Experimental Investigations of Tool Pin Geometry and Process Parameter Influence on Mechanical Property of Friction Stir Welded 6101-T6 and 7075-T651 Aluminium Alloys

Olatunji P Abolusoro¹* and Esther T Akinlabi²

¹, ²Department of Mechanical Engineering Science, University of Johannesburg, Gauteng, South Africa.
² Department of Mechanical Engineering, Covenant University, Ota, Ogun State, Nigeria
* Corresponding Author: abolusorooolatunji@yahoo.com

Abstract-
One of the variables that significantly affect the joint integrity of welds carried out with friction stir welding (FSW) is the tool pin geometry. This particular factor considerably affects the mechanical properties, joint size and microstructural evolution of the weld. The extent to which tool geometry affects the mechanical behaviour of welds under different processing parameters needs to be fully understood in order to achieve highly reliable joints for various industrial applications. This work is, therefore, an attempt at, investigating tool pin geometry and processing parameters effects on the mechanical behaviour and stability of friction stir welds through joining of 6101-T6 and 7075-T651 aluminium alloys via FSW. Two pin designs named tapered unthreaded and tapered threaded were used for this study. The result obtained shows that low rotational speed and high welding speed promote the tensile strength of the welded alloys and that welds carried out with the tapered threaded tool gave higher tensile values than the tapered unthreaded.

Keywords: Mechanical properties, tensile strength, tool geometry, friction stir welding

1. Introduction
Friction stir welding is a system of welding categorized under solid state form of welding where a tool made up of pin and shoulder rotates on the joint interface of the workpiece to be joined, producing heat in the process thereby causing plasticization of the materials. The pin stirring mechanism mixes the plasticized interface materials together and produces bonding as the tool traverse the joint line [1], [2], [3], [4], [5]. Friction stir welding has become the most suitable technique for joining aluminium alloys [6], [7], [8]. The mechanical properties and general quality of welds produced from FSW are often affected by a number of variables. Principal among them are the geometry or profile of the tool pin and their rotational and travel speed [9], [10], [11]. Material movement and temperature distributions are often influenced by the tool pin design and the tool movements, consequently, the microstructural development and the mechanical qualities of the weld are also affected [12], [13]. The design of an efficient tool for friction stir welding required that the tool shape be simple enough to minimize cost and must possess adequate stirring ability to produce good welds. Many researchers have therefore been attracted to the investigations of tool profile effects on the performance of friction stir welded materials especially aluminium alloys. Chent et al [14] used computational fluid dynamics (CFD) to investigate the effects of threaded and unthreaded tool pin on material flow. They noted that threaded tool pin geometry performs better through the formation of vertical pressure slope. This was in agreement with Illangova et al’s studies [15]. Reza-E-Rabby et al [16] investigated pin thread effects on weld performance of FSW of AA 6061-T651. Their report
indicated that flat threaded tool pin largely excludes defects unlike the threaded tool with flat and without a flat. Elangovan et al [17] obtained sound mechanical properties and welds free from defects by using square pin under medium rotational speed to friction stir weld AA6061. Bayazid et al [18] equally employed cylindrical, triangle and square pin tool to weld 7075 alloy. They observed that cylindrical and square pin gave various defects but welds obtained with square pin tool were defects free. Colligan investigated material flow pattern during FSW by embedding a tracer into the weld path. He reported that the tool thread influenced the full flow of plasticized materials around the probe [19]. Zhang et al [20] and Querin et al [21] in their separate investigations confirmed that tool profile significantly affects material movement and heat supplied to the weld. Aval [22] studied the effects of tool pin profile on mechanical behaviour and microstructure development of 6082 and 7075 aluminium alloys welded through friction stir method. They observed that square frustrum pin gave homogenous mixing of the two metals. Madhav et al [23] in their study on FSW of AA6061 and AA7075 reported that cylindrical threaded pin having 3 flat surfaces and cylindrical groove demonstrated better tensile strength than the other tools used. In a related study, Palanivel et al [24] welded AA5083-H111 and AA6351-T6 via FSW using five different tool pin geometry to investigate their effects on microstructure and tensile strength. They revealed that the straight square pin design produced the highest strength. Processing parameters influence on some FSW of aluminium alloys has also been reported. Aissani [25] demonstrated how processing parameter mostly pin profile and tool rotational speed affect the tensile strength of welded aluminium alloys via friction stir. Lombard et al [26] employed eleven parameters of tool travel and rotational speed combinations for optimization. Their results showed that the highest value of 313MPa was obtained at 200rpm and 80mm/min rotational and travel speed respectively. Ghosh et al [27] reported better joint strength for dissimilar weld of A356 and 6061 aluminium alloys at an optimized tool rotational and travel speed. Rajakumar et al [28] demonstrated the existence of a range of tool rotational speed within which weld quality can be ascertained. Although works in contemporary literature indicate that pin profile, tool rotational and travel speed affects microstructure, defects and mechanical behaviour of welds, however, a comparative analysis of basic tool geometry, rotational and travel speed for dissimilar welding of aluminium alloys is yet to be fully reported. The welding of dissimilar aluminium alloys using friction stir welding method still demand special attention own to variation in mechanical strength, the thermal stability of the base materials, material movement pattern and metallurgical properties. This work, therefore, seeks to investigate the effect of tool pin design and welding variables such as travel speed and rotational speed of the tool on the mechanical behaviour of FSW of 6101-T6 and 7075-T651 aluminium alloys.

2 Experimental procedures

2.1 Sample’s Elemental Composition and Properties

The elemental compositions of the two alloys are presented in table 1.

Table 1: chemical components of the welded alloys

| Alloy     | Si   | Cu  | Fe  | Mn  | Mg  | Ti  | Cr  | Zn  | Al  |
|-----------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| 6101-T6   | 0.53 | 0.01| 0.14| 0.002| 0.600| 0.008| 0.001| 0.003| Others |
| 7075-T651 | 0.40 | 1.70| 0.50| 0.300| 2.40 | 0.20 | 0.22 | 5.50 | Others |
2.2 Welding set up

The FSW was carried out on aluminium alloys 6101-T6 and 7075-T651 of 6mm thickness each. Prior to the welding, the alloys were cut into pieces of about 130mm × 60mm each. The edges to be joined were milled to allow proper lapping and positioning for welding. The surface areas of both alloys were cleaned with emery paper and washed with acetone to remove oxide layer deposits and oil or grease on the alloy surfaces. Two tools with cylindrical tapered pins, one threaded and the other unthreaded both having 22mm shoulder diameter, pin root diameter of 7.5mm and pin mouth diameter of 5.5mm as presented in figure 1 (a) and (b) and figure 2 (a) and (b) were investigated for this work. The plates to be joined were positioned in butt configuration. The 6101-T6 was kept on the advancing side while the 7075-T651 was located on the retrieving side. The two alloys were clamped in this arrangement for the welding as shown in figure 3. The welding took place in the rolling direction of the alloys. The five variable parameters employed for this work are shown in table 2. Other process parameters remained constant. These include tilt angle of 2° and plunge depth of 0.15mm. Five welds were carried out with each tool using the processing parameters shown in table 2. Three tensile samples each were cut from each weld for evaluation following ASTM standard E8 as presented in figure 4. The ultimate tensile strengths of the parent materials are shown in table 3.

![Figure 1: Diagram of cylindrical tapered threaded tool](image)

(a)  (b)
Figure 2: Diagram of cylindrical tapered unthreaded tool (a) Schematic (b) picture

![Diagram of cylindrical tapered unthreaded tool](image)

Figure 3: Welding arrangement

![Welding arrangement](image)

Table 2: Processing parameters

| S/N | Rotational speed (rpm) | Travel speed (mm/min) |
|-----|------------------------|-----------------------|
| 1   | 1550                   | 50                    |
| 2   | 1550                   | 80                    |
| 3   | 1550                   | 110                   |
| 4   | 1250                   | 110                   |
| 5   | 1850                   | 110                   |
Table 3: Mechanical properties of the welded alloy

| Alloy  | Tensile Strength (MPa) | Ultimate Tensile Strength (MPa) | Elongation (%) |
|--------|------------------------|---------------------------------|----------------|
| 6101-T6 | 172                    | 180                             | 21             |
| 7075-T651 | 462                | 575                             | 18             |

3 Results and Discussion

Three samples each as shown in figure 4 were cut from the welds upon which the tensile tests were carried out. The average values of the ultimate tensile strengths obtained for all the welding variables used are shown in table 4.

Figure 4: Tensile samples from weld of each parameter for both tools

Table 4: Processing parameters and corresponding ultimate tensile strength values for threaded and unthreaded tool pins.

| S/N | Rotational Speed (rpm) | Travel Speed (mm/min) | Ultimate Tensile Strength (MPa) (Threaded Tool) | Ultimate Tensile Strength (MPa) (Unthreaded Tool) |
|-----|------------------------|-----------------------|--------------------------------------------------|--------------------------------------------------|
| 1   | 1550                   | 50                    | 140                                              | 140                                              |
| 2   | 1550                   | 80                    | 144                                              | 142                                              |
| 3   | 1550                   | 110                   | 147                                              | 144                                              |
| 4   | 1250                   | 110                   | 155                                              | 148                                              |
| 5   | 1850                   | 110                   | 142                                              | 139                                              |
3.1 Effects of Rotational Speed on the tensile behaviour of the welds from both tools

The tensile behaviour similarly varies across all the rotational speeds at a constant travel speed of 110mm/min in both tools used for the experiment. The tensile strength generally decreases as the rotational speed increases as shown in figure 5. This can be ascribed to increase in the heat supplied to the weld when the rotational speed increases. The higher thermal cycle set up in the weld causing microstructural reorientations at the three regions of the thermomechanical affected zone (TMAZ), heat affected zone (HAZ) and the nugget zone (NZ) of the weld. Coarsening of the precipitates occurred at greater rotational speed but at lesser rotational speed, greater grain boundary of precipitates took place which promotes high tensile strength.

![Graph showing effects of rotational speed on tensile strength of threaded and unthreaded tools](image1)

**Figure: 5**

Figure 5: Effects of rotational speed on the ultimate tensile strength of both threaded and unthreaded tool pin.

![Graph showing effects of travel speed on tensile strength of threaded and unthreaded tools](image2)

**Figure: 6**

Figure 6: Effects of travel speed on the ultimate tensile strength of both threaded and unthreaded tool pin.

3.2 Influence of travel speed on the tensile behaviour of the welds from both tools

Both tools exhibited similar behaviour across the varied speeds at constant tool rotational speed of 1550rpm. Although both tools demonstrate the same tolerance to tensile strength at 50mm/min travel speed however, the tensile strength decreases as the travel speed increases as shown in fig. 5 and 6. This is due to less tool dwelling time on the workpiece at higher travel speeds. This implies that less heat is impacted into the weld as the tool travel faster on the workpiece. Also, part of the heat emanating from the tool is absorbed as latent heat for plasticization. The resulting less heat promotes grain bonding at the joint interface of the weld and consequently promotes the tensile strength of the joint leading to greater values obtained as the speed increases.
3.3 Effects of pin profile on Tensile behaviour.

The Ultimate tensile strength obtained for both the threaded and the unthreaded tools at constant travel speed and constant rotational speed exhibited similarities. However, the ultimate tensile values obtained for the threaded tool pin are higher than those of the unthreaded pin for all the processing parameters as shown in table 4 except at 1550rpm and 50mm/min where the values are the same. The highest ultimate tensile strength of 155MPa was recorded for the threaded tool. The better performance of the threaded tool pin over the unthreaded can be attributed to homogenous material mixing and enhancement of resistance to grain boundary dislocations own to the threads on the pin.

4 Conclusions

Conclusions can be drawn based on this experiment as follows
1. Both the threaded and the unthreaded tool pin developed, are suitable for friction stir welding of aluminium alloys.
2. Rotational speed increase during the friction stir welding does not promote tensile properties in both tools. However, increase in travel speed favours increase in ultimate tensile strength.
3. The threaded tool pin performs better than the unthreaded tool pin in terms of tensile strength.

Reference

[1] Kadian, A.K. and Biswas, P. (2017) Effect of tool pin profile on the material flow characteristics of AA6061. Journal of Manufacturing Processes, 26, 382–92. https://doi.org/10.1016/j.jmapro.2017.03.005
[2] Azmal Hussain, M., Zaman Khan, N., Noor Siddiquee, A. and Akhtar Khan, Z. (2018) Effect of Different Tool Pin Profiles on the Joint Quality of Friction Stir Welded AA 6063. Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2017.11.680
[3] Jadhav, G.C. and Dalu, R.S. (2014) Friction Stir Welding – Process Parameters and its Variables: A Review. International Journal Of Engineering And Computer Science, 3.
[4] Sidhu, M.S. and Chatha, S.S. (2012) Friction Stir Welding – Process and its Variables: A Review. 2.
[5] Akinlabi, E.T., Andrews, A. and Akinlabi, S.A. (2014) Effects of processing parameters on corrosion properties of dissimilar friction stir welds of aluminium and copper. Transactions of Nonferrous Metals Society of China (English Edition), The Nonferrous Metals Society of China. 24, 1323–30. https://doi.org/10.1016/S1003-6326(14)63195-2
[6] J. Brian Jordon, Harish Rao, Robert Amaro, P.A. (2019) CHAPTER 1 Introduction to Fatigue in Friction Stir Welding 1.1. Fatigue in Friction Stir Welding, 1–8.
[7] Ranjan, R., Carlos, A., Miranda, D.O., Hui, S., Walbridge, S. and Gerlich, A. (2019) Fatigue analysis of friction stir welded butt joints under bending and tension load. Engineering Fracture Mechanics, 206, 34–45.
[8] Akinlabi, E.T., Andrews, A. and Akinlabi, S.A. (2014) Effects of processing parameters
on corrosion properties of dissimilar friction stir welds of aluminium and copper. Transactions of Nonferrous Metals Society of China (English Edition), 24, 1323–30. https://doi.org/10.1016/S1003-6326(14)63195-2

[9] Lim, S., Kim, S., Lee, C.G. and Kim, S. (2004) Tensile behaviour of friction-stir-welded A356-T6/Al 6061-T651 bi-alloy plate. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 35 A, 2837–43. https://doi.org/10.1007/s11661-004-0231-4

[10] Kumar, R.A. and Thansekhar, M.R. (2014) Effects of Tool Pin Profile and Tool Shoulder Diameter on the Tensile Behaviour of Friction Stir Welded Joints of Aluminium Alloys. Advanced Materials Research, 984–985, 586–91. https://doi.org/10.4028/www.scientific.net/amr.984-985.586

[11] Ravikumar, S., Seshagiri Rao, V. and Pranesh, R. V. (2014) Effect of Process Parameters on Mechanical Properties of Friction Stir Welded Dissimilar Materials between AA6061-T651 and AA7075-T651 Alloys. International Journal of Advanced Mechanical Engineering, 4, 101–14. https://doi.org/10.1016/j.matdes.2014.10.065

[12] Leal, R.M., Galvão, I., Loureiro, A. and Rodrigues, D.M. (2015) Effect of friction stir processing parameters on the microstructural and electrical properties of copper. International Journal of Advanced Manufacturing Technology, 80, 1655–63. https://doi.org/10.1007/s00170-015-7141-z

[13] Leal, R.M., Leitão, C., Loureiro, A., Rodrigues, D.M. and Vilaça, P. (2008) Material flow in heterogeneous friction stir welding of thin aluminium sheets: Effect of shoulder geometry. Materials Science and Engineering A, 498, 384–91. https://doi.org/10.1016/j.msea.2008.08.018

[14] Chen, G., Li, H., Wang, G., Guo, Z., Zhang, S., Dai, Q. et al. (2018) Effects of pin thread on the in-process material flow behaviour during friction stir welding: A computational fluid dynamics study. International Journal of Machine Tools and Manufacture, 124, 12–21. https://doi.org/10.1016/j.ijmachtools.2017.09.002

[15] Elangovan, M., Rajendra Boopathy, S. and Balasubramanian, V. (2015) Effect of tool pin profile on microstructure and tensile properties of friction stir welded dissimilar AA 6061–AA 5086 aluminium alloy joints. Defence Technology, 11, 174–84. https://doi.org/10.1016/j.dt.2015.01.004

[16] Reza-E-Rabby, M., Tang, W. and Reynolds, A.P. (2018) Effects of thread interruptions on tool pins in friction stir welding of AA6061. Science and Technology of Welding and Joining, 23, 114–24. https://doi.org/10.1080/13621718.2017.1341363

[17] Elangovan, K., Balasubramanian, V. and Valliappan, M. (2008) Effect of tool pin profile and tool rotational speed on mechanical properties of friction stir welded AA6061 aluminium alloy. Materials and Manufacturing Processes, 23, 251–60. https://doi.org/10.1080/10426910701860723

[18] Bayazid, S.M., Farhangi, H. and Gahramani, A. (2015) Effect of Pin Profile on Defects of Friction Stir Welded 7075 Aluminum Alloy. 11, 12–6. https://doi.org/10.1016/j.mspro.2015.11.013

[19] Colligan, K. (1999) Material flow behaviour during friction welding of aluminium. Welding Journal, 229–37.

[20] Zhang, Y.N., Cao, X., Larose, S. and Wanjara, P. (2012) Review of tools for friction stir welding and processing. Canadian Metallurgical Quarterly, 51, 250–61. https://doi.org/10.1179/1879139512Y.0000000015
[21] Querin, J.A., Rubisoff, H.A. and Schneider, J.A. (2009) Effect of weld tool geometry on friction stir welded Ti-6Al-4V. *ASM Proceedings of the International Conference: Trends in Welding Research*, p. 108–12. https://doi.org/10.1361/cp2008twr108

[22] Jamshidi Aval, H. (2015) Influences of pin profile on the mechanical and microstructural behaviours in dissimilar friction stir welded AA6082-AA7075 butt Joint. *Materials and Design*, 67, 413–21. https://doi.org/10.1016/j.matdes.2014.11.055

[23] Raturi, M., Garg, A. and Bhattacharya, A. (2019) Joint strength and failure studies of dissimilar AA6061-AA7075 friction stir welds: Effects of tool pin, process parameters and preheating. *Engineering Failure Analysis*, 96, 570–88. https://doi.org/10.1016/j.engfailanal.2018.12.003

[24] Palanivel, R., Koshy Mathews, P., Murugan, N. and Dinaharan, I. (2012) Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminium alloys. *Materials and Design*, 40, 7–16. https://doi.org/10.1016/j.matdes.2012.03.027

[25] Givi, M.K.B. and Asadi, P. (2014) Advances in Friction-Stir Welding and Processing. *Adv. Frict. Weld. Process*. https://doi.org/10.1016/C2013-0-16268-X

[26] Lombard, H., Hattingh, D.G., Steuwer, A. and James, M.N. (2008) Optimising FSW process parameters to minimise defects and maximise fatigue life in 5083-H321 aluminium alloy. *Engineering Fracture Mechanics*, 75, 341–54. https://doi.org/10.1016/j.engfracmech.2007.01.026

[27] Ghosh, M., Kumar, K., Kailas, S. V. and Ray, A.K. (2010) Optimization of friction stir welding parameters for dissimilar aluminium alloys. *Materials and Design*, 31, 3033–7. https://doi.org/10.1016/j.matdes.2010.01.028

[28] Rajakumar, S. and Balasubramanian, V. (2012) Establishing relationships between mechanical properties of aluminium alloys and optimised friction stir welding process parameters. *Materials and Design*, 40, 17–35. https://doi.org/10.1016/j.matdes.2012.02.054