

Investigation of Process Specifications on Friction Stir Welded Aluminium 5083 and 6082 Alloys

H.M. Anil Kumar¹, V. Venkata Raman², Mahendra K C³, Sreenivasa C.G⁴

Abstract

Aluminium 5083 alloys were mainly used for naval based applications because of better corrosion resistance features. Similarly aluminium 6082 alloy being a structurally significant material found its applications in construction sector. Fusion welding of these two heterogeneous alloys is bit hard, since it evolves with many defects. Present Investigation deals with two cases of distinct alloys through FSW process. Case 1 represents 31 experimental trails performed by 5 various tool pin geometry. Case 2 Emphasized on 20 trails considering single profiled tool. Testing was carried out for both the cases on Response surface methodology and ANOVA, to determine the adequacy of the model suggested. Experimentation revealed a critical parameter such as taper square tool of 18mm shoulder dia possessing at rotational speed of 1000 rpm and welding speed of 90 mm/min, tensile strength exhibits significant response. Offsetting the tool resulted in less significant contributions on tensile properties. Tilt angle reported considerable results within strengthening the mechanical characteristics. Shoulder diameter contributed to considerable improvement of overall strength of the joint strength. Further, rotational speeds of the tool played an influential role in producing better tensile properties. Response graphs indicated that tensile elongation was initially high at low rotational speeds, decreases when Rotational speeds increase.

Keywords: FSW, tensile strength, elongation, tool offset, shoulder diameter

INTRODUCTION

FSW technology is an economical process for non-ferrous alloys as compared to ferrous alloys. FSW has produced better tensile strength without defects [1]. In this strong tool is used to weld with rigid clamping. The material placement is important to get sound welded joint [2]. The material needs to be placed based on their tensile strength [3, 4]. FSW produces sound joints than arc welding process among

*Author for Correspondence

Mahendra K C
E-mail: mahiubdt@gmail.com

¹Associate Professor, Department of Mechanical Engineering, Ballari Institute of Technology and Management, Ballari, Karnataka State, India

²Professor, Department of Mechanical Engineering, Ballari Institute of Technology and Management, Ballari, Karnataka State, India

³Assistant Professor, Department of Mechanical Engineering, RYM Engineering College, Ballari, Karnataka State, India

⁴Associate Professor, Department of Mechanical Engineering, University BDTCE, Davanagere, Karnataka State, India

Received Date: September 20, 2024

Accepted Date: December 21, 2024

Published Date: January 11, 2025

Citation: H.M. Anil Kumar, V. Venkata Raman, Mahendra K C, Sreenivasa C.G. Investigation of Process Specifications on Friction Stir Welded Aluminium 5083 and 6082 Alloys. Journal of Polymer & Composites. 2025; 13(Special Issue 2): S1-S11p

aluminium and low alloy steels [5]. In addition, fewer defects are seen since red hot condition is not attained [6]. It finds wide applications in the area of aerospace, automotive and marine industries as it resolves many issues flutters from fusion process [7]. V. Saravanan et al reported that D/d ratio is significant factor to find the joint properties of 2xxx and 7xxx aluminium alloys [8]. E. G. Cole et al highlighted that tool offset values also have impact joint properties of aluminium 6xxx and 7xxx alloys. [9]. A S Hassan et al (2010) analyzed the post weld heat treated aluminium alloy A319 and A356 alloys [10]. M. Ghosh et al (2010) observed that aluminium alloys (A356 and 6061) used for defense and aerospace applications need low rotation and traversing speed to produce fine grain size [11]. S.K. Park et al (2010) showed that material

mixing occurred when 5052 was on the advancing side [12]. S. Rajakumar et al (2011) examined the impact of variables on the various mechanical strengths of aluminium 7075 alloy [13].

Huijie Liu et al (2012) observed that concave tool shoulder with conical right hand screw pin has better tensile properties [14]. Astarita et al (2014) analyzed the effect of forces and grain size on aluminium 2024-T3 alloy [15]. J. C. Hou et al (2014) used self-reacting tool to analyze the effect of rotary motion on aluminium 6061 joints [16]. Sefika Kasman et al (2014) observed that joint strength decreases with raising traverse speed or increasing rotational speed AA5754 and AA7075 alloys [17]. Beytullah Gungor et al (2014) found that fatigue limits for all joints without voids are observed on 6mm thick aluminium 5 and 6 series alloys [18].

R. Hariharan et al (2014) analyzed the tensile properties of aluminium 6061 and 7075 alloy by CNC vertical machining center [19]. Heena K Sharma et al (2015) used the AA6061 and Mg AZ31 alloys to analyze the effect of variables like traverse and rotational speeds using CNC vertical milling machine [20]. H. Shirazi et al (2015) studied macrostructure of the weld done using AA5456 alloy and observed that defects, i.e. hooking, kissing-bond and cavity [21]. Mohammad Ketal (2016) investigated the dynamic interaction forces on AA 6082-T6 having 4mm thickness [22]. P. Mastanaiah et al (2016) studied the material inter-mixing, defect formation and joint properties on 5mm thick aluminum 2219-T6 and 5083 [23]. Further D. A. Dragatogiannis et al also investigated by adding TiC nano materials had improved the weld properties [24]. Vahid Farajkhan and Yi Liu (2016) studied the clamping effect and traverse speed on AA6061-T6 using ANSYS model [25]. P H Shah et al (2016) analyzed the heat distribution of aluminium 6.5 mm thick 7075-T651 alloy at constant rotations of tool at 1500 rpm [26]. K. Jagathesh et al (2017) analyzed aluminium 2024 and 6061 alloys by RSM [27]. Mohammad Mahdi Moradi examined the evolution of texture and microstructure on aluminium 2024 and 6061 alloy [28]. Abdel-Wahab El-Morsy et al (2018) examined that joint strength of aluminum 2024-T4 alloy using five speeds and speeds. The results indicated that at 900 rpm and 35 mm/min the sound joints are reproduced with joint efficiency of 86.3% [29]. Guoqiang Huan et al (2019) compared the joint efficiencies of aluminum 6061-T6 alloy using conventional tool and modified tool with disc at the top of probe [30]. B. B. Wang et al (2019) analyzed the fatigue behaviour with and without water on 2.8 mm thick 5083Al-H19 plates [31]. G. H. Li et al (2019) examined that lower welding speeds results tunnel defects in aluminium AA2219-T87 alloys and which can be prevented by increasing the welding speeds [32]. Mohamed M. Abd Elnabi et al (2019) reported tool speed, traverse speed, D/d ratio and plunge distance play vital role on aluminium 5454 and 7075 alloys [33].

The joining of two different constituents of aluminum alloys is an intricate task by fusion welding process because of low melting point and moreover produces defects due to metallurgical distortion. Fatigue strength of welded joints will be low because of welding defects & stress concentrations. Since friction at the interface results in generation of heat, it leads to grain refinement. Various kinds of grains affect the alloys because of slower and rapid cooler rate. The FSW process is a proven technique for aluminum alloys in joining similar and dissimilar conditions. Combining the properties of two different alloys by applying appropriate process parameters at selected levels is crucial with respect to dissimilar alloys. FSW process finds wide applications in Automotive, Structural, Aerospace, Marine industries. The present study concentrates on the FSW of 5083-H11 and 6082-T6 aluminium alloy. They are used mostly in construction purposes in the marine industries to manufacture of a ship hull because of their extensive corrosion resistance and structural properties. Even though many literatures are available on the set of two alloys but dissimilar FSW, under wider range of process parameters are limited. The study on mechanical and microstructural properties of this joint combination using different parameters like tool pin profiles, speeds, feeds, axial loads, shoulder diameters, tilt angles and tool offsets at various levels is not reported. The present paper also investigates the influence of tool factors like shoulder diameter, tool offset and tool tilt angle on the tensile properties of the joint.

EXPERIMENTAL WORK

The experiments are conducted in two cases. In the first case different tool pin profiles with varying speeds, feeds and axial loads are considered [34]. In the second case single tool pin profile (Taper square) with varying the shoulder diameter, tool offset and tilt angle at constant speeds and feeds are considered [35]. For both the cases dimensions of the workpiece remains same as 140*70*4 mm. The plates are cleaned to remove the dust, dirt, etc., with acetone. For both the cases Central Composite Design Technique with Response Surface Methodology is adopted to develop the mathematical equation for tensile properties of the joint. Design Expert (V11) software utilized to design the set of experiments and for analysis purposes. ANOVA (Analysis of Variance) is also used to check the adequacy of the model. The tools used for case 1 and case 2 experiments are shown in Figure 1 and 2. It is observed that using taper square tool pin profile at tool rotational speed of 1000 rpm, welding speed of 90 mm/min and axial load of 7.8 kN better tensile properties are produced in case 1 investigation. During case 2 investigations better, tensile properties witnessed when shoulder diameter 18 mm with the same tool parameters as used in case 1. Material location is a very important aspect especially in the case of dissimilar welding process. Based on the previous research works, it is found that high strength alloys must be located on the retreating side (RS) and low strength alloy on the advancing side (AS). Aluminium 5083-H111 alloy is positioned on to the AS which has low strength and AA6082-T6 alloy is positioned on to the RS. The material location for case 1 and 2 investigations are shown in Figure 3 and 4 respectively. Design of tool also influences the weld joints; different profile of tools contributes for variable set of results with respect to the parameters selected. Hence suitable process specifications can be estimated.

RESULTS AND DISCUSSION

Case: 1 Experimentations

The pin profile is major influencing factors for the joints. Tool material has its significant impact on joints, because the harder is the tool materials: the rate of stirring at the zone with respect to rotational speeds produces better welded joints. The threaded cylindrical and taper octagon tool pin profiles have produced low UTS at low speeds, force and axial force. The taper square pin profile has produced highest UTS of 256 MPa at 1000 rpm, 90 mm/min and 7.8 kN in contrast to other pin profiles. The pin profile with flat faces has a high number of pulses and better flow of material [36,37, 38]. Hence, tools with two, four and six faces (square/ hexagon) profiles create the joints with rising levels of weld properties. Further nil pulsing acts for threaded cylindrical or plain cylindrical tools hence joints would be of poor tensile strengths. The tool rotational speeds are the second major influencing parameter to produce better tensile properties. As the tool rotational speeds vary from low (600 rpm) to high (1400 rpm), ultimate tensile strength also increases up to certain level of rotational speed and extra rise in speed leads to reduced tensile strength. It is seen that at 1000 rpm, a maximum UTS is produced. The frictional heat generated is lowest at lowest rotational speed (600 rpm) which gives rise to poor plastic flow and consequently lowers UTS. The metallurgical transition takes place at the WZ during the highest rotational speed (1400 rpm) [39] and lowers dislocation density [40] which correspondingly decreases the joint strength. Tapered square pin produces smooth material flow than Tapered hexagon and triangular pin profile. The maximum UTS is obtained Tapered square tool at 1000 rpm.



Figure 1. Tools used for case 1 experiments.



Figure 2. Tools used for case 2 experiments.



Figure 3. Material locations for case 1 investigation.

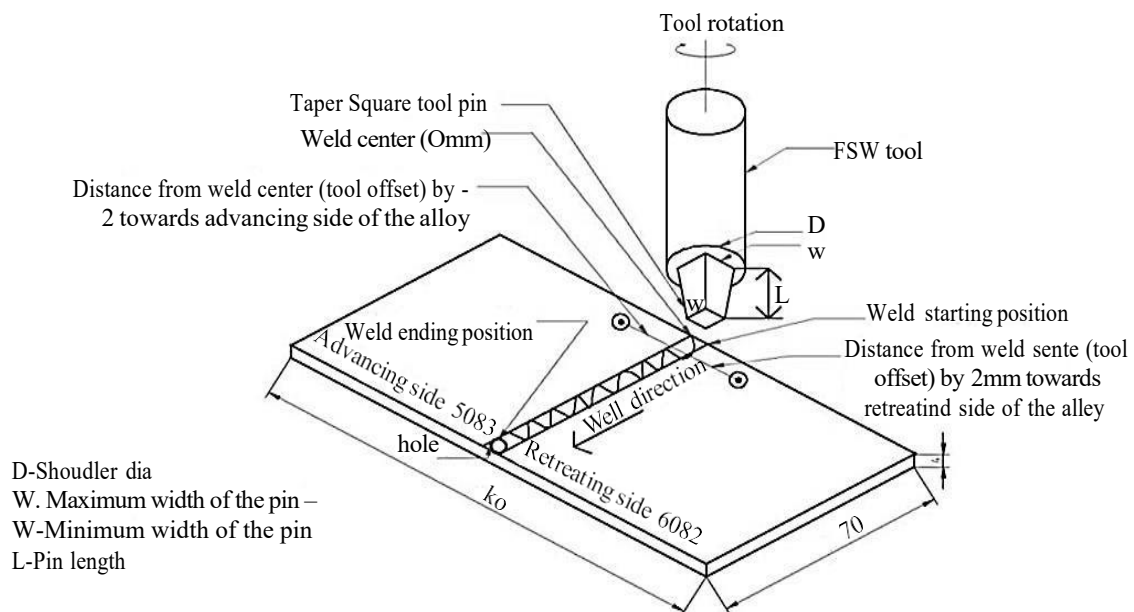


Figure 4. Material locations for case 2 investigation.

Referring to Figure 5 it is seen that at lowest (50mm/min) and highest welding speeds (130mm/min), lowest UTS is produced. Higher welding speeds allow the material to be exposed for short moments in the weld pool leading to inadequate heat and meager plastic flow of the alloy. This results in some kinds of voids as defects in the weld and decreases its strength. Further at higher welding speeds, heat inputs are low and make welded joints cool rapidly hence tensile strength decreases. The low welding speed attracts the changes in metallurgical transformations of the WZ and yields to lower UTS. Tapered square tool at 90mm/min have shown highest UTS than any other welding speeds and pin profiles. The fourth major influencing parameter which affects the UTS of the joints is axial force. As the axial force increases lower value to higher value, tensile strength increases up to certain level of axial force and upon further intensifying the force, UTS decreases. At the lowest force (3.9kN) and highest axial force (11.7kN), minimum UTS is seen. As the force is lowest, pressure acting on the work surface by the shoulder surface is comparatively low which leads to the lowest heat generated due to friction and consequently yields lower UTS. As the axial force is highest, plunge depth made by the tool pin inside the plates is more which yields lower tensile strength [41]. Joints produced at 7.8kN by taper square pin using at 1000 rpm and 90mm/min produced maximum strength.

Figure 6 shows response surface graphs drawn tensile elongation versus with various parameters. The effect of pin on the elongation is moderate. It is observed that triangular pin and taper square profiles have produced better tensile elongations than the other profiles. This is due to the high amount of pulsing effect and turbulence produced by triangular and taper square profiles because of flat faces. Further the presence of a greater number of cutting edges, stir efficiency also increases leading to higher tensile elongations when compared to other pin profiles [42]. Joints produced by taper square profile have shown maximum elongation. Referring to response graphs Figure 4 initially tensile elongation is high at low rotational speeds and it decreases as the rpm increases. This is because of strong clustering of precipitates in the WZ, TMAZ and HAZ [43,44]. Joints made by triangular pin at 800rpm and taper square pin profile at 1000rpm have maximum elongation. Further as the welding speed increases, tensile elongation also increases. This happens because the welding speed could not allow clustering of precipitates, plastic flow of material and local strain. The joints made by taper square pin at 90mm/min yields maximum tensile elongation of 13. It is observed that elongation decreases with rise in axial force. The higher amount of force generates more amounts of frictional heat in turn increases the plunge depth [45]. Therefore, higher tool force attracts the clustering of the precipitates and extreme plastic movement. This causes localized strain in base material particles. Hence as tool axial force increases, decline in the elongation is witnessed. Welds produced from taper square pin at 7.8kN axial force have produced maximum elongation.

The above discussions summarize that experimental investigations and mathematical model have found taper square tool pin produced maximum UTS and TE at 1000rpm, 90mm/min and 7.8kN.

Case 2 Experimentations

Referring to the response surface graph Figure 7 (a) that zero effect of tool offset on UTS; any variation in tool offset would not affect the UTS. Any change in diameter will certainly influence the joint strength. At minimum and maximum value of shoulder diameter, low UTS is observed. But at the center point, UTS is high, where shoulder diameter is 18mm. Referring to Figure 7 (b), low values of tilt angles, low UTS is observed and high values of tilt angles, high UTS is observed. It implies that tilt angle is proportional to the UTS. Further it confirms that the shoulder has impact on the UTS. It is observed that at 18mm shoulder diameter high ultimate tensile strength is produced. Referring to Figure 7 (c), once again it is confirmed that offset is neutral on UTS and the tilt angle is proportional to the UTS. Referring to Figure 8 (a) that zero effect of tool offset on YS; it means that any variation of tool offset value, YS would not be affected. But shoulder diameter is not neutral on YS. It means that any low/high values vary the YS of the joint. But at the center point it is high, where tool shoulder diameter is 18mm. Referring to Figure 8(b) at minimum tilt angles, low YS is observed and maximum tilt angles, high YS is observed. It means that the tilt angle is related to the YS. Figure 9 (a) shows the high influence of offset and shoulder on % E. Any variation in the shoulder and offset will certainly influence the percentage elongation. Minimum and maximum shoulder diameters and offset, low %E is evidenced.

But when the two parameters are at center point, percentage elongation is high, shoulder diameter is 18mm and tool offset is at 0 levels. Referring to Figure 9 (b), it is observed that tool inclination has nil effect on %E but diameter of the shoulder has influence on %E. Low and high shoulder diameters, lower %E is observed and at center value of shoulder diameter (i.e., at 18mm), the %E is high. Moreover Figure 9 (b) also confirms that shoulder has influence on %E of the joint. Figure 9 (c) shows that offsets have high effect on %E and tool inclination has nil effect on %E. From the response graphs, tensile properties of the joint are low at minimum and maximum levels of tool diameters of the shoulder. When the weld is performed by setting at shoulder diameter of 16mm, offset as -2mm and tool inclination as 0° degree, low joint properties are observed. It is because of less friction producing less frictional heat [46]. Further the contact of two surfaces is less leading to insufficient heat generation resulting in absence of dynamic recrystallization, plastic deformation of the grains and grain growth [47, 48]. When the process of FSW is done at +1 level: shoulder diameter 20 mm, offset of +2 mm at 2° angle, more frictional heat is produced due to more contact area [49]. Though heat generated by the process is high, high joint properties are not observed. The possible reasons underlying may be at high temperatures the rate of formation of precipitates and intermetallic compounds along with high plasticity affects the dynamic recrystallization.

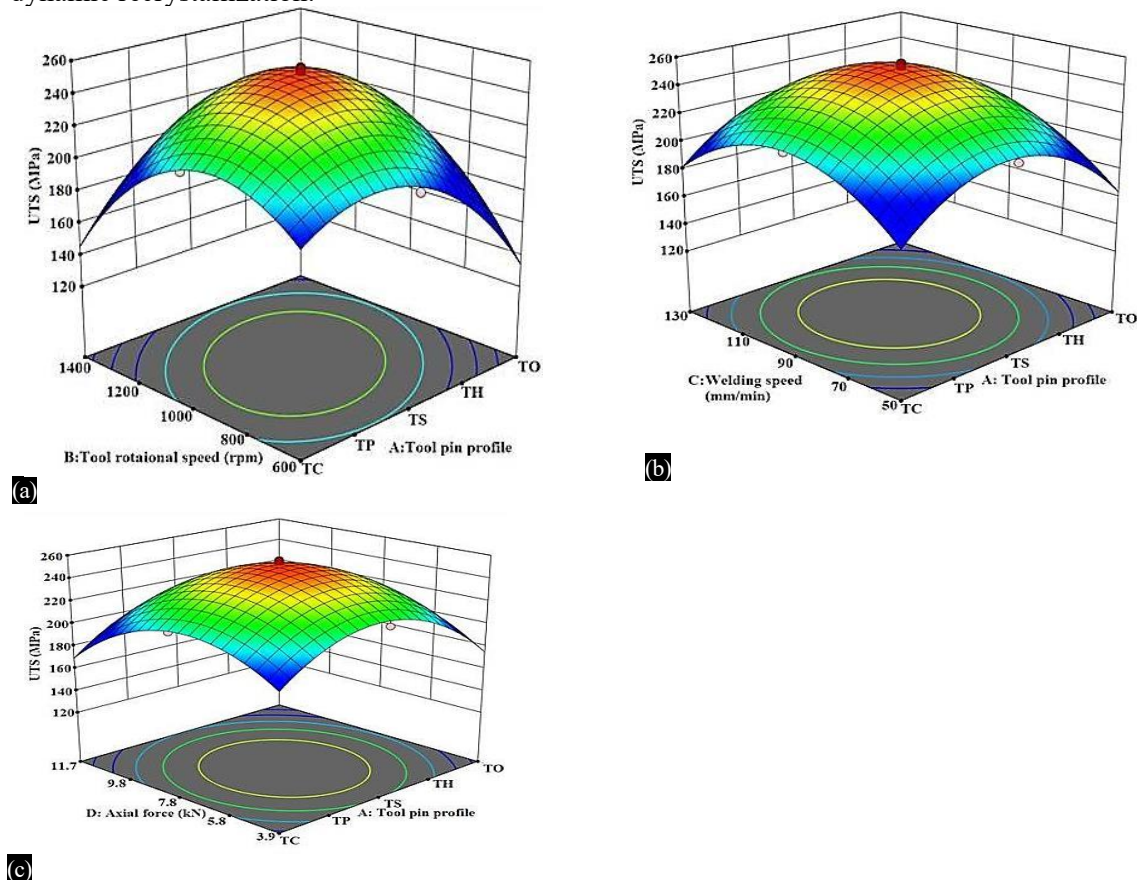


Figure 5. Influence of parameters on UTS.

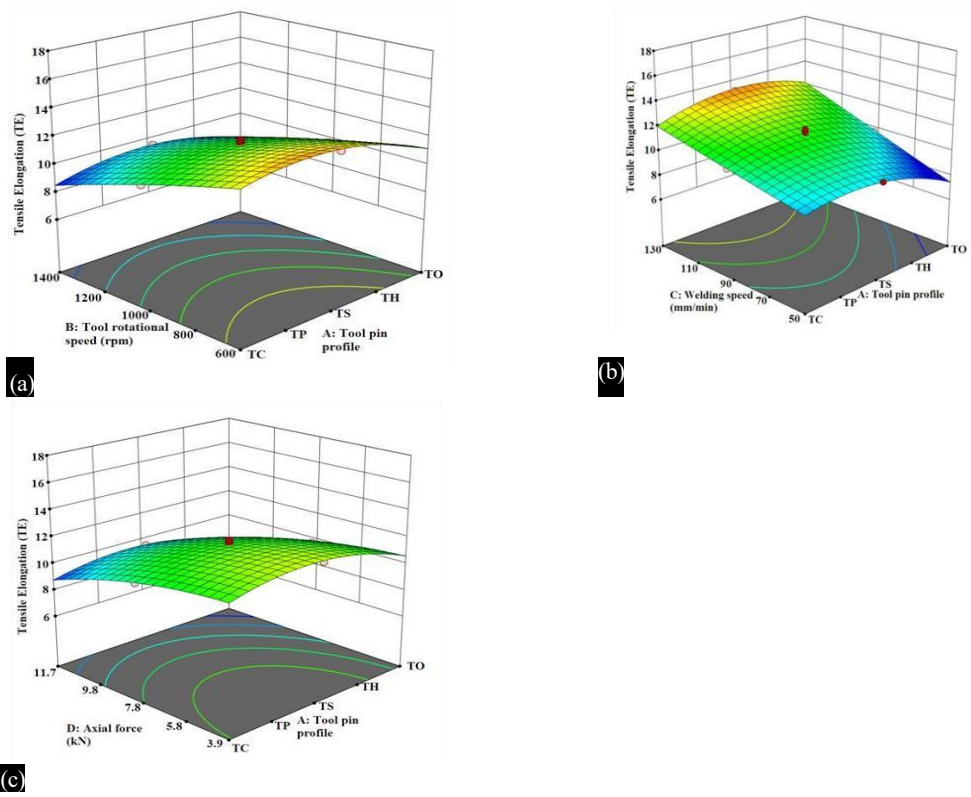


Figure 6. Influence of parameters on TE.

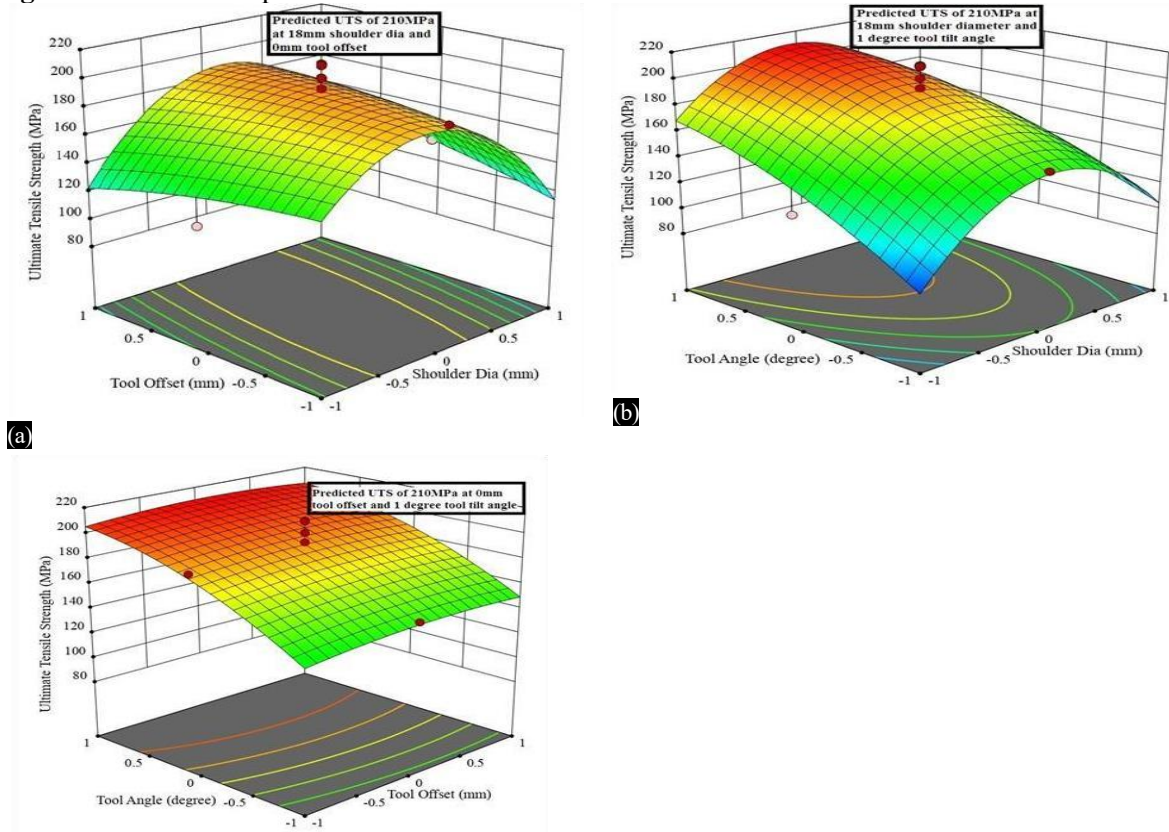


Figure 7. Effect of tool parameters on UTS.

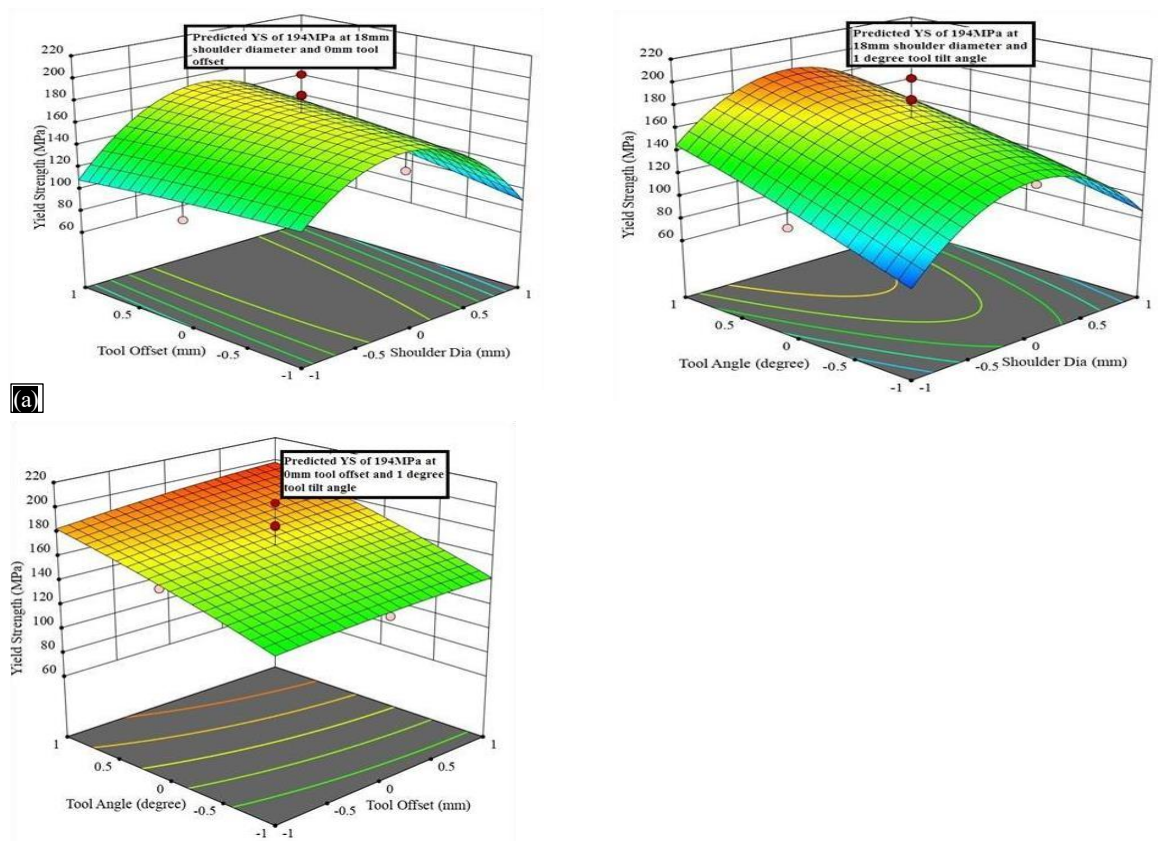
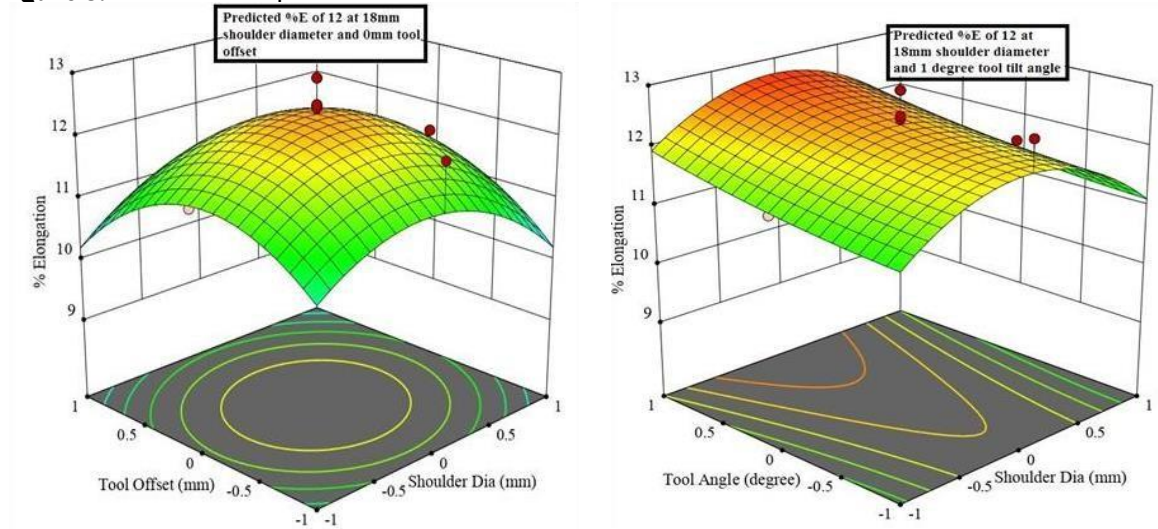


Figure 8. Effect of tool parameters on YS.



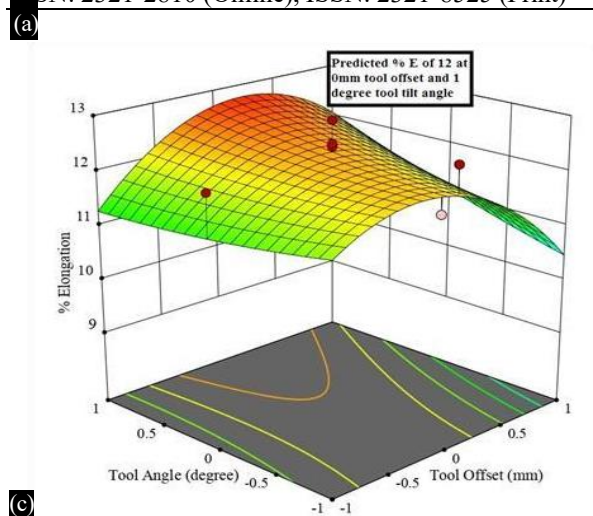


Figure 9. Effect of tool parameters on % elongation.

It is clear from the graphs that when tool parameters are set at 0 level as shoulder is 18mm, offset of 0mm and 1° tool inclination, maximum weld properties were observed: UTS: 210MPa, YS: 203MPa and %E: 12. The possible reasons could be proper occurrence of dynamic recrystallization. Since shoulder is the key element which influences tensile properties at all the levels.

CONCLUSIONS

The dissimilar joining of aluminium 5083 and 6082 alloys using various parameters performed successfully. Effect of parameters on UTS and elongation were studied using response surface graphs. The following

conclusions could be drawn:

- Tapered square tool pin improved that the weld possesses better mechanical properties.
- Shoulder diameter has effect on tensile properties hence significantly improves strength.
- No effect of tool off set on the tensile properties.
- Tool tilt angle has significant effect on the mechanical properties.

Acknowledgements

The authors are grateful to Ballari Institute of Technology and Management, Ballari, TEHRD Trust and UB DTCE, Davanagere for their financial support rendered for the research work.

REFERENCES

1. Hassan AM, Qasim T, Ghaithan A. Effect of pin profile on friction stir welded aluminum matrix composites. *Materials and Manufacturing Processes*. 2012 Dec 1;27(12):1397-401.
2. Daniolos NM, Pantelis DI. Microstructural and mechanical properties of dissimilar friction stir welds between AA6082-T6 and AA7075-T651. *The International Journal of Advanced Manufacturing Technology*. 2017 Feb;88:2497-505.
3. Sundaram NS, Murugan N. Tensile behavior of dissimilar friction stir welded joints of aluminium alloys. *Materials & Design*. 2010 Oct 1;31(9):4184-93.
4. Reza-E-Rabby, Md., Tang, W., Reynolds, A.P.: Effects of thread interruptions on tool pins in friction stir welding of A6061. *Sci. Technol. Weld. Join.* (2017).
5. Jagathesh, K., Jenarathanan, M.P., Dinesh Babu, P., Chanakyan, C.: Analysis of factors influencing tensile strength in dissimilar welds of AA2024 and AA6061 produced by Friction Stir Welding (FSW). *Aust. J. Mech. Eng.* 15(1), 19–26 (2017).
6. Rajakumar, S., Balasubramanian, V.: Establishing relationships between mechanical properties of aluminium alloys and optimised friction stir welding process parameters. *Mater. Des.* 40, 17–35 (2012).

7. Ahmeda, M.M.Z., Atayaa, S., El-Sayed Seleman, M.M., Ammara, H.R., Ahmeda, E.: Friction stir welding of similar and dissimilar AA7075 and AA5083. *J. Mater. Process. Technol.* 242, 77–91 (2017).
8. V. Saravanan, S. Rajakumar, Nilotpal Banerjee R. Amuthakkannan, Effect of shoulder diameter to pin diameter ratio on microstructure and mechanical properties of dissimilar friction stir welded AA2024-T6 and AA7075-T6 aluminum alloy joints, *Int J Adv Manuf Technol* (2016) 87:3637–3645.
9. E. G. Cole, A. Fehrenbacher, N. A. Duffie, M. R. Zinn, F. E. Pfefferkorn, N.J. Ferrier, Weld temperature effects during friction stir welding of dissimilar aluminum alloys 6061-t6 and 7075-t6, *Int J Adv Manuf Technol* (2014) 71:643–652.
10. A. S. Hassan, T. S. Mahmoud, F. H. Mahmoud & T. A. Khalifa Friction stir welding of dissimilar A319 and A356 aluminium cast alloys, *Science and Technology of Welding and Joining*, (2010) 15:5, 414-422.
11. M. Ghosh, K. Kumar, S.V. Kailas, A.K. Ray, Optimization of friction stir welding parameters for dissimilar aluminum alloys, *Materials and Design* 31 (2010) 3033–3037.
12. S.-K. Park, S.-T. Hong, J.-H. Park, K.-Y. Park, Y.-J. Kwon & 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), 15:4, 331-336.
13. S. Rajakumar, C. Muralidharan, V. Balasubramanian, Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints, *Materials and Design* 32 (2011) 535–549.
14. Huijie Liu & Huijie Zhang & Qing Pan & Lei Yu, Effect of friction stir welding parameters on microstructural characteristics and mechanical properties of 2219-T6 aluminum alloy joints, *Int J Mater Form* (2012) 5:235–241.
15. A. Astarita, A. Squillace, and L. Carrino. “Experimental Study of the Forces Acting on the Tool in the Friction-Stir Welding of AA 2024 T3 Sheets”, *JMEPEG* (2014) 23:3754–3761.
16. J. C. Hou, H. J. Liu, Y. Q. Zhao, “Influences of rotation speed on microstructures and mechanical properties of 6061-T6 aluminum alloy joints fabricated by self-reacting friction stir welding tool”, *Int J Adv Manuf Technol* (2014) 73:1073–1079.
17. Şefika Kasman & Zafer Yenier, “Analyzing dissimilar friction stir welding of AA5754/AA7075”, *Int J Adv Manuf Technol* (2014) 70:145–156.
18. Beytullah Gungor, Erdinc Kaluc, Emel Taban, Aydin Sik, Mechanical, fatigue and microstructural properties of friction stir welded 5083-H111 and 6082-T651 aluminum alloys, *Materials and Design* 56 (2014) 84–90.
19. R. Hariharan and R.J. Golden Renjith Nimal, Friction Stir Welding of Dissimilar Aluminium Alloys (6061&7075) By Using Computerized Numerical Control Machine, *Middle-East Journal of Scientific Research* 20(5):601-605, 2014.
20. Heena K Sharma, Kamlesh Bhatt, Krupal Shah Unnati Joshi, “Experimental Analysis of Friction Stir Welding of Dissimilar Alloys AA6061 and Mg AZ31”, *Procedia Technology* 23 (2015) 566–572.
21. H. Shirazi, Sh. Kheirandish, M.A. Safarkhanian, “Effect of process parameters on the macrostructure and defect formation in friction stir lap welding of AA5456 aluminum alloy”, *Measurement* 76 (2015) 62–69.
22. Mohammad K. Sued, and Dirk J. Pons, Dynamic Interaction between Machine, Tool, and Substrate in Bobbin Friction Stir Welding, Hindawi Publishing Corporation International Journal of Manufacturing Engineering Volume 2016, Article ID 8697453, 14 pages <http://dx.doi.org/10.1155/2016/8697453>.
23. P. Mastanaiah, Abhay Sharma, G. Madhusudhan Reddy, Dissimilar Friction Stir Welds in AA2219-AA5083 Aluminium Alloys: Effect of Process Parameters on Material Inter-Mixing, Defect Formation, and Mechanical Properties, *Trans Indian Inst Met* (2016) 69(7):1397–1415.

24. D. A. Dragatogiannis, E.P.Koumoulos, I. A. Kartsonakis, D.I. Pantelis, P. N. Karakizis & C. A. Charitidis (2016) Dissimilar Friction Stir Welding Between 5083 and 6082 Al Alloys Reinforced With TiC Nanoparticles, *Materials and Manufacturing Processes*, 31:16, 2101-2114.
25. Vahid Moosabeiki Dehabadi, Saeede Ghorbanpour, Ghasem Azimi, Application of artificial neural network to predict Vickers microhardness of AA6061 friction stir welded sheets, *J. Cent. South Univ.* (2016) 23:2146–2155.
26. Mr. P H Shah, Dr. Vishvesh Badheka, An experimental investigation of temperature distribution and joint properties of Al 7075 T651 friction stir welded aluminium alloys, *Procedia Technology* 23 (2016) 543 – 550.
27. K. Jagathesh, M.P. Jenarathanan, P. Dinesh Babu & C. Chanakyan (2017) Analysis of factors influencing tensile strength in dissimilar welds of AA2024 and AA6061 produced by Friction Stir Welding (FSW), *Australian Journal of Mechanical Engineering*, 15:1, 19-26.
28. M.M.Z. Ahmed, Sabbah Ataya, M.M. El-Sayed Seleman, H.R. Ammar, Essam Ahmed, Friction stir welding of similar and dissimilar AA7075 and AA5083, *Journal of Materials Processing Technology* 242 (2017) 77–91.
29. Abdel-Wahab El-Morsy, Mohamed M. Ghanem, Haitham Bahaiham, Effect of Friction Stir Welding Parameters on the Microstructure and Mechanical Properties of AA2024-T4 Aluminum Alloy, *Engineering, Technology & Applied Science Research* Vol. 8, No. 1, 2018, 2493-2498.
30. Guoqiang Huang, Dongxu Cheng, Haoming Wang, Qihui Zhou & Yifu Shen (2019): Effect of tool probe with a disc at the top on the microstructure and mechanical properties of FSW joints for 6061-T6 aluminum alloy, *Journal of Adhesion Science and Technology*.
31. B. B. Wang, P. Xue, B. L. Xiao, W. G. Wang, Y. D. Liu & Z. Y. Ma (2019): Achieving equal fatigue strength to base material in a friction stir welded 5083-H19 aluminium alloy joint, *Science and Technology of Welding and Joining*.
32. G. H. Li, L. Zhou, S. F. Luo, Z. Y. Du, J. C. Feng & F. X. Meng (2019): Microstructure and mechanical properties of self-reacting friction stir welded AA2219-T87 aluminium alloy, *Science and Technology of Welding and Joining*.
33. Mohamed M. Abd Elnabi, Abou Bakr Elshalakany, M.M. Abdel-Mottaleb, T.A. Osman, A. El Mokadem, Influence of friction stir welding parameters on metallurgical and mechanical properties of dissimilar AA5454– AA7075 aluminum alloys, *J Mater Res Technol* . 2019; 8(2):1684–1693.
34. H.M. Anil Kumar, V. Venkata Raman, S.P. Shanmughanathan, Jacob John and U. Mohammed Iqbal Optimization of Dissimilar Friction Stir Welding Process Parameters of AA5083-H111 and AA6082-T6 by CCD-RSM Technique, Springer Nature Singapore Pte Ltd. 2019, *Advances in Manufacturing Processes, Lecture Notes in Mechanical Engineering*, https://doi.org/10.1007/978-981-13-1724-8_5.
35. H.M. Anil Kumar, V. Venkata Ramana, Influence of tool parameters on the tensile properties of friction stir welded aluminium 5083 and 6082 alloys, *Materials Today: Proceedings* 27, Part 2 (2020) 951-957, doi.org/10.1016/j.matpr.2020.01.270.
36. Landry Giraud, Hugo Robe, Christophe Claudin, Christophe Desrayaud, Philippe Bocher, Eric Feulvarch, Investigation into the dissimilar friction stir welding of AA7020-T651 and AA6060-T6, *Journal of Materials Processing Technology* 235 (2016) 220–230.
37. Bazani Shaik, G. Harinath Gowd and B. Durga Prasad, Investigations and optimization of friction stir welding process to improve microstructures of aluminum alloys, *Cogent Engineering* (2019), 6: 1616373.
38. Elangovan K, Balasubramanian V, Valliappan M. Influences of pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy. *Int J Adv Manuf Technol* 2008;38(3-4).
39. Lomolino S, Tovo R, Dos Santos J. On the fatigue behavior and design curves of friction stir butt welded Al alloys. *Int J Fatigue* 2005;27:305–16.
40. Benavides S, Li Y, Murr LE, Brown D, McClure JC. Low-temperature friction-stir welding of 2024 aluminum. *Scripta Mater* 1999;41(8):809–15.

41. Threadgill P. Friction stir welds in aluminium alloys preliminary microstructural assessment, TWI Bulletin-The Welding Institute, Abington, UK; 1997: Industrial report no: 513/2/97.
42. Colligan J, Paul J, Konkol, James J, Fisher, Pickens Joseph R. Friction stir welding demonstrated for combat vehicle construction. *Weld J* 2003:1–6.
43. R. Palanivel, P. Koshy Mathews, N.Murugan, Optimization of process parameters to maximize ultimate tensile strength of friction stir welded dissimilar aluminum alloys using response surface methodology, *J. Cent. South Univ.* (2013) 20: 2929–2938.
44. Ouyang JH, Kovacevic R. Material flow and microstructure of the friction stir butt welds of the same and dissimilar aluminum alloys. *J Mater Eng Perform* 2002;11(1):51–63.
45. Zhang Z, Zhang HW. Numerical studies on effect of axial pressure in friction stir welding. *Sci Technol Weld Joining* 2007;12(3):226–48.
46. Masoud Ahmadnia& Saeid Shahraki& Mojtaba Ahmadi Kamarposhti, Experimental studies on optimized mechanical properties while dissimilar joining AA6061 and AA5010 in a friction stir welding process, *Int J Adv Manuf Technol* (2016) 87:2337–2352.
47. Sato YS, Urata M, Kokawa H, Ikeda K. Hall–petch relationship in friction stir welds of equal channel angular- pressed aluminium alloys. *Mater Sci Eng* 2003;A354:298–305.
48. Srivatsan TS, Satish Vasudevan, Lisa Park. The tensile deformation and fracture behavior of friction stir welded aluminum alloy 2024. *Mater Sci Eng A* 2007;466:235–45.
49. M.I.Costa, C.Leitao, D.M.Rodrigues, Influence of post-welding heat-treatment on the monotonic and fatigue strength of 6082-T6 friction stir lap welds, *Journal of Materials Processing Tech.* 250 (2017) 289–296