space Station [22]. Also, the use B/Al in truss and frame of aeroplanes saved 45% weight from an all-aluminium design. Another application of AMCs is a 3.6 m antenna for Hubble Space Telescope manufactured from Gr/Al (P100/6061 Al). It offers high stiffness, superb electrical conductivity, and low coefficient of thermal expansion [23]. In addition, AMCs have found a wide range of applications in military sector such as armour, due to the combined static strength and high ballistic performance [24].

The strength of pure aluminium is inadequate for structural applications. Therefore, to eliminate this limitation it is alloyed with other metals like copper, manganese, magnesium, zinc, and silicon. Different mechanical properties can be achieved by controlling the amount of alloying elements and heat treatments. Wrought aluminium is classified into two types depending on the main alloying elements. Non heat treatable weldable aluminium alloys including AA1xxx, AA3xxx, and AA5xxx series are strengthened by cold working, whereas AA2xxx, AA6xxx and AA7xxx series are heat treatable, non-weldable alloys that can be strengthened by precipitation hardening [25,26].

In general, welding of aluminium and its alloys needs considerable attention. Problems may occur including the loss of strength and defect formation when fusion welding processes are used. Centre-line or solidification cracking is also a serious problem in fusion welding of aluminium alloys. The variations in heating and cooling cycle in the HAZ normally result in lowered the strength of joint in heat treatable alloys [25,27] In contrast, a good joint was achieved by FSW and there was no significant change in reinforcement volume fraction for both AMC joints. Therefore, the findings of this study gave a clear indication of the suitability of FSW to weld different types of AMCs.

4. PROCESS PARAMETERS

The most important factors affecting the quality of FSW weld are the process parameters. Due to material movement during the process, microstructural properties of weld highly depend on the design to tool (tool pin profile, shoulder diameter, tool material) and process parameters (tool rotational speed, tool feed rate, tool tilt angle, axial force, tool plunge depth).

5. MACROSTRUCTURE OBSERVED IN FSW JOINTS

As the workpieces are exposed to thermal cycles and severe plastic deformation at high temperature through the rotation of the tool in FSW. As a result of either excessive or insufficient heat input in the weld zone, defects such as tunnel defects and kissing bonds may occur in the welded joint. Also, there are significant changes in the shape and structure of the welding zone.

The macrostructure examination of welding zone can be used to reveal the quality of welded joints. Three different zones; nugget zone (NZ), thermo-mechanically affected zone (TMAZ), HAZ can be identified in the macrostructure of FSW joints as shown in Figure 2.

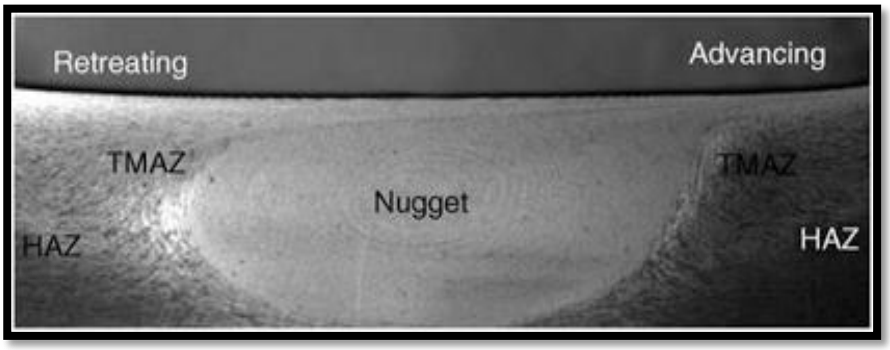

Figure 2 Cross-sectional macrostructure view of FSW joint

Due to plastic deformation and frictional heat generated during FSW process generation of a recrystallized fine-grained microstructure within the stirred zone takes place and the region which is observed is generally referred as weld nugget. Depending on the process parameter, tool geometry, temperature of work piece and thermal conductivity of the material, various shapes of nugget zone have been observed. Basically, nugget zone can be classified into two types, basin shaped nugget that widens near the upper surface and elliptical nugget [28]. The formation of basin shaped nugget zone has been reported in many investigations [29]-[31]. Lombard et al. [32] investigated the effect of varying welding parameters on the properties of friction stir welded AA5083-H321 aluminum alloys and found concentric rings (onion skin structure) in the weld nugget and the width of the nugget was of the order of the pin diameter. Cavaliere et al. [33] reported the formation of elliptical onion structure in the weld centre. Nami et al. [34] reported tunnel defect in FSW Al/Mg2Si/15p at low and high rotation speeds. It is found that the frequency of tunnel defect generation in FSW depends on the speed of tool rotation.

Dynamic recrystallization during FSW results in formation of fine and equiaxed grains in nugget zone [33]-[36]. FSW parameters, tool geometry, workpiece composition, temperature of the workpiece, vertical pressure exerts important influence on the size of the recrystallized grains.

The thermo-mechanically affected zone (TMAZ) lies between the heat-affected zone (HAZ) and nugget zone (NZ). The grains of the original microstructure are retained in this region, but in a deformed state. The TMAZ experiences both temperature and deformation during FSW. The initial grains are rotated in the TMAZ [31], [37], [38] and the recrystallization begins at TMAZ/nugget boundary. The TMAZ grain size of the joints was considerably larger than that of the NZ and high density of precipitates was observed within each grain. Similar results have been reported by other researchers [30], [32] [39].

Beyond the TMAZ there is a heat-affected zone (HAZ). In the HAZ the plastic deformation is absent or insufficient to modify the initial grain structure [30], [31], [39]. This zone is subjected to only thermal alterations. In HAZ the hardening precipitates can dissolve or coarsen depending upon the base material condition and thermal exposure. Sullivan and Robson [39] investigated the effect of friction stir welding on the microstructure of 40 mm thick AA7449 aluminum alloy in TAF as well as in T7 temper conditions. They reported that in HAZ, the grain size is the same as in the original parent material, but measurements of particle size show a marked change which becomes more distinct closer to the TMAZ/nugget zone. FSW process results in dissolution, phase transformation, coarsening of precipitates and formation of large precipitate free zone. Additional post-weld heat treatment resulted in marginal increase in the coarsening of precipitates in the HAZ.

In conclusion, nugget shape, onion ring, and tunnel defect are the main macrostructure features of FSW joints. Rotational speed and amount of heat input have a great effect on the nugget shape and tunnel defects, while material flow behaviour, recrystallization, and plate thickness effect are main factors for the appearance of onion ring. Hence the quality joints can be improved if the temperature of the weld zone can be carefully controlled.

6. MECHANICAL PROPERTIES

Significant microstructural changes are observed within and around the stirred zone during Frictions stir welding. Due to this changes post weld mechanical properties are affected. In the sections to follow, typical mechanical properties, such as hardness, tensile strength, and fatigue are briefly reviewed.

6.1 Hardness

Many researchers use hardness data as an initial assessment of mechanical properties. Aluminum alloys are classified into heat-treatable (precipitation-hardenable) alloys and non-heat treatable (solid-solution-hardened) alloys. A number of investigations established that the change in hardness in the friction stir welds is different for precipitation-hardened and solid-solution-hardened aluminum alloys. Many studies on the mechanical properties of FSW joints of heat-treatable aluminum alloys such as 2219-O [31], [36], [38], [40], [41] have indicated that FSW gives rise to softening of the joints and results in significant degradation of the mechanical properties. Xu et al. [37] showed that in case of friction stir welded thick 2219-O aluminum alloy, the hardness presents an asymmetrical distribution through the weld centre line and the maximum hardness was obtained at the weld top on the advancing side because of the piling of materials on advancing side. The weld top was significantly harder than the weld bottom. Cavaliere et al. [42] investigated the effect of processing parameters on the mechanical and metallurgical properties of dissimilar AA6082-AA2024 joints produced by friction stir welding. The joints were produced with different alloy positioned on the advancing side of the tool. The joints were realized with a rotation speed of 1600rpm and by changing the advancing speed from 80 to 115mm/min. It was reported that the highest value of microhardness was reached in the case of dissimilar AA2024-AA6082 when the 2024 alloy was on the advancing side of the tool and the welding speed was 115 mm/min. When 6082 alloys were employed on the advancing side of the tool, the microhardness profile in the weld nugget appeared more uniform, indicating a better mixing of the material. The hardness in the nugget zone was slightly higher than that in the base material, and the maximum hardness was located in the TMAZ. In all the cases of welding, minimum hardness was reported in the HAZ because of over aging effect. Bousquet et al. [43] reported that the AA2024-T351 friction stir welded joint exhibited a significant microhardness evolution through the weld due to modifications in microstructure.

6.2 Tensile strength

6.2.1 Effect of Design of Tool

The design of tool is important for proper material flow and it is also used to find the traverse rate for FSW joint. FSW tool has two basic functions: (i) localized heating, and (ii) material flow. The shape of tool shoulder and pin plays a significant role in the tensile strength of FSW joints. Vijay and Murugan [44] investigated the effect of different pin shapes (square, hexagonal, and octagon) in tapered and un-tapered profile on the tensile properties of FSW Al/TiB2/10. The joint efficiency fabricated by un-tapered square pin exhibits a maximum tensile strength which reaches 99.47% of that of the base material in comparison to other profiles. From the available literature, it is known that a cylindrical threaded pin, truncated cone and concave shoulder are widely used welding tool features. Elangovan and Balasubramaniam [45] investigated the effect of tool pin profile and tool shoulder diameter on the friction stir processing zone formation in AA6061 aluminum alloy. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) with three different shoulder diameters were used to fabricate the joints. Their investigation revealed that transverse tensile properties are dependent on the pin profile and tool shoulder diameter. Wang et al. [46] found that the use of conical threaded pin at high traverse speed at 800 mm/min rather than a flat cylinder in joining AA2009/ SiC/17p led to an increase of the joint efficiency to 97% due to the improvement of the flowability of softened material. In a study reported by Yigezu et al. [47] in FSW 5 mm thick Al–12%Si/TiC/10 plates, three shoulder diameters (18, 20, and 22 mm) and threaded cylinder pin were used as FSW tool. They reported that the tensile strength of the weld joints varied from 124 MPa to 172 MPa depending on the tool type and process parameters. A 20 mm shoulder diameter is preferable for obtaining the maximum ultimate tensile strength (UTS).

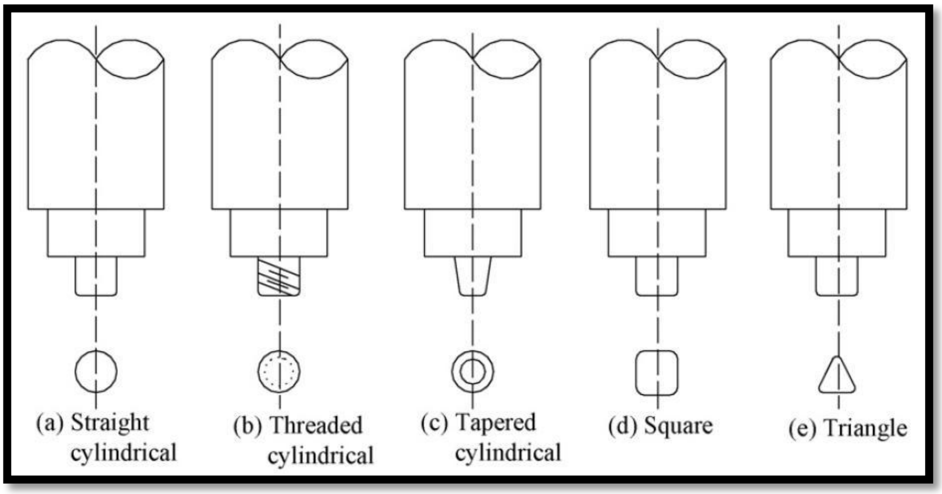

Figure 3 Schematic Diagram of different tool pin profile used for FSW

6.2.2 Effect of Welding Parameters

In FSW joints the process parameters used are tool rotational speed (rpm), axial force (N), tool feed rate (mm/min), tool tilt angle and tool pin plunge depth (mm). From all of above the two most important factors affecting the FSW weld quality are (i) Tool rotational speed (rpm) and (ii) Tool feed rate (mm/min). The tool rotational speed helps in stirring and mixing of material whereas the tool feed rate helps in moving the stirred material around the tool pin inline of weld direction to get the required welded joint. So, we can say that the material stirring and mixing is in direct proportion with the tool rotational speed i.e. Higher the tool rotational speed the higher the heat will be generated and so the material stirring and mixing will be high and vice-versa. Tool tilt angle also plays an important role when FSW is used for dissimilar materials, in that scenario proper tilt angle will help the material to flow around the pin and will help in getting good quality welded joint.

Chen et al. [40] studied the effect of post-weld solution ageing heat treatment on the tensile properties and fracture locations of 2219-O aluminum alloy FSW joints. Their finding suggests that heat-treated joints exhibits higher tensile strength and lower elongation than the as-welded joints and post-weld heat treatment process has a significant effect on the fracture location of the joints. The welding parameters have a significant effect on the ductility and strength of friction stir welded aluminum joints [37], [42], [48], [49]. Rajamanickam et al. [50] investigated the statistical significance of process parameters such as tool rotation and weld speed on thermal history and mechanical properties of aluminum alloy AA2014. From analysis of tensile property data of joints, it was concluded that the weld speed was the main input parameter that had the highest statistical influence on tensile properties. Liu et al. [51] studied the effect of FSW parameters on the tensile properties and fracture locations of FSW 2017-T351 aluminum alloy. It was reported that for revolutionary pitch greater than a definite value, some void defects exist in the joints, the tensile properties of the joints were considerably low, and the joints fractured at the weld centre. Hatamleh [30] investigated the local tensile properties at the different regions of the weld of AA 2195 joint produced by friction stir welding using digital image correlation technique. Highest tensile properties were located in the heat affected zone and the lowest in the weld nugget. More recently Malarvizhi and Balasubramaniam [52] compared the tensile behaviour of AA2219 joints produced by GTAW, EBW and FSW. They reported that of the three welded joints, FSW joints exhibited superior tensile properties compared to EBW and GTAW joints. Dinaharan and Murugan [53] reported that the maximum tensile strength of joint was obtained at 6 kN axial force when joining in-situ composite AA6061/ZrB2. Further increment in hydrostatic pressure leads to a reduction in the tensile strength.

7. CONCLUSIONS

This review aims to outline the current state-of-the-art of joining Aluminium alloys by FSW with a number of specific issues discussed including the FSW process, weldability of aluminium alloys, macrostructure and mechanical properties of FSW joint. FSW as a solid-state welding process, is considered to be potentially a viable route for joining Aluminium Alloy materials. Its potential benefits in cost reduction, joint efficiency improvement, and high production accuracy make it even more attractive for the non-weldable series AA2xxx, AA6xxx and AA7xxx. However, the maturity of using this joining process to weld Aluminium Matrix Composites is still at an early stage in research and has not yet been fully implemented in industry. The mechanical properties of Aluminium Alloys joined by FSW are largely dependent on the combined effect of both the composition of Aluminium Alloys and the FSW processing conditions. Early researches showed that FSW is a potential welding process to achieve defect free joints of Aluminium Alloys. There is a clear need for more efforts to understand the effect of FSW on these materials in adequate depth to meet design and production requirements. More work is needed to understand the performance of FSW joint of AA2xxx and AA7xxx series metals.

Furthermore, welding parameters such as tool rotation speed, traverse speed, and axial force have a significant effect on the amount of heat generation and strength of FSW joints. Macrostructural evaluation showed the formation of tunnel defects due to inappropriate flow of plasticized metal. Microstructural evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameters. However, there is no general trend between welding parameters and mechanical properties for different types of Aluminium Alloys. Further work needs to be carried out to define the welding window of each composite metal for optimised mechanical properties.

References

[1] G. Çam, M. Koçak, Progress in joining of advanced materials, Int. Mater. Rev. 43 (1) (1998) 1–44.
[2] A.M. Hassan, M. Almomani, T. Qasim, A. Ghaithan, Effect of processing parameters on friction stir welded aluminum matrix composites wear behaviour, Mater. Manuf. Process. 27 (12) (2012) 1419–1423.
[3] K. Suryanarayanan, R. Praveen, S. Raghuraman, Silicon carbide reinforced aluminium metal matrix composites for aerospace applications: a literature review, Int. J. Innov. Res. Sci. Eng. Technol. 2 (11) (2013).
[4] M.B.D. Ellis, Joining of aluminium basedmetal matrix composites, Int.Mater. Rev. 41 (2) (1996) 41–58.
[5] R.Y. Huang, S.C. Chen, J.C. Huang, Electron and laser beam welding of high strain rate superplastic Al-6061/SiC composites, Metall.Mater. Trans. A Phys.Metall.Mater. Sci. 32 (10) (2001) 2575–2584.
[6] W.M. Thomas, D.G. Staines, I.M. Norris, R. de Frias, Friction stir welding tools and developments, Weld. World 47 (2003) 10–17.
[7] R. Rai, A. De, H.K.D.H. Bhadeshia, T. DebRoy, Review: friction stir welding tools, Sci. Technol. Weld. Join. 16 (4) (2011) 325–342.
[8] Y.N. Zhang, X. Cao, S. Larose, P.Wanjara, Review of tools for friction stir welding and processing, Can. Metall. Q. 51 (3) (2012) 250–261.
[9] P.L. Threadgill, A.J. Leonard, H.R. Shercliff, P.J. Withers, Friction stir welding of aluminium alloys, Int. Mater. Rev. 54 (2) (2009) 49–93.
[10] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Temple-Smith, and C. J. Dawes, “'Friction stir butt welding,” GB patent no. 9125978· 8, 1991
[11] P. L. Threadgill, A. J. Leonard, H. R. Shercliff, and P. J. Withers, “Friction stir welding of aluminum alloys,” *Int Mater Rev*, vol. 54, pp. 49-93, 2009.
[12] W. Tang, X. Guo, J. C. McClure, and L. E. Murr, “Heat input and temperature distribution in friction stir welding,” *Journal of Materials Processing and Manufacturing Science*, vol. 37, pp. 163-172, 1999.
[13] M. W. Mahoney, C. G. Rhodes, J. G. Flintoff, R. A. Spurling, and W. H. Bingel, “Properties of friction-stir-welded 7075 T651 aluminum,” *Metallurgical and Materials Transactions A*, vol. 29, pp. 1955-1964, 1998.
[14] A. P. Reynolds, W. D. Lockwood, and T. U. Seide, “Processing property correlation in friction stir welds, ” Material Science Forum, 331-337, pp. 1719-1724, 2000.
[15] W. B. Lee, and S. B. Jung, “The joint properties of copper by friction stir welding, ” Materials Letters, vol. 58, pp. 1041-1046, 2004. World Academy of Science, Engineering and Technology International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering Vol:7, No:12, 2013 1319 International Scholarly and Scientific Research & Innovation 7(12) 2013 International Science Index Vol:7, No:12, 2013 waset.org/Publication/9996603
[16] H. S. Park, T. Kimura, T. Murakami, Y. Nagaro, K. Nakata, and M. Ushio, “Microstructures and mechanical properties of friction stir welds of 60%Cu-40%Zn Copper alloy, ” *Materials Science and Engineering A*, vol. 371, pp. 160-169, 2004.
[17] J. A. Esparza, W. C. Davis, E. A. Trillo, and L. E. Murr, “Friction-stir welding of magnesium alloy AZ31B,” *Journal of Materials Science Letters*, vol. 21, pp. 917-920, 2002.
[18] C. Y. Lee, W. B. Lee, Y. M. Yeon, and S. B. Jung, “Friction stir welding of dissimilar formed Mg alloys (AZ31/AZ91),” *Materials Science Forum*, vol. VI, pp. 249-252, 2005.
[19] M. Peel, A. Steuwer, P. 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,” *Metallurgical and Materials Transactions A*, vol. 37A, no. 7, pp. 2183-2193, 2006.
[20] M. Peel, A. Steuwer, and P. Withers, “Dissimilar friction stir welds in AA5083-AA6082. Part II: Process parameter effects on microstructure,” *Metallurgical and Materials Transactions A*, vol. 37A, no. 7, pp. 2195- 2206, 2006.
[21] W.J. Arbegast, Friction stir welding after a decade of development — it's not just welding anymore, Weld. J. 85 (3) (2006).
[22] T. Prater, Friction stirwelding ofmetalmatrix composites for use in aerospace structures, Acta Astronaut. 93 (2014) 366–373.
[23] S. Rawal, Metal–matrix composite for space application, JOM 53 (4) (2001) 14–17.
[24] R.S. Mishra, Z.Y. Ma, Friction stir welding and processing, Mater. Sci. Eng. R Rep. 50 (1–2) (2005) 1–78.
[25] G. Mathers, TheWelding of Aluminium and Its Alloys, Woodhead Publishing Limited, Cambridge, England, 2002.
[26] Aluminum and Aluminum Alloys, in: J.R. Davis (Ed.) ASM International, 1993.
[27] S. Kou, Welding Metallurgy, Second ed. John Wiley & Sons, New Jersey, 2003.

[28] R. S. Mishra, and Z. Y. Ma, "Friction stir welding and processing," *Materials Science and Engineering*, vol. 50, pp. 1-78, 2005.
[29] O. Hatamleh, "A comprehensive investigation on the effects of laser and shot peening on fatigue crack growth in friction stir welded AA 2195 joints," *International Journal of fatigue*, vol. 31, pp. 974-988, 2009.
[30] O. Hatamleh, and A. DeWald, "An investigation of peening effects on the residual stresses in friction stir welded 2195 and 7075 aluminum alloy joints," *Journal of Materials Processing Technology*, vol. 209, no. 10, pp. 4822-4829, 2009.
[31] H. Aydin, A. Bayram, A. Uguz, and S. K. Akay, "Tensile properties of friction stir welded joints of 2024 aluminum alloys in different heattreated- state," *Materials and Design*, vol. 30, pp. 2211-2221, 2009.
[32] H. Lombard, D. G. Hattingh, A. Steuwer, and M. N. James, "Effect of process parameters on the residual stresses in AA5083-H321 friction stir welds," *Materials Science and Engineering A*, vol. 501, pp. 119-124, 2009.
[33] P. Cavaliere, G. Campanile, F. Panella, and A. Squillace, "Effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by friction stir welding," *Journal of Materials Processing Technology*, vol. 180, pp. 263-270, 2006.
[34] H. Nami, H. Adgi, M. Sharifitabar, H. Shamabadi, Microstructure and mechanical properties of friction stir welded Al/Mg2Si metal matrix cast composite, Mater. Des. 32 (2) (2011) 976–983.
[35] P. Cavaliere, D. A. Santis, F. Panella, and A. Squillace, "Effect of anisotropy on fatigue properties of 2198 Al-Li plates joined by friction stir welding," *Engineering Failure Analysis*, vol. 6, pp. 1856-1865,2008.
[36] K. Surekha, B. S. Murty, and K. R. Prasad, "Microstructural characterization and corrosion behaviour of multipass friction stir processed AA 2219 aluminium alloy," *Surface & Coatings Technology*,vol. 202, pp. 4057-4068, 2008.
[37] W. Xu, J. Liu, G. Luan, and C. Dong, "Temperature evolution, microstructure and mechanical properties of friction stir welded thick 2219-O aluminum alloy joints," *Materials and Design*, vol. 30, pp. 3460-3467, 2008.
[38] H. Aydin, A. Bayram, and I. Durgun, "The effect of post-weld heat treatment on the mechanical properties of 2024-T4 friction stir-welded joints," *Materials and Design*, vol. 31, pp. 2568-2577, 2010.
[39] A. Sullivan, and J. D. Robson, "Microstructural properties of friction stir welded and post-weld heat-treated 7449 aluminum alloy thick plate," *Material Science and Engineering A*, vol. 478, pp. 351-360, 2008.
[40] Y. C. Chen, H. J. Liu, and J. C. Feng, "Effect of post-weld heat treatment on the mechanical properties of 2219-O friction stir welded joints," *Journal of Material Science*, vol. 40, pp. 4657-4659, 2005.
[41] G. Pouget, and A. P. Reynolds, Residual stress and microstructure effects on fatigue crack growth in AA2050 friction stir welds," *International Journal of Fatigue*, vol. 30, pp. 463-472, 2008.
[42] P. Cavaliere, D. A. Santis, F. Panella, and A. Squillace, "Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082-AA2024 joints produced by friction stir welding," *Materials and Design*, vol. 30, pp. 609-616, 2009.
[43] E. Bousquet, A. Poulon-Quintin, M. Puiggali, O. Devos, and M. Touzet, "Relationship between microstructure, microhardness and corrosion sensitivity of an AA 2024-T3 friction stir welded joint," *Corrosion Science*, vol. 53, pp. 3026-3034, 2011.
[44] S.J. Vijay, N.Murugan, Influence of tool pin profile on the metallurgical and mechanical properties of friction stir welded Al–10 wt.% TiB2 metal matrix composite, Mater. Des. 31 (7) (2010) 3585–3589.
[45] K. Elangovan, and V. Balasubramaniam, "Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy," *Materials and Design*, vol. 29, pp. 362-373, 2008.
[46] D. Wang, Q.Z. Wang, B.L. Xiao, Z.Y. Ma, Achieving friction stir welded SiCp/Al–Cu– Mg composite joint of nearly equal strength to base material at high welding speed, Mater. Sci. Eng. A 589 (2014) 271–274.
[47] B.S. Yigezu, D. Venkateswarlu,M.M.Mahapatra, P.K. Jha, N.R.Mandal, On friction stir butt welding of Al + 12Si/10 wt%TiC in situ composite, Mater. Des. 54 (2014) 1019–1027.
[48] P. Cavaliere, R. Nobile, F. W. Panella, and A. Squillace, "Mechanical and microstructural behaviour of 2024-7075 aluminium alloy sheets joined by friction stir welding," *International Journal of Machine Tools & Manufacture*, vol. 46, pp. 588-594, 2006.
[49] P. Cavaliere, A. Squillace, and F. Panella, "Effect of welding parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding," *Journal of Materials Processing Technology*, vol. 200, pp. 364-372, 2008.
[50] N. Rajamanickam, V. Balusamy, M. G. Reddy, and K. Natarajan, "Effect of process parameters on thermal history and mechanical properties of friction stir welds," *Materials and Design*, vol. 30, pp. 2726-2731, 2009.
[51] H. J. Liu, H. Fujii, M. Maeda, and K. Nogi, "Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy," *Journal of Materials Processing Technology*, vol. 142, pp. 692- 696, 2003.
[52] S. Malarvizhi, and V. Balasubramaniam, "Effect of welding processes on AA2219 aluminium alloy joint properties," *Trans. Nonferrous Met. Soc. China*, vol. 21, pp. 962-973, 2011.
[53] I. Dinaharan, N. Murugan, Optimization of friction stir welding process to maximize tensile strength of AA6061/ZrB2 in-situ composite butt joints,Met.Mater. Int. 18 (1) (2012) 135–142.

