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Effect of tool pin profile on the tensile characteristics of friction stir welded joints of AA8011

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ABSTRACT

Introduction. Aluminum alloys are in abundant demand of shipbuilding and aircraft industries. This study emphasizes on the effects of two different tool pin profiles on the tensile characteristics of welded joints made of *AA8011* aluminum alloy welded joints. The joining technique used is friction stir welding (*FSW*) due to its unique characteristics such as very low heat affected zone when joining in a solid state. The microstructure and mechanical properties of the welded joint are influenced by the geometry of the tool and such parameters as rotational speed and traverse speed of the tool. **The methods of investigation.** The experiments on *FSW* were performed on universal milling machine with taper cylindrical and cylindrical threaded tool pin profiles using the three different combination of tool rotational and traverse speed (a) 320 rpm, 45 mm/min; b) 400 rpm, 50 mm/min; c) 575 rpm, 60 mm/min.). To analyze the joint characteristics, tensile tests were conducted and ultimate tensile strength as well as joint efficiency was calculated for individual joint. **Results and Discussion.** Based on the revised results, it is evident that higher *RPM* values have a positive impact on joint efficiency and tensile strength for both the taper cylindrical pin profile and the threaded cylindrical pin profile. The findings show that the joint efficiency and tensile strength are consistently higher for the threaded cylindrical pin profile compared to the taper cylindrical pin profile, regardless of the *RPM* and feed rate. From the results, it was found that joint efficiency and tensile strength is maximum at higher *RPM* irrespective of the tool pin profile i.e. 73.6 % and 123 MPa for taper cylindrical pin profile and 85 % and 142 MPa for threaded cylindrical pin profile at 575 rpm, 60 mm/min. These are the highest in comparison to 72.5 % and 119 MPa at 320 rpm, 45 mm/min and 70.1 % and 115 MPa at 400 rpm, 50 mm/min for taper pin profile tool and 82.6 % and 138 MPa at 320 rpm, 45 mm/min and 77.8 % and 130 MPa at 400 rpm, 50 mm/min for threaded cylindrical pin profile. Overall, the study demonstrates that joints obtained using the threaded cylindrical pin profile demonstrate higher joint efficiency and tensile strength than those prepared using the taper cylindrical pin profile. The highest joint efficiency and tensile strength of 84.5 % and 142 MPa, respectively, were achieved using the threaded cylindrical pin profile at 575 rpm and 60 mm/min.

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Introduction

Friction stir welding (*FSW*), which was invented by *Wayne Thomas* at TWI in 1991, is well suited for joining solid state metals [1–2]. Aluminum alloys are often used in the aircraft and automobile industries, railway transport, and bridge construction due to its high strength-to-weight ratio and corrosion resistance [2]. As compared to the other conventional welding process, the material undergoes severe

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plastic deformation, resulting in the formation of a stir zone with very fine recrystallized grains [3], called a dynamic recrystallization zone [4–6]. Friction stir welding is also characterized by low energy consumption [7]. Melting and recrystallization do not occur, so the materials are joining in a solid state.

FSW is of particular importance for joining of aluminum and magnesium alloys since it can significantly reduce defects such as solidification cracking, porosity and distortions, which are the commonly observed during fusion welded. These process capabilities of *FSW* have made it very practical for joining some alloys. The interaction of the tool bottom surface and the pin surface with material being processed results in the generation of sufficient frictional heat to soften the material without melting [8–9]. Thus, the surface of the tool pin plays a critical role in the generation of frictional heat, material flow and plastic deformation. The tool offset is also critical factor that determines the heat generated when the tool tip rubs against the material [10], therefore it determines the thermal-physical properties in the weld zone [11–12]. The quality of the joints depends on the correct choice of *FSW* process parameter [13, 14]. As practice shows, some investigations are focused on the friction stir welding of hot and cold-worked aluminum alloys [15] using some specially designed tools [16] with various pin shapes such as hexagon, pentagon and square [17]. Some recent studies have shown that *FSW* is capable of joining both similar and dissimilar aluminum alloys [18–21]. Butt joints in friction stir welding are very common, compared to aluminum alloy lap joints, which have been studied by only a few researchers [22, 23]. *Davidson et al.* [24] investigated the tensile strength characteristic of the friction stir welded joints of *AA8011* aluminum under different process parameter and concluded that the joint fabricated at traverse speed of 45 mm/min and tool rotational speed of 1,400 rpm and axial thrust of 2.15 kN have better tensile strength compared to the other joints. *K. Palani et al.* [25] fabricated dissimilar *FSW* joint and focused on the impact of process variables and tool design on joint quality. Consequently, this work attempted to determine the effect of three different tip profiles (square, pentagonal, and hexagonal) and the combination of tool rotational speed and traverse speed on the tensile properties of *FSW* joints of dissimilar aluminum alloys *AA6061*-T6 and *AA8011*. By implementing *FSW*, *Elangovan* and *Balasubramanian* [26–28] examined the performance of five various geometries of pin namely “threaded cylindrical”, “tapered cylindrical”, “triangular”, “square”, “straight cylindrical” on *AA2219* aluminum alloy. Although previous research have shown that the tool pin profiles [29—31] or pin shapes [32] and welding speed influence strength enhancement, a connection between low welding speed and pin profile has not yet been established. Therefore, in the present research, *AA8011* aluminum alloy was friction stir welded at low welding speed with the different pin profiles, and effect on joint quality is evaluated in terms of hardness and tensile properties.

Investigation Technique

An experiment was conducted to obtain defect-free *FSW* joints of *AA8011* on a vertical milling machine; the plates to be welded were mounted on the base plate with clamps, as shown in fig. 1. Fig. 2 represents the plastic flow of the material during the welding process. The chemical composition of *AA8011* is shown in table 1. The process parameters considered include tool pin profiles as shown in fig. 3, with all the tool characteristics listed in table 2 and few combinations of tool rotational speed and traverse speed. These parameters are known to have an important impact on the strength and other mechanical properties of the joint.

A rolled plate 6 mm thick was cut into the required size using a hand hacksaw. Two plates were arranged in square butt joint arrangement to create the *FSW* joint. The plates were clamped over a base plate, and the welding was performed in the direction of rolling. Welding was carried out using two different non-consumable tools made from *D2* steel. The chemical composition of *D2* steel is shown in table 3. The choice of tool material depends on the material being welded. For soft materials, tool steel or stainless steel can be used, while refractory materials are necessary for hard materials. The evaluation of the mechanical properties of the joints was conducted through tensile tests on standard specimens. The specimens were cut transversely to the welding direction, and the tensile tests were performed on a universal testing machine with a constant strain rate, specifically a crosshead speed of 1 mm/min.

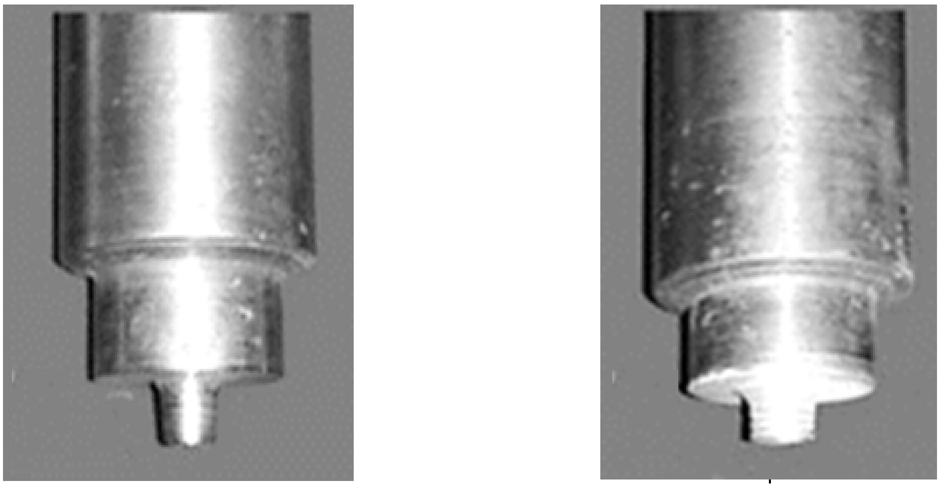
Fig. 1. Plates mounted on the bed of vertical milling machine

Fig. 2. Material flow during *FSW*

Table 1

Chemical Composition of *AA8011*

Component	*Al*	*Fe*	*Si*	*Cu*	*Mn*	*Mg*	*Zn*
Content (%)	97.5–99.1	0.6–0.90	0.5–0.6	0–0.1	0–0.1	0–0.1	0–0.1



a *b*

Fig. 3. Tool pin profiles:
a – taper cylindrical; *b* – threaded cylindrical

Table 2

Tool Features

TOOLS	(A)	(B)
Pin Profile	Taper cylindrical	Threaded cylindrical
Diameter of The Pin	6 mm at Top 4 mm at Bottom	6 mm, Thread with pitch of 1.2 mm
Length of the Pin	5.7 mm	5.7 mm
Diameter of the Shoulder	14 mm	14 mm

Table 3

Chemical Composition of *D2* steel

Element	Content (%)	Element	Content (%)
C	1.40–1.60	*Mo*	0.70–1.20
Mn	0.60	*V*	1.10
Si	0.60	*Ni*	0.30
Co	1.00	*P*	0.03
Cr	11.0–13.0	*Cu*	0.25
S	0.03	*Al*	Balance

Results and Discussion

The base material's tensile strength was measured and used as a reference for comparison. Fig. 4, *a* shows a specimen of the base material that was tested and fig. 4, *b* represents the fractured specimen of the base material after the tensile test. Table 4 contains the results of the tensile test on the base material. Fractured specimens of the welded joints are shown in fig. 5 and fig. 7 and stress-strain diagrams obtained after tensile test of the welded joints, which were fabricated using cylindrical pin profile and taper cylindrical pin profile, are shown in fig. 6 and fig. 8, respectively.

a *b*

Fig. 4. Tensile test specimens:
a – before tensile test; *b* – after tensile test

Table 4

Tensile test results of base material

Load at peak, kN	Tensile strength, MPa	Elongation at break, mm
15.060	167	21.01

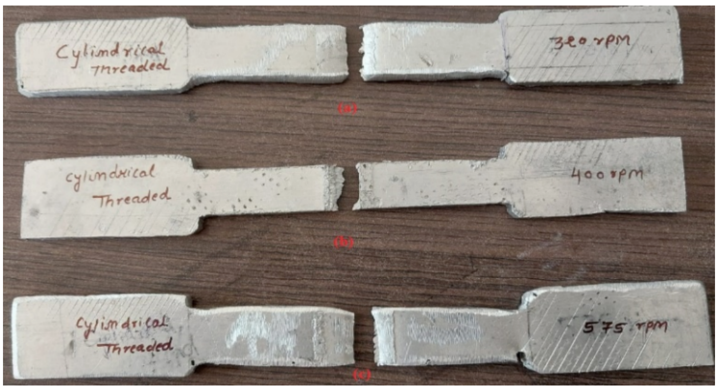
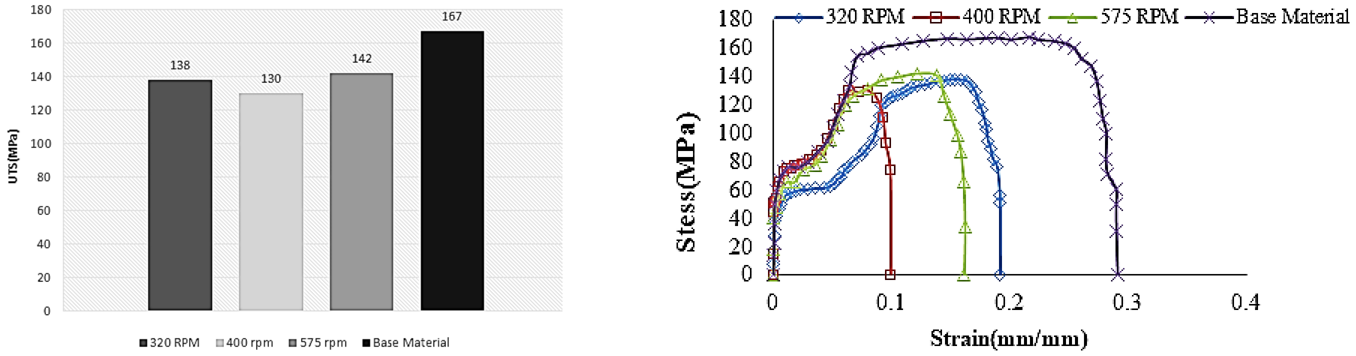


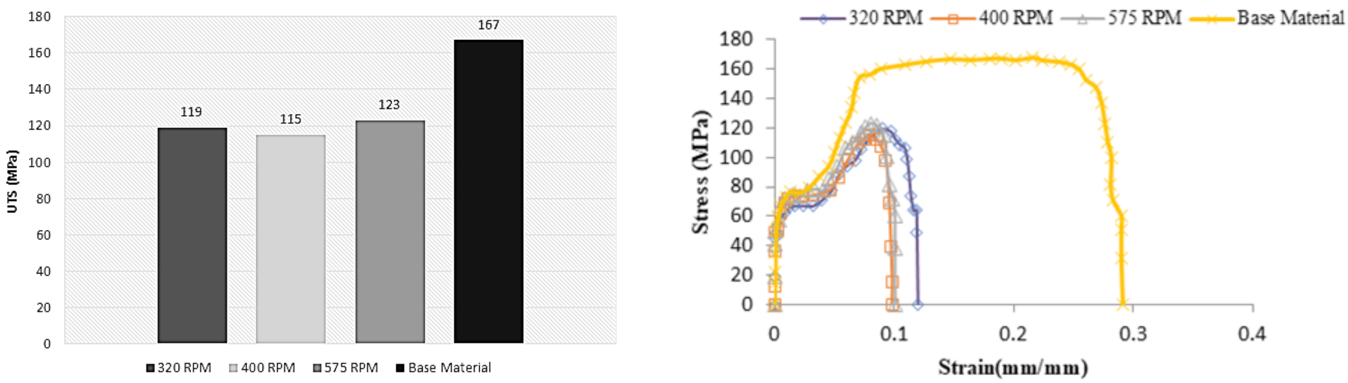
Fig. 5. Fractured specimens after tensile test of joints fabricated using threaded cylindrical pin



a *b*

Fig. 6. Tensile test result of weld fabricated by cylindrical threaded pin profile:
a – bar chart of *UTS*; *b* – stress-strain diagram

Fig. 7. Fractured specimens after tensile test of joints fabricated using taper cylindrical pin



a *b*

Fig. 8. Tensile test results of welds fabricated by cylindrical taper pin profile:
a – bar chart of *UTS*; *b* – stress-strain diagram

The results indicate that the tensile strength of welded joints fabricated using threaded cylindrical pin profile and taper cylindrical pin profile is lower, than that of the base material.

Based on the results presented, it is evident that with increasing tool rotation speed (*RPM*), the strength of the welded joint and the joint efficiency increases, regardless of the tool tip profile. For the tool with threaded cylindrical pin profile, joint efficiency and tensile strength are highest at 575 rpm and 60 mm/min and are equal to 84.5 % and 142 MPa, respectively (table 5). Lower values of rotation speed (320 rpm and 45 mm/min) result in slightly lower values of the joint efficiency and tensile strength (138 MPa and 82.6 %).

For the taper cylindrical pin profile, the joint efficiency and the tensile strength are highest at 575 rpm and 60 mm/min i.e. 73.6 % & 123 MPa (table 6). Lower values of rotation speed (320 rpm and 45 mm/min) result in lower joint efficiency and tensile strength i.e. 71.25 % & 119 MPa. Intermediate values of rotation speed (400 rpm and 50 mm/min) also give slightly lower values of the joint efficiency and the tensile strength i.e. 68.86 % and 115 MPa.

Table 5

Tensile test results of joints fabricated with cylindrical threaded pin profile tool

Properties	320 rpm, 40 mm/min	400 rpm, 45 mm/min	575 rpm, 60 mm/min
Tensile strength (MPa)	138	130	142
Joint Efficiency (%)	82.6	77.8	85

Table 6

Tensile test result of joints fabricated with cylindrical taper pin profile tool

Properties	320 rpm, 40 mm/min	400 rpm, 45 mm/min	575 rpm, 60 mm/min
Tensile strength (MPa)	119	115	123
Joint Efficiency (%)	71.2	68.8	73.6

Overall, it appears that 575 rpm and 60 mm/min are the optimal operating conditions for achieving maximum joint efficiency and tensile strength, regardless of whether a taper cylindrical pin profile or a threaded cylindrical pin profile is used. At these specific parameters, the tensile strength is 142 MPa for the threaded cylindrical pin profile and 123 MPa for the taper cylindrical pin profile. The results show that the subsequently created stir zone is entirely dependent on tool rotational speed, traverse speed. Better mixing of the material is observed at higher rotational speed of tool. The shape of the mixing zone is influenced by the shape of the tip. A wider mixing zone is observed when using a tool with a threaded cylinder tip.

Conclusions

Research shows that aluminum alloy *AA8011* can be joined by different pin profiles at different combination of rotational speed and tool traverse speed. A defect-free joint fabricated using a cylindrical threaded tool at a rotation speed of 575 rpm and a traverse speed of 60 mm/min, is characterized by comparatively higher mechanical properties in terms of maximum tensile strength and the joint efficiency. Regardless of the tool pin type, the mechanical properties and joint efficiency was decreased at lower the rotational speed. However, this may be due to some kind of defects. An increase in tensile strength and the joint efficiency was achieved when using a cylindrical threaded pin, which may be due to the formation of fine grains in the stirring zone.

References

1. Thomas W.M., Nicholas E.D., Needham J.C., Murch M.G., Temple-Smith P., Dawes C.J. *Friction Stir Butt Welding*. Patent GB, no. 9125978.8, 1991.

2. Dawes C., Thomas W. Friction stir joining of aluminum alloys. *TWI Bulletin*, 1995, vol. 6, pp. 124–127.

3. Rhodes C.G., Mahoney M.W., Bingel W.H., Spurling R.A., Bampton C.C. Effects of friction stir welding on microstructure of 7075 aluminium. *Scripta Materialia*, 1997, vol. 36 (1), pp. 69–75.

4. Liu G., Murr L.E., Niou C.S., McClure J.C., Vega F.R. Microstructural aspects of the friction-stir welding of 6061-T6 aluminum. *Scripta Materialia*, 1997, vol. 37 (3), pp. 355–361.

5. Jata K.V., Semiatin S.L. Continuous dynamic recrystallization during friction stir welding of high strength aluminum alloys. *Scripta Materialia*, 2000, vol. 43 (8), pp. 743–749.

6. Benavides S., Li Y., Murr L.E., Brown D., McClure J.C. Low-temperature friction-stir welding of 2024 aluminum. *Scripta Materialia*, 1999, vol. 41 (8), pp. 809–815.

7. Rajak D.K., Pagar D.D., Menezes P.L., Eyvazian A. Friction-based welding processes: friction welding and friction stir welding. *Journal of Adhesion Science and Technology*, 2020, vol. 34 (24), pp. 2613–2637. DOI: 10.1080/01694243.2020.1780716.

8. Acerra F., Buffa G., Fratini l., Troiano G. On the FSW of AA2024-T4 and AA7075-T6 T-joints: an industrial case study. *The International Journal of Advanced Manufacturing Technology*, 2010, vol. 48, pp. 1149–1157. DOI: 10.1007/s00170-009-2344-9.

9. Cavaliere P., Cerri E., Squillace A. Mechanical response of 2024-7075 aluminium alloys joined by friction stir welding. *Journal of Materials Science*, 2005, vol. 40, pp. 3669–3676. DOI: 10.1007/s10853-005-0474-5.

10. Rajpoot Y.S., Narayanan R.G., Das S. Predicting the effect of tool configuration during friction stir welding by cellular automata finite element analyses. *International Journal of Manufacturing Research*, 2018, vol. 13 (4), pp. 359–381. DOI: 10.1504/IJMR.2018.095377.

11. Song Z., Nakata K., Wu A., Liao J., Zhou L. Influence of probe offset distance on interfacial microstructure and mechanical properties of friction stir butt welded joint of Ti6Al4V and A6061 dissimilar alloys. *Materials & Design*, 2014, vol. 57, pp. 269–278. DOI: 10.1016/j.matdes.2013.12.040.

12. Shah L.H., Guo S., Walbridge S., Gerlich A. Effect of tool eccentricity on the properties of friction stir welded AA6061 aluminum alloys. *Manufacturing Letters*, 2018, vol. 15, pt. A, pp. 14–17. DOI: 10.1016/j.mfglet.2017.12.019.

13. Hussain A.K., Quadri S.A.P. Evaluation of parameters of friction stir welding for aluminium AA6351 alloy. *International Journal of Engineering Science and Technology*, 2010, vol. 2 (10), pp. 5977–5984.

14. Rajpoot Y.S., Saxena K., Deepak D. A review on the influence of tool pin profile on microstructure and mechanical properties of friction stir welded joints. *Advances in Manufacturing Engineering: Select Proceedings of ICFAMMT 2022*. Singapore, Springer, 2022, pp. 119–149. DOI: 10.1007/978-981-19-4208-2_10.

15. Cam G., Mistikoglu S. Recent developments in friction stir welding of Al-alloys. *Journal of Materials Engineering and Performance*, 2014, vol. 23, pp. 1936–1953. DOI: 10.1007/s11665-014-0968-x.

16. Mikhail J., Ibrahim R., Lathabai S. Effect of tool design on the microstructure and microhardness of friction stir processed 5005-H34 aluminium alloy. *Proceedings of SPIE*, 2013, vol. 8793, pp. 334–340. DOI: 10.1117/12.2026587.

17. Venkata Rao Ch., Madhusudhan Reddy G., Srinivasa Rao K. Influence of tool pin profile on microstructure and corrosion behaviour of AA2219 Al–Cu alloy friction stir weld nuggets. *Defence Technology*, 2015, vol. 11 (3), pp. 197–208. DOI: 10.1016/j.dt.2015.04.004.

18. Leitao C., Emílio B., Chaparro B.M., Rodrigues D.M. Formability of similar and dissimilar friction stir welded AA 5182-H111 and AA 6016-T4 tailored blanks. *Materials & Design*, 2009, vol. 30 (8), pp. 3235–3242. DOI: 10.1016/j.matdes.2008.12.005.

19. Cole E.G., Fehrenbacher A., Duffie N.A., Zinn M.R., Pfefferkorn F.E., Ferrier N.J. Weld temperature effects during friction stir welding of dissimilar aluminum alloys 6061-t6 and 7075-t6. *The International Journal of Advanced Manufacturing Technology*, 2014, vol. 71, pp. 643–652. DOI: 10.1007/s00170-013-5485-9.

20. Sharma N., Khan Z.A., Siddiquee A.N. Friction stir welding of aluminum to copper – an overview. *Transactions of Nonferrous Metals Society of China*, 2017, vol. 27 (10), pp. 2113–2136. DOI: 10.1016/S1003-6326(17)60238-3.

21. Moreira P.M.G.P., Santos T., Tavares S.M.O., Richter-Trummer V., Vilaça P., de Castro P.M.S.T. Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6. *Materials & Design*, 2009, vol. 30 (1), pp. 180–187. DOI: 10.1016/j.matdes.2008.04.042.

22. Ge Z., Gao S., Ji S., Yan D. Effect of pin length and welding speed on lap joint quality of friction stir welded dissimilar aluminum alloys. *The International Journal of Advanced Manufacturing Technology*, 2018, vol. 98, pp. 1461–1469. DOI: 10.1007/s00170-018-2329-7.

23. Buffa G., Campanile G., Fratini L., Prisco A. Friction stir welding of lap joints: Influence of process parameters on the metallurgical and mechanical properties. *Materials Science and Engineering: A*, 2009, vol. 519 (1–2), pp. 19–26. DOI: 10.1016/j.msea.2009.04.046.

24. Davidson B.S., Neelakrishnan S. Influence of friction stir welding parameters on tensile properties of AA8011 aluminium alloy plate. *Journal of Computational and Theoretical Nanoscience*, 2018, vol. 15 (1), pp. 93–98. DOI: 10.1166/jctn.2018.7060.

25. Palani K., Elanchezhian C., Vijaya Ramnath B., Bhaskar G.B., Naveen E. Effect of pin profile and rotational speed on microstructure and tensile strength of dissimilar AA8011, AA01-T6 friction stir welded aluminum alloys. *Materials Today: Proceedings*, 2018, vol. 5 (11), pp. 24515–24524. DOI: 10.1016/j.matpr.2018.10.248.

26. Elangovan K., Balasubramanian V. 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, vol. 459 (1–2), pp. 7–18. DOI: 10.1016/j.msea.2006.12.124.

27. Elangovan K., Balasubramanian V. Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium alloy. *Journal of Materials Processing Technology*, 2008, vol. 200 (1–3), pp. 163–175. DOI: 10.1016/j.jmatprotec.2007.09.019.

28. Elangovan K., Balasubramanian V. Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy. *Materials & Design*, 2008, vol. 29 (2), pp. 362–373. DOI: 10.1016/j.matdes.2007.01.030.

29. Chandana R., Saraswathamma K. Impact of tool pin profiles in friction stir welding process – A review. *Materials Today: Proceedings*, 2023, vol. 76, pt. 3, pp. 602–606. DOI: 10.1016/j.matpr.2022.12.097.

30. Shimpi R., Kumar C.S., Katarane R., Shukla A.K. Investigation on effects of variation of tool pin profile in a Friction stir welding process by finite element approach for joining dissimilar materials. *Materials Today: Proceedings*, 2022, vol. 66, pt. 3, pp. 1361–1364. DOI: 10.1016/j.matpr.2022.05.154.

31. Di Bella C., Alderucci T., Favaloro F., Borsellino C. Effect of tool tilt angle on mechanical resistance of AA6082/AA5083 friction stir welded joints for marine applications. *Procedia CIRP*, 2023, vol. 118, pp. 879–884. DOI: 10.1016/j.procir.2023.06.151.

32. Balamurugan S., Jayakumar K., Anbarasan B., Rajesh M. Effect of tool pin shapes on microstructure and mechanical behaviour of friction stir welding of dissimilar aluminium alloys. *Materials Today: Proceedings*, 2023, vol. 72, pt. 4, pp. 2181–2185. DOI: 10.1016/j.matpr.2022.08.459.

Conflicts of Interest

The authors declare no conflict of interest.