Friction stir welding and processing-a perspective review

Sanjeev Verma¹, a) and Vinod Kumar², b)
¹Research Scholar, Mechanical Engg. Department, Punjabi University, Patiala-147002, India
²Professor, Mechanical Engg. Department, Punjabi University, Patiala-147002, India

a) Corresponding author(s): er.verma.11@gmail.com

b) vk_verma5@rediffmail.com

Abstract. The paper reviews the basic principles of friction stir welding, its methodology, and all other technical aspects. As reported by different researchers, the effect of varying welding variables such as tool geometry, tool-tilt angle and tool materials on the microstructure and mechanical properties of the welded materials, and weld quality are reported and discussed. The paper covers the various mechanical and metallurgical properties of similar/dissimilar aluminium alloys and other metal joints welded using friction stir welding (FSW). The attempt has been made to present a comprehensive review of some of the salient works carried out by various researchers pertaining to friction stir processing (FSP)/FSW of aluminium alloys. The paper also identifies the existing research gaps in the area of FSW, which should be explored in future.

Keywords: Friction stir welding, welding parameters, Al alloys, mechanical properties, microstructure, dissimilar alloys.

1. INTRODUCTION

Friction stir welding (FSW), a solid state welding process, was invented in 1999 by the welding institute¹ and is used to join various non ferrous materials like aluminium, copper, magnesium etc. In this welding technique, a non consumable tool pin profile rotates between the parent materials to generate friction heat, which stir the material and the stirred material joined. In FSW (figure 1) a rotating tool is passed through the joint line to produce frictional heat. The rotating tool stirs and mixes the materials around the tool pin and with the translation of the tool the material is also stirred from the front to back of the rotating tool pin to complete the welding process. ²-³
Figure 1. Schematic of FSW.\textsuperscript{2,3}

In comparison to conventional welding processes, FSW is an eco-friendly and cleaner welding technique, which does not produce fumes, smoke or arc glare. The main advantages of FSW are less distortion and no melt-reacted defects. The macrographs shown in figures 2(a) and 2(b) shows the four different welded regions marked as base material zone (BMZ), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stir zone (SZ)/weld nuggets on both advancing and retreating sides.\textsuperscript{4}

Figure 2(a). Macrographic view of FS welded regions for AA6061 alloy on both sides.\textsuperscript{4}

HAZ (Zone B) lies closer to weld center and does not exhibit plastic deformation. The material is plastically deformed in TMAZ (zone C). The highest strain is in the SZ/weld nuggets (zone D) zone, with the evidence of recrystallisation in this region\textsuperscript{4}.
Figure 2(b). Schematic illustration of different zones in friction stir welded AA 6061 alloys (A: BMZ, B: HAZ, C: TMAZ and D: SZ).

Mishra and Ma in their review article discussed the developments in the area of FSW and FSP. The review article mainly described the impact of different process parameters of FSW/FSP on the mechanical and metallurgical properties of aluminium alloys as well as the mechanisms involved in forming the weld and refining the microstructure. The salient benefits of FSW in terms of metallurgical, environmental and energy are summarized in table 1 below:

| Metallurgical benefits of FSW | Environmental benefits of FSW | Energy benefits of FSW |
|-------------------------------|-------------------------------|------------------------|
| Very low distortion in welded parts. | No requirement of shielding gas | Material used improve because of very less wastage. |
| Robust in-phase process. | Solvent and grinding wastes are eliminated | Less energy requirement as compared to other welding techniques. |
| High dimensional stability with repeatability | Cleaner surface produced | Reduced fuel consumption in lightweight aviation, automotive and marine applications. |
| Nil alloying elements loss | No use consumable material | |
| No cracking | | |
| Excellent improvement in metallurgical properties | | |
| Replace various attachments and fasteners. | | |

2. FSW MATERIAL COMBINATION STUDIES

2.1. FSW of Similar Aluminium Alloys

Prasanna et al. analyzed the role of heat treatment processes and using different profiles of tool pin during FSW of AA6061 (aluminium alloy). The study employed the use of various types of tool pin profiles for producing the butt joints while maintaining the tool rpm, welding speed and axial force as 1200, 14mm/min and 7kN, respectively. The effect of various heat treatment processes annealing, normalizing and quenching was also investigated on the metallurgical aspects and mechanical properties of the welded joints. The use of hexagonal shaped pin profile of the tool was noticed to produced the welded joint having good ductility and tensile strength. Rohilla and Kumar investigated the impact of tool geometry on the mechanical properties of FSW butt joint of AA6061 plate having 6mm thickness. The tensile strength, micohardness and percentage elongation during single and double pass were determined by using half square (HS), full square (FS), half cylindrical (HC) and full
cylindrical (FC) tool pin profiles. The joint obtained by using single pass weld exhibited lower percentage elongation and tensile strength as compared to joints produced by employing double pass welding. Raf et al. \textsuperscript{7} examined the role of various FSW parameters on the tensile behavior rods shaped AA7075-T6. The study indicates that the most critical parameters influencing the joint strength of FS welded AA70755 are spindle speed, friction pressure and burn-off length. The findings also revealed that FSW can be employed to attain a joint efficiency of 89\% for AA7075-T6 through proper selection of welding parameters. Bisadi et al. \textsuperscript{8} studied the role of various parameters on the microstructural aspects, mechanical properties and weld defects in lap joint composed of AA5083 and produced through FSW. Amongst the various welding zones, the nugget zone was found to have the better grain size and thus exhibiting higher hardness. The best joint properties were noticed corresponding to tool rpm of 825 and a weld speed of 32 mm/min. Cavaliere et al. \textsuperscript{9} analyzed the influence of welding parameters on the microstructural aspects mechanical properties FS welded joints made of AA6056. The experiments were performed at three different tool rpm (i.e. 500, 800 and 1000) and welding speed (i.e. 40, 56 and 80 mm/min.) and their effect was investigated on the micro-hardness, tensile and fatigue (low and high cycle) behavior of the welded joint. During the fatigue tests, the ratio R (= \( \sigma_{\text{min}}/\sigma_{\text{max}} \)) was kept 0.1. The specimen corresponding to welding speed of 56 mm/min. was noticed to have the highest fatigue properties in the low cycle fatigue regime.

\textbf{2.2. FSW of Dissimilar Aluminium Alloys}

Park and Kim \textsuperscript{10} examined the influence of tool rotation speed and tool traverse speed on the stirring phenomenon and friction heat generated during FSW of AA5052-O and AA6061-T6. The mechanical strength of FS welded joints, obtained for various combinations of welding parameters, was evaluated. The maximum weld strength was noticed for the welded joint corresponding to tool rpm of 1600 and transverse speed of travel speed of 61 mm/min. The examination of plastic flow behavior of the material in the welded joint indicated that with the increase in stirring effect and decrease in traverse speed the defects in the welded joint decrease. Park et al. \textsuperscript{11} investigated the role of material locations on the properties of FS welded joints for AA5052-H32 and AA6061-T6 alloys. The study revealed that the mixing of the materials in the welded joints depends on the location of the base materials. The materials were observed to have proper mixing when AA6061-T6 was on the retreating side and AA5052-H32 was on the advancing side, as compared to the case where AA5052-H32 was on the retreating side and AA6061-T6 was on the advancing side during the FSW process. For A5052-H32 alloy the lowest micro-hardness was noticed in the HAZ, and as a consequence the fracture during the tensile test was observed on the AA5052-H32 side for both types of material arrangements. Sundaram and Murugan \textsuperscript{12} investigated the tensile behavior of FS welded joints made of two dissimilar aluminium alloys (i.e. AA2024-T6 and AA5083-H321). The study used five different types of pin profiles of the tool. A mathematical model using central composite design and response surface methodology (RSM) was used to predict the optimal solution for the experiment. The maximum tensile strength and maximum elongation were obtained for the welded joint corresponding to tool pin having tapered hexagonal profile. However, the lowest tensile strength and the lowest elongation were noticed for the welded joint produced using tool-pin with straight cylindrical profile. The study also reveals that with the increase in tool rpm the tensile strength of the welded joint increases initially, reaches a maximum value, followed by decrease beyond a certain tool speed. Madhusudhan et al. \textsuperscript{14} investigated the microstructure and mechanical properties of FS welded joints between plates made of AA 6262-T6 and AA 7075-T6. The study employed tool having square pin profile and different values of welding parameters such as tool rotation speed, welding speed and axial force. The welded joints fabricated corresponding to tool speed of 1200 rpm, welding speed of 0.6 mm/sec. and axial force of 9 kN exhibited the best mechanical properties. Ghaffarpour et al. \textsuperscript{15} investigated the role of varying the welding parameters on the microstructure and mechanical properties of FS welded 6061 and 5083 aluminium alloys. To predict the optimal mechanical properties, RSM was used. It has been observed from the optimal solution that the amongst the various welding parameters responsible for deciding the tensile strength of the welded joint, the tool rotation speed is the most dominant. Palanivel et al. \textsuperscript{16}
investigated the influence of tool-pin profile and tool rpm on the tensile strength and microstructural properties of FS welded joints between dissimilar AA5083 and AA6351 alloy. The study employed different types (five types) of tool pin profiles and three different tool rotation speeds for obtaining the welded joints. The study demonstrated three different regions in weld zone. The welded joint obtained using tool with straight square pin profile and rotating at 9500 rpm possess the maximum tensile strength of 273 MPa.

2.3. FSW of Aluminium Alloys with other Materials

Dressler et al. 17 made an attempt to join TiAl6V4 and 2024-T3 by using FSW technique. The study focused on the feasibility of the joint apart from investigating the microstructure, tensile strength and hardness of the welded joints. The ultimate joint strength was found to be 73% of the basic material strength AA2024-T3. Pandya and Menghani 18 examined the impact of welding parameters on the ultimate tensile strength of FS welded joints between AA6061-T6 and CU dissimilar by using Sn powder as filler material. The study used different combinations of tool rpm, tool speed, tool-pin offset and gap (for adding Sn filler powder). The study concluded that the tool rotation speed and tool travel speed are the major parameters that affect the strength of the welded joint. The joints prepared were also investigated for microstructural changes, micro-hardness measurement and X-ray diffraction analysis. The study revealed that the optimum tensile properties are attained for the welded joint produced with 0.05 mm gap for Sn filler material.

3. PROCESS PARAMETERS STUDIES

The most significant process parameters in FSW of similar or dissimilar materials are tool geometry and rotation speed, welding speed, axial force and tilt angle of the tool. Mishra and Ma 3 studied various aspects pertaining to FSW and noticed that tool geometry is the most significant parameter in affecting the material flow during FSW process. It has been found that the tool geometry influences the speed of the FS welding process. Amongst various tool-pin profiles, the threaded cylindrical pin profile and concave shoulder pin profile are widely used. The use of higher tool rotational speed has been shown to result in high frictional heat due to higher temperature generated during the course of FSW process. Koirraj et al. 15 analyzed the influence FSW parameters like tool profile, tool rpm, tool transverse speed, and the ratio of tool shoulder to tool-pin diameter on the tensile strength of the joint. The study demonstrated that wide range of FSW parameters can be used to produce highly efficient and defect free welded joints. The study also suggested the recommended range of process parameters for achieving the best tensile properties of the welded joint. The use of Analysis of variance (ANOVA) suggested that the ratio of tool shoulder diameter to tool-pin diameter is the most significant factor in yielding the soundness of the welded joint. Besides, the tool-pin profile and welding speed are also play a significant role in deciding the properties of the welded joint.

4. MECHANICAL PROPERTIES AND MICROSTRUCTURAL CHARACTERIZATION

Fuji al. 20 studied the effect of varying the amount of carbon in IF (interstitial free), S12C (low carbon) and S35C (medium carbon) steels on the FSW. The strength of S12C steel was noticed to increase with the increases in welding speed. Figure 3 shows the ultimate tensile strength of IF, S12C and S35C carbon steels FSW joints for different welding speeds. It is noticed that with the increase in welding speed, the strength of IF steel joint decreases slightly; attributed to decrease in heat input. In case of FSW of S12C steel, the strength of the joint is observed to increase with the increase in welding speed, attributed to decrease in amount of heat input. The maximum strength of the joint for S35C steel has been noticed around a welding speed of 200 mm/min. Figures 4 (a) -(c) depict Vicker’s hardness values of FS welded joints corresponding to IF, S12C and S35C steels obtained at different welding speed.
Figure 3. Effect of welding speed on ultimate tensile strength of FS welded carbon steels.  

Figure 4. Microhardness profiles for FS welded carbon steels: (a) IF, (b) S12C and (c) S35C steels.
The microstructure examinations of IF, S12C and S35C steels reveal uniform grain structure comprising of equiaxed grains with the sub-structures noticed in the SZ. It has been found that the grain sizes in the welded SZ center were 5 and 6μm for the highest and lowest levels of input conditions, respectively, which are quite small as compared to that noted in BMZ (24μm). It has also been noted that in IF steel single-phase ferrite region is observed no transformation has been observed in the region. S12C steel shows that under all welding conditions ferrite-pearlite micro-structure were formed with a small amount of pearlite. Figure 5 shows microstructure of S12C and S35C steels.

![Microstructures of (a) S12C and (b) S35C steels.](image)

Charita et al. examined the various grain growth phenomenon observed during FSW of different alloys. The study reveals that abnormal grain growth (AGG) is not observed in pure aluminium. AGG occurs when the normal grain growth gets suppressed. A few samples of optical macrographs showing AGG, upon treatment at 763K for 1 hour, are shown in figure 6. The study indicates that during FSW process, the primary factors contributing to the presence of AGG in the friction stirred materials are consistent with the inhomogeneous pattern of deformation.
Figure 6. Optical macrographs of FSP 7075 Al alloy exhibiting AGG corresponding to different combinations of process parameters.  

5. CONCLUSIONS

Friction stir welding is an effective welding process that can be used to join different types of aluminium alloys and other materials. FSW is a solid-state joining technique that possesses numerous benefits as compared to other welding processes. The most important factor for the development of defect-free welds is tool geometry. The profile of the tool pin must be designed in such a way that the material strain rate in the stir zone increases and the clogging of material with the tool surface decreases. The origin of weld defect is clogging of base material with tool which results to reduce the joint strength. To accomplish sound and defect free weld joints, parameters such as welding speed, tool rpm, tool profiles, tilt angle of the tool, and axial force play an important role. There are three distinct zones in the friction stir welded joints, viz., nugget zone, HAZ and TMAZ. The optimum heat generated during the course of FSW is dependent on the thermal conductivity of the tool material, initial temperature of the tool and base material, and the amount of heat contributed due to phase deformation in the different zones. Each of these parameters directly or indirectly influences the material flow and heat generated during the FSW process. FSW is observed to exhibit a significant
increase in the tensile strength, elasticity, ductility, fatigue strength and toughness of the welded joints, as compared to joints obtained using fusion welding techniques. It has been observed that the welded joint exhibits lower fatigue strength as compared to base materials, but significantly higher fatigue strength than that noticed for laser welded and MIG welded joints. Preheating of the material to be welded is advantageous for improving the consistency of the weld and besides improving the weld quality. FSW can be successfully employed for joining different materials such as copper, steel, titanium, composites and magnesium, apart from joining aluminium alloys. It is revealed that more research work is needed to produce reliable and cost-effective joining of aluminium and other lightweight alloys, in addition to welding of harder materials like steels and composites.

6. REFERENCES

[1] R. Palanivel, P. Koshy Mathews, N. Murugan and I. Dinaharan, Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys, Materials and Design, 2012; 40: pp. 7–16.
[2] Arvin Bagheri, Taher Azdast and Ali Doniavi, An experimental study on mechanical properties of friction stir welded ABS sheets, Materials and Design, 2013; 43: pp. 402–409.
[3] K. Elangovan and V. Balasubramanian, Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminium alloy, Materials Science and Engineering A, 2007; 459: pp. 7–18.
[4] P. Prasanna, Dr.Ch.Penchalayya and Dr.D.Anandamohana Rao, Effect of tool pin profiles and heat treatment process in the friction stir welding of AA 6061 aluminium alloy, American Journal of Engineering Research, 2013; 07: pp-07-15.
[5] Mishra RS and Ma ZY, Friction stir welding and processing, Mater Sci Eng R Rep, 2005; 50:1–78.
[6] Rohlla Puneet and Kumar Narinder, Experimental investigation of tool geometry on mechanical properties of friction stir welding of AA6061, International journal of innovative technology and exploring engineering(UIITEE), 2013; vol. 03.
[7] H. Khalid Rafi, G.D. Janaki Ram, G. Phanikumar and K. Prasad Rao, Microstructure and tensile properties of friction welded aluminum alloy AA7075-T6, Materials and Design, 2010; vol.31 pp. 2375–2380.
[8] H. Bisadi, M. Tour and A. Tavakoli, The influence of process parameters on microstructure and mechanical properties of friction stir welded al 5083 alloy lap joint, American Journal of Materials Science, 2011; 1(2): pp. 93-97.
[9] Effect 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, 2006; vol.180, pp. 263–270.
[10] J. C. Park and S. J. Kim, The effect of traveling and rotation speeds on mechanical properties during friction stir welding of dissimilar Al alloys, Defect and Diffusion Forum, 2010; vol. 297–301, pp. 590–595.
[11] S. K. Park, S. T. Hong, J. H. Park, K. Y. Park, Y. J. Kwon, and H. J. Son, Effect of material locations on properties of friction stir welding joints of dissimilar aluminium alloys, Science and Technology of Welding and Joining, 2010; vol. 15, no. 4, pp. 331–336.
[12] R. Palanivel, P. Koshy Mathews, The tensile behaviour of friction-stir- welded dissimilar aluminium alloys, Materials and technology. 45 (2011) 6, pp. 623–626.
[13] S. N. Sundaram and N. Murugan, Tensile behavior of dissimilar friction stir welded joints of aluminium alloys, Materials and Design, 2010; pp. 4184–4193.
[14] R. Madhusudhan, M.M.M.Sarcar, N.Ramanaiah, K.PrasadaRao, An experimental study on the effect of weld parameters on mechanical and micro structural properties of dissimilar
aluminium alloy FS welds”, *International Journal of Modern Engineering Research*, 2012; vol.2, Issue.4, pp. 1459-1463.

[15] M. Ghaffarpour, B. M. Dariani, A. H. Kokabi and N. A Razani, Friction stir welding parameters optimization of heterogeneous tailored welded blank sheets of aluminium alloys 6061 and 5083 using response surface methodology, *ProcIMechE Part B: J Engineering Manufacture* **226**(12), 2012; pp. 2013–2022.

[16] R. Palanivel, P. Koshy Mathews, N. Murugan and I. Dinaharan, Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys”, *Materials and Design* **40** (2012); pp.7–16.

[17] Ulrike Dressler, Gerhard Biallas and Ulises Alfaro Mercado, Friction stir welding of titanium alloy TiAl6V4 to aluminium alloy AA2024-T3, *Materials Science and Engineering A*, vol. **526** (2009); pp. 113–117.

[18] Shailesh N Pandya and J V Menghani, A parametric investigation on effects of friction stir welding process parameters on mechanical properties of AA6061-T6 to Cu dissimilar joints, *Indian Journal of Engineering and Materials Sciences*, vol. **25**, 2018; pp. 131-146.

[19] M. Koilraj, V. Sundareswaran, S. Vijayan and S.R. Koteswara Rao, Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083—optimization of process parameters using taguchi technique”, *Materials and Design* (2012); vol. **42**, pp. 1-7.

[20] H. Fujii, L. Cui, N. Tsuji, M. Maeda, K. Nakata and Kiyoshi Nogi, “Frictions stir welding of carbon steels”, *Materials Science and Engineering A*, vol.**429** (2006); pp. 50–57.

[21] I. Charita, and R.S. Mishra, “Abnormal grain growth in friction stir processed alloys”, *Scripta Materialia*, vol. **58** (2008); pp. 367–371.