Chapter 1
Optimization-Related Studies on the Operational Parameters of Friction Stir Welding: An Overview

Manish Kumar Singh, Rajesh Kumar Porwal and Sanjay Mishra

Abstract Friction stir welding technique is one of the most emerging, environmental-friendly and rapid-growing solid-state joining technique based on heat generated due to friction and application of pressure. This technique is generally used to join materials that have wide range of industrial applications and that are difficult to weld by fusion welding process, like aluminum, copper, nickel. In the past, researchers have searched a number of approaches to improve joint properties by analyzing process parameters that affect the mechanical and microstructural characteristics of the joint. The experimental and theoretical studies show that the weld joint properties can be improved considerably by proper selection of process parameters. This article shows an overview of various optimization techniques that can be used to find the optimum welding operational parameters during the joining of similar and dissimilar materials.

Keywords Friction stir welding · Operational parameters · Optimization

1.1 Introduction

The applications of aluminum and copper, categorized as soft materials, are mostly in the aircraft, shipping, defense and transportation industries as they possess certain properties, like being lightweight, having a high corrosion resistance, good mechanical properties and a good strength-to-weight ratio. Coalesce of these soft materials is difficult using fusion welding as there is an establishment of brittle inter-metallic compound at the interface of weld joint that results in decrease in the mechanical and microstructural properties. This problem was overcome by using FSW, in which metallic bond is produced at a lower temperature. The weld strength is stronger in

M. K. Singh · R. K. Porwal (✉)
Faculty of Mechanical Engineering, Shri Ramswaroop Memorial University, Lucknow, India
e-mail: porwal.me@srmu.ac.in

S. Mishra
Department of Mechanical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, India

I. Singh et al. (eds.), *Trends in Manufacturing Processes*,
Lecture Notes on Multidisciplinary Industrial Engineering,
https://doi.org/10.1007/978-981-32-9099-0_1

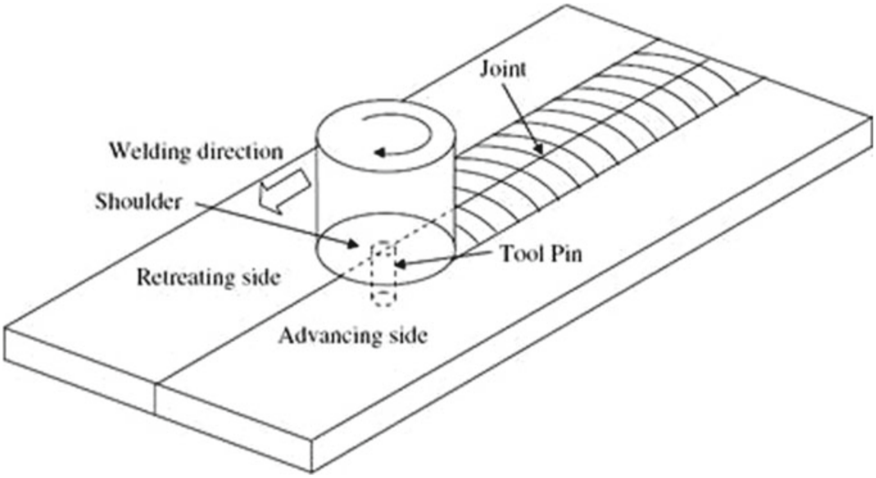

Fig. 1.1 Schematic view of FSW [6]

FSW because there is no melting of base metal; thus the heat-affected zone is narrower in this process compared with the fusion welding. Although FSW was initially developed to join aluminum and its alloy, recently it is applied successfully and effectively to join other metals and materials [1–3]. There are some other materials which were joined successfully by the FSW technique, such as magnesium, nickel, titanium, steels and metal matrix composites. This technique can also be used to join dissimilar and thermally un-weldable materials [4].

Friction stir welding was first introduced by Thomas and Nicholas at The Welding Institute, Cambridge, UK in 1991. It uses a non-consumable rotating tool having a pin below the shoulder. Both the pin and shoulder of tool contributed to heat generation. Pin mixes the base materials while shoulder controls the material flow. The movement between the tool and workpiece produces heat by means of friction which softens the base materials. Soften material flow attributable to major plastic deformation and is united in order to make a successful joint. The schematic view of friction stir welding is shown in Fig. 1.1. There are two welded sides in the FSW; first one is the advancing side in which the direction of rotating tool and the weld are in the same direction, while the second one is known as retreating side, in which the direction of rotating tool and weld direction are in a different direction [5–7].

1.2 Review Related to Experimental and Theoretical Studies of FSW

This literature is a review of the experimental and theoretical studies performed by the researchers across the globe, which shows the effect of various process parameters, such as rotational speed, travel speed and tool geometries, on the weld joint properties. For example, Liu et al. performed FSW on 6061-T6 Al alloy having thickness of 0.63 cm, with RS varying from 300 to 1000 rpm and traverse speed compassed from 0.15 to 0.25 cm/s. The hardened carbon steel as a tool material having 0.63 cm pin diameter along with 1.25 cm shoulder diameter was used for their experimental study. They compared weld joint mechanical properties with the base metal and it was found that the residual hardness varied from 55 VHN at the top of weld to 65 VHN at the bottom of the weld as compared with the workpiece hardness, which varied from 85 to 100 VHN, as shown in Fig. 1.2 [8]. Weld joint strength was investigated by Saeid et al. during the FSW of 1060 Al alloy with pure copper in lap configuration. Quenched and tempered steel as a tool material having a 15 mm shoulder diameter with threaded pin profile was used for their experimental investigation. They concluded that the maximum tensile shear strength of the joint was achieved at 95 mm/min welding speed. They also observed cavity defect at 118 and 190 mm/min welding speed [9]. Yabuuchi et al. performed FSW on oxide dispersion strengthened steel to investigate the effect of RS on mechanical properties and microstructure of the weld joint. They demonstrated that there was a reduction in stirred weld zone hardness at all RS because of recrystallization lured by temperature generation during the joining process. Furthermore, recrystallization was followed by a modification in grain structure from prolonged to isotropic grains and grain size was increased with an increase in RS [10]. Fratini et al. studied the impact of work material characteristics on plasto-mechanics during the FSW of Al alloys 2024-T4 and 6082-T6 in T-joints configuration. The authors used a special design fixture to determine the process conditions effect, metallurgical and mechanical behavior of joints. The thermal and plastic flow fields of workpiece materials were calculated and compared by using numerical methods. Their result showed that at a particular temperature and strain rate fields, Al alloy 6082-T6 had low flow stress value as compared to AA2024-T4 [11].

Piccini and Svoboda studied the effect of tool penetration depth and sheet positions of the weld joint of dissimilar AA5052–AA6063 Al alloy during friction stir spot welding. The authors found that plastic flow was influenced by tool penetration

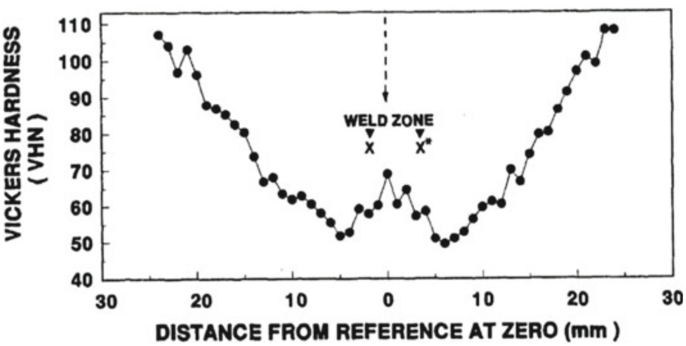

Fig. 1.2 Vickers micro hardness traverse through the section [8]

depth and sheet positions. Their results showed that the effective welded width was increased and hook height decreased with the increase of TPD, when AA6063 alloy was in upper sheet position. Furthermore, the effective welded width was found lower along with a higher hook height, when AA5052 was in upper sheet positions [12].

Cao and Jahazi investigated the effect of probe length and rotational speed on lap joint quality on 2 mm AZ31B Mg alloy using friction stir welding. They concluded that as the rotational speed increased there was an increase in tensile shear load, and a further increase in rotational speed resulted in a decrease in tensile shear load. They also found that the grain advancement appeared in the stir zone at a leading rate of small welding speed as compared to a base metal [13]. Padmanaban and Balasubramanian made an attempt to select the tool pin profile, tool materials and tool shoulder diameter during FSW of AZ31B Mg alloy. They selected four differently shaped pin profile and five types of tool materials to fabricate the weld joint along with 15, 18 and 21 mm tool shoulder diameter. They observed that high carbon steel tool with the threaded pin profile and 18 mm shoulder diameter provided superior tensile properties of joint as compared to other parameters [14]. Kush and Mehta conducted an experiment on dissimilar copper and aluminum workpiece materials using friction stir welding. The authors used a different design of tool pin profile, like cylindrical, square, triangular and hexagonal. They observed that polygonal pin design provided a large and irregular detachment of copper particles from the base material, while in the case of triangular tool pin profile they noticed maximum irregular and large copper particles in the weld zone. They also reported that an increase in the polygonal tool edge decreases the defects, and cylindrical tool pin profile had defect-free macro joint [15].

1.3 Review Related to Optimization Studies of FSW

Process parameter optimization has a significant aspect in the improvement of weld joint properties. It helps in the identification and determination of the appropriate value of process parameters at which the maximum and desired output can be achieved. This section deals with the various optimization techniques used to optimize the FSW process parameters carried out by the researchers.

Farzadi et al. used the response surface methodology to optimize friction stir welding operational parameters for the ultimate tensile strength of AA7075 Al weld joints. A conclusion was drawn that the WS has a more substantial contribution to the ultimate tensile strength, as shown in Fig. 1.3. UTS first declined and then increased with the escalation in WS. They found 513 MPa UTS with 94% joint efficiency under optimum welding condition of 514 rpm rotational speed, 95 mm/min travel speed whereas the tool shoulder and pin diameter were 16.1 and 6 mm, respectively [16]. Shanavas and Dhas used RSM and ANOVA to optimize the FSW parameters of AA5052-S32 Al alloy. They found that the welding parameters, like WS, tilt angle, pin profile and RS, play an extensive role to define the weld joint qualities. Their optimization results revealed that at 600 rpm rotational speed, 65 mm/min WS and

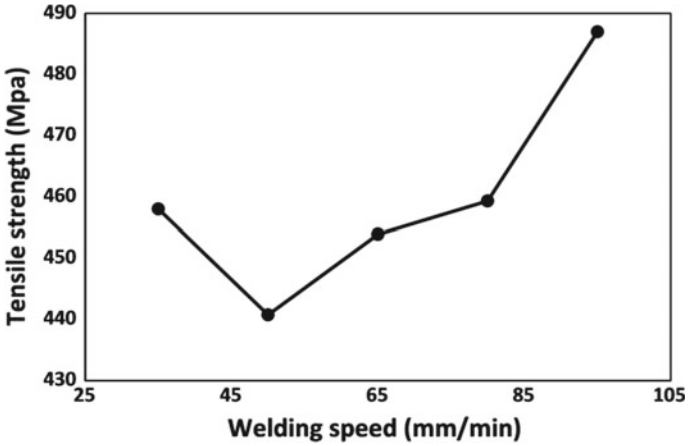

Fig. 1.3 Response of WS on the UTS of weld joints [16]

1.5° tilt angle, the weld joint exhibited superior tensile properties with 93.51% joint as compared to other joints. Moreover, a defect-free weld joint in and around the stir zone was observed during macro and microstructure study of the weld [17]. Kumar et al. analyzed the UTS and percentage elongation of dissimilar AA5083-H111 and AA6082-T6 Al alloy weld joint during FSW and optimized the input parameters with RSM. The input parameters were tool pin profile, RS, WS and axial force. They observed higher value of UTS and percentage elongation of 234 MPa and 12.07%, respectively, at 1000 rpm RS, 90 mm/min WS and 7.8 kN axial load along with tapered square pin profile [18].

Laxminarayanan and Balasubramanian applied Taguchi parametric design and optimization approach technique to determine the effect of process parameters on tensile strength of RDE40 Al alloy weld joint during FSW. A non-consumable tool made of high carbon steel with threaded cylindrical pin profile was used to fabricate the joints. Their optimum values were 1400 rpm RS, 45 mm/min travel speed and 6 kN axial force, which contributed 41, 33 and 21% to tensile strength of weld joints, respectively [19]. Koilraj et al. performed Taguchi method using ANOVA to optimize the process parameters, such as rotational speed, tool speed, tool geometry and the ratio between tool shoulder and pin diameter with respect to tensile strength of weld joint during FSW of dissimilar Al alloy.

AA2219 with AA5083: They found that the tool pin geometry and welding speed played a significant role in deciding the joint soundness (JS), while diametrical ratio of tool to pin diameter was an utmost dominating element for JS and cylindrical threaded pin tool profile was obtained to be the best as compared to other tool pin profiles. Their optimization results were 700 rpm RS, 15 mm/min travel speed, 3 D/d ratio [20]. Elanchezhian et al. have optimized the process parameters of friction stir welded AA8011-6062 Al alloy. They used Taguchi method for condition optimization and ANOVA for evaluating their experimental results. They found WS has negligible effect on the tractile tenacity of the welded joint and was the 153 MPa maximum tenacity at optimal condition of 1400 rpm RS, 75 mm/min WS and 7 kN axial force [21]. Taguchi's grey-based approach has been used by Kesharwani et al. for the multi-objective optimization of FSW parameters of 2 mm thin dissimilar Al sheet AA5052-H32 and AA574-H22 that affect the weld joint quality. They used L9 orthogonal array for their design of experiment. Their optimized parameters to fabricate the joint were 1800 rpm rotational speed, 50 mm per minute travel speed and 20 mm tool shoulder diameter with square pin geometry. They also found that maximum weld strength was 175 MPa and 13.854% maximum elongation at optimum values of welding parameters [22]. Taguchi L9 array was considered by Sachin et al. for the optimization of operational parameters like RS, WS and tool tilt angle during FSW of aluminum matrix composites. They used ANOVA and found that RS was the most influencing parameters as compared to WS for determining tensile strength and hardness of weld joint. Furthermore, they concluded that RS of 1200 rpm and 3° tilt angles were the optimal parameters for UTS and hardness, while optimum WS was 60 mm/min for UTS and 80 mm/min for hardness [23].

Khansari et al. optimized the number of experimental test and mechanical properties of welded FSW of 3 mm thick 2024 Al alloy using Mamdani-type fuzzy logic. They found that high tool rotational speed or low tool forward speeds caused the alter material to plastic phase and produced defects in weld zone. Their optimal value of rotational and forward speed was 1000 rpm and 90 mm/min, respectively [24]. Ashok et al. developed a regression model for optimizing the FSW parameters of Stir cast AA6061-T6/AA1NP composite materials to predict ultimate tensile strength and percentage elongation. They observed that UTS and percentage elongation of joint was 1% greater at the optimum condition, but 9.1% lesser than joint of work material as per the design matrix [25]. Roshan et al. investigated an experimental work for optimization of FSW process parameters of AA7075 Al alloy to achieve desirable mechanical properties such as tensile strength, yield strength and hardness of weld joint by using a simulated annealing algorithm. They utilized four factors and five levels of central composite design for minimizing the number of experimental observations. Their single response and multi-response optimization results showed that at 1400 rpm RS, 1.75 mm/s travel speed and 7.5 kN axial force desirable mechanical properties of weld joint were achieved. Also, their confirmation tests and its verifications showed that the simulated annealing algorithm was an appropriate tool for optimization of FSW process parameters [26]. Ajith et al. used particle swarm optimization method to optimize the friction welding process parameters of UNS S32205 duplex stainless steel. They found the tensile strength to be 827.17 MPa and the maximum hardness of weld joint at 322 HV, which were higher than the tensile strength and hardness of the base material, and the nature of fracture occurred was ductile, as displayed in Fig. 1.4. Their optimal result was 105 MPa frictional pressure, 180 MPa upsetting pressure and 2000 rpm rotational speed [27].

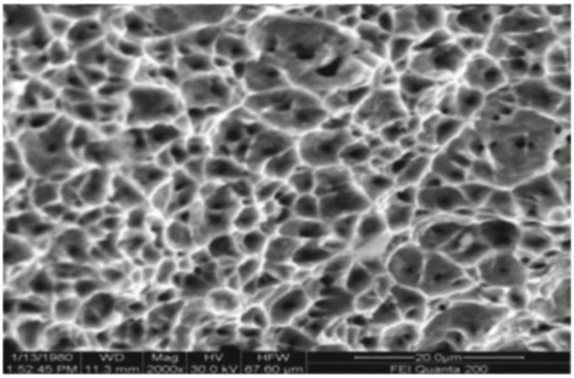

Fig. 1.4 Fractured surface of tensile tested weld sample [27]

1.4 Conclusion

Joining of soft materials like aluminum and copper with high mechanical and microstructural properties is not achieved by fusion welding processes because of the generation of blow holes, brittle inter-metallic compound, porosity and solidification cracking. In order to minimize this, friction stir welding technique is more relevant as the melting of base metal does not take place in this process. FSW is also used to join hard materials like steel and titanium. Following are the outcomes of present work:

- The weld joint properties are mainly affected by the RS, WS and tool geometries. Thus tensile strength, hardness and percentage elongation of weld joint can be improved by varying these operational parameters.
- Discussion on optimization techniques has revealed that at optimum parameters the weld joint possesses good mechanical and microstructural properties.
- Most of the researchers used the Taguchi optimization method, except a few studies that were carried out on the particle swarm optimization method. Therefore, a lot of scopes are available for future work in the area of optimization of FSW process.

References

1. Baffari, D., Buffa, G., Campanella, D., Fratini, L., Micari, F.: Friction based solid state welding techniques for transportation industry applications. Procedia CIRP **18**, 162–167 (2014)
2. Kassim, M.H.: Comparative study between friction stir welding and metal inert gas welding of 2024 T4 aluminum alloy. ARPN J. Eng. Appl. Sci. **6**(11), 36–40 (2011)
3. Thirunavukarasu, G., Chatterjee, S., Kundu, S.: Scope for improved properties of dissimilar joints of ferrous and non-ferrous metals. Trans. Nonferrous Metal. Soc. **27**(7), 1517–1529 (2017)
4. Magalhaes, V.M., Leitao, C., Rodrigues, D.M.: Friction stir welding industrialization and research status. Sci. Technol. Weld. Join. **22**, 1 (2017)

5. Madhavi, B., Jeevan, J., Teja, M.K.: Optimization study of friction stir welding process parameters and nugget properties of aluminium alloy. In: Proceedings of the International Conference on Structural Integrity (ICONS), pp. 4–7. Kalpakkam, India (2014)
6. Nandan, R., Roy, T.D., Bhadeshia, H.K.: Recent advances in friction stir welding-process, weldment structure and properties. Prog. Mater. Sci. **53**, 980–1023 (2008)
7. Singh, M.K., Porwal, R.K.: An overview on solid state welding process. In: National Seminar on Advances in Materials, Manufacturing and Renewable Energy Systems, IJTRA, Lucknow (2018)
8. Liu, G., Murr, L.E., Niou, C.S., McClure, J.C., et al.: Microstructural aspects of the friction-stir welding of 6061-T6 aluminum. Scr. Mater. **37**(3), 355–361 (1997)
9. Saeid, T., Abdollah-zadeh, A., Sazgari, B.: Weldability and mechanical properties of dissimilar aluminum-copper lap joints made by friction stir welding. J. Alloys Compd. **490**, 652–655 (2010)
10. Yabuuchi, K., Tsuda, N., Kimura, A., Morisada, Y., et al.: Effects of tool rotation speed on the mechanical properties and microstructure of friction stir welded ODS steel. Mater. Sci. Eng. A **595**, 291–296 (2014)
11. Fratini, L., Buffa, G., Shivpuri, R.: Influence of material characteristics on plasto mechanics of the friction stir welding process T-joints. Mater. Des. **30**, 2435–2445 (2009)
12. Piccini, J.M., Svoboda, H.G.: Effect of the tool penetration depth in friction stir spot welding of dissimilar aluminum alloys. In: International Congress of Science and Technology of Metallurgy and Materials, SAMCONAMET (2013)
13. Cao, X., Jahazi, M.: Effect of tool rotational speed and probe length on lap joint quality of a friction stir welded magnesium alloy. Mater. Des. **32**, 1–11 (2011)
14. Padmanaban, G., Balasubramanian, V.: Selection of friction stir welding tool pin profile, shoulder diameter and material for joining AZ31B magnesium alloy-an experimental approach. Mater. Des. **30**, 2647–2656 (2009)
15. Kush, P.M., Badheka, V.J.: Effects of tool pin design on formation of defects in dissimilar friction stir welding. In: 3rd International Conference on Innovation and Mechatronics Engineering, ICIAME, pp. 513–518 (2016)
16. Farzadi, A., Bahmani, M., Haghshenas, D.F.: Optimization of operational parameters in friction stir welding of AA7076-T6 aluminum alloy using response surface method. Arab. J. Sci. Eng. **42**(11), 4905–4916 (2017)
17. Shanavas, S., Dhas, J.E.R.: Parametric optimization of friction stir welding parameters of marine grade aluminium alloy using response surface methodology. Trans. Nonferrous Met. SOC. **27**, 2334–2344 (2017)
18. Kumar, H.M.A., Venkata, V.R., Shanmughanathan, S.P., Jacob, J., Mohammed, U.I.: Optimization of dissimilar friction stir welding process parameters of AA5083-H111 and AA6082-T6 by CCD-RSM technique. Adv. Manuf. Process. 49–60
19. Lakshminarayanan, A.K., Balasubramanian, V.: Process parameters optimization for friction stir welding of RDE-40 aluminum alloy using Taguchi technique. Trans. Nonferrous Met. Soc. **18**, 548–554 (2008)
20. Koilraj, M., Sundareswaran, V., Vijayan, S., Rao, S.R.K.: Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083 optimization of process parameters using Taguchi technique. Mater. Des. **42**, 1–7 (2012)
21. Elanchezhian, C., Vijaya, B.R., Venkatesan, P., Sathish, S., et al.: Parameter optimization of friction stir welding of AA8011-6062 using mathematical method. In: 12th Global Congress on Manufacturing and Management (2014)
22. Kesharwani, R.K., Panda, S.K., Pal, S.K.: Multi objective optimization of friction stir welding parameters for joining of two dissimilar thin aluminum sheets. In: 3rd International Conference on Materials Processing and Characterization, pp. 178–187. Hyderabad, India (2014)
23. Sachin, K., Narendranath, S., Chakradhar, D.: Process parameters optimization for FSW of AA6061/SiC/fly ash AMCs using Taguchi technique. Emerg. Mater. Res. 1–8 (2018)
24. Khansari, N.M., Namdar, K., Sarbour, M.H.: Optimization of friction stir welding by fuzzy logic. In: Presented at the 13th Iranian Conference of Fuzzy Systems, Tehran, Iran (2013)

25. Kumar, B.A., Murugan, N.: Optimization of friction stir welding process parameters to maximize tensile strength of stir cast AA6061-T6/AlNp composite. Mater. Des. **57**, 383–393 (2014)
26. Babajanzade, R.S., Behboodi, J.M., Teimouri, R., Ahmadi, G.A., et al.: Optimization of friction stir welding process of AA7075 aluminum alloy to achieve desirable mechanical properties using ANFIS models and simulated annealing algorithm. Int. J. Adv. Manuf. Technol. **69**(5–8), 1803–1818 (2013)
27. Ajith, P.M., Birendra, K.B., Sathiya, P., Aravindan, S.: Multi objective optimization of friction welding of UNS S32205 duplex stainless steel. Def. Technol. **11**, 157–165 (2015)