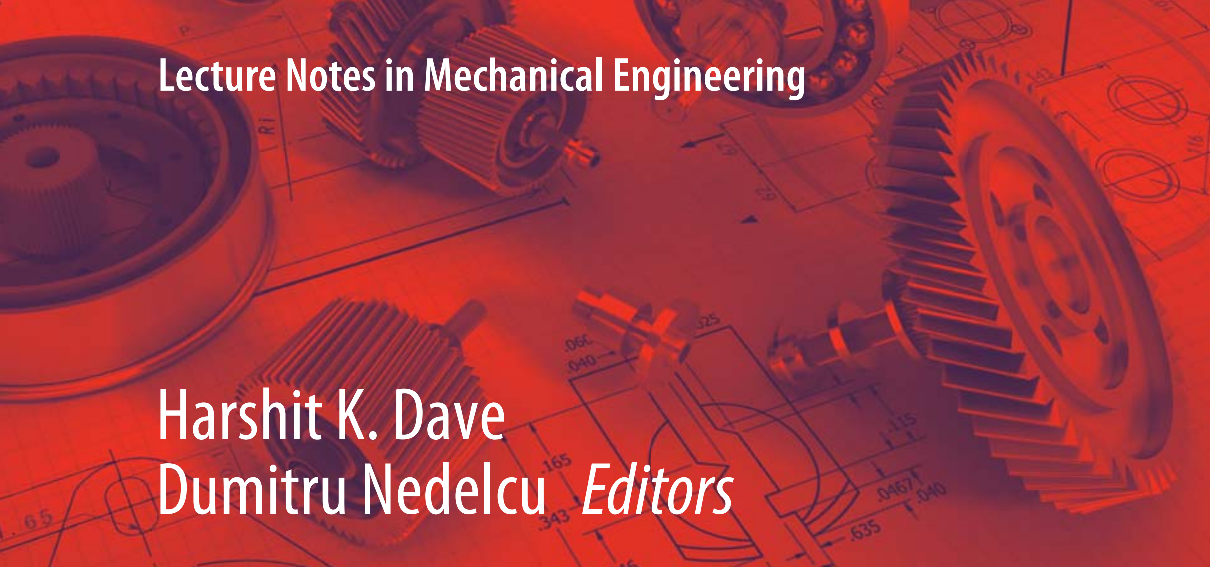

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ISSN 2195-4356 ISSN 2195-4364 (electronic)
Lecture Notes in Mechanical Engineering
ISBN 978-981-15-9116-7 ISBN 978-981-15-9117-4 (eBook)
https://doi.org/10.1007/978-981-15-9117-4

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Preface

Since 2010, Department of Mechanical Engineering at Sardar Vallabhbhai National Institute of Technology, Surat, has been organizing a series of conferences on "Recent Advances in Manufacturing." In order to enable the sharing of knowledge in the areas of manufacturing technologies, we have organized six national conferences on "Recent Advances in Manufacturing" and now we have planned the International Conference on Recent Advances in Manufacturing (RAM-2020). The conference is organized to bring the academicians, researchers and practicing engineers for sharing their experiences in the field of advance manufacturing. RAM-2020 will provide the opportunity for networking among participant institutes/organizations/industries to systematically confront the challenges in mutual areas of interest to advance manufacturing technology in these areas.

The proceedings volumes are published in the Springer series Lecture Notes in Mechanical Engineering in two volumes, viz. Volume 1—Advance Manufacturing Processes and Volume 2—Advance Manufacturing Systems. We also acknowledge the academic support from Prof. Dumitru Nedelcu and Prof. K. P. Rajurkar while editing the volumes 1 and 2, respectively.

As the entire world is facing the threat from corona pandemic, the international as well as interstate travel is restricted. However, we have tried our best to carve out a comprehensive schedule, keynote speakers and oral presentations in both online and offline modes, all of which will facilitate stimulating insightful discussions within the research community. In spite of such a pandemic situation, 60 participants have presented their findings and exchanged ideas related to manufacturing domain.

We are thankful to the conference organizing committee members, the advisory committee members, the reviewers, the session chairs and the volunteers, without whose generous contributions this conference would not number of presentations and number of participants.

Most of all, we thank the participants for enriching the international conference with their active participation.

Surat, India

Dr. Shailendra Kumar
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Organizing Secretary, RAM-2020

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Effect of Process Parameters on Tensile Strength in FSW of Aluminium and Stainless Steel

Niraj Kumar, Dhrupal Kotadiya, Vishvesh J. Badheka, and Vijay S. Gadakh

1 Introduction

Presently, different types of metals, ceramics and compounds can be joined together but still there are many unsolved issues in the joining due to their different thermal, mechanical and structural properties. On the contrary, there is an increasing demand towards the use of dissimilar joints in shipbuilding, military vehicles, aerospace and automobile industries. The industry acceptable sound joint is a major concern where the joint quality has given more priority than other concerns. Honda Accord used dissimilar joint of Aluminum and steel where they achieved weight reduction with increased fuel efficiency [1]. To date, many works are related to join dissimilar materials using different joining processes but the joint is a big challenge due to the brittle intermetallics formation [2]. As mentioned joining of Aluminium and steel is complex due to different thermal properties, dissimilar thermal expansion, heat capacity and thermal conductivity, lattice transformation, large difference between the melting points (660 °C for Al alloy and 1497 °C for steel) and nearly zero solid

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H. K. Dave and D. Nedelcu (eds.), *Advances in Manufacturing Processes*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-15-9117-4_18

solubility of iron in aluminium are creating the large discrepancy between the metals causing distortion, formation of the cavities and cracks, leading to the reduction of the mechanical properties after the joining processes [3]. Laser roll bonding [4], friction welding [5], FSW [6–10], laser brazing/welding [11], and laser pulse welding [12] are the processes employed till date to join different grades of the steels to the aluminum alloys.

The objective of the present work is to find process window to get defect-free welds and to study the effect of process parameters namely tool rotational speed (TRS) and weld speed (WS) on the FSWed joint strength of aluminium alloy (AA 6061) and austenitic stainless steel (AISI 304). Literature on FSW of these material combinations was reported. However, Bang et al. [13] studied conventional FSW and GTAW assisted FSW by considering effect of TRS on mechanical properties and microstructure of the joints. Similarly, Harwani and Badheka [14] investigated the effect of tool shoulder size on the mechanical properties and microstructure of the joints. Ghosh et al. [15] joined these materials using different TRS. Bang and Bijoy [16] have done thermal studies of TIG assisted FSW using three-dimensional finite element analysis. Ogawa et al. [17] have studied residual stress measurements for these weld materials. The motivation behind to do FSW experiments on these materials is that reported literature lacks to make process windows to get defect-free welds by considering effect of individual process parameters on the mechanical properties.

2 Experimental Procedure

A 100 × 50 × 3 mm thick plate of AA 6061-T651 and AISI 304L was used as a workpiece material for FSW. The chemical composition of AA6061-T651 is 1.03% Mg, 0.56% Si and 0.12% Mn and AISI 304 is 18.78% Cr, 8.2% Ni and 1.69% Mn [14]. The tensile strength of 668 and 302 MPa was found for AISI 304 and Al 6061-T651, respectively. Al 6061-T651 temper is solution heat-treated artificially aged where the aluminium material is extruded and given 1–3% stretching, which relives the internal residual stresses. The experiments were conducted modified vertical milling machine shown in Fig. 1 at Welding Research Laboratory of School of Technology, PDPU, Gandhinagar. The tilt angle (TA) (2°), Tool offset (2 mm) towards Aluminium on advancing side (AS), plunging depth (0.1 mm), and dwell time of 30 s were kept constant.

The values of the FSW process parameters that have varied during the execution of experiments are shown in Table 1. Based on previous work [14] and pilot experimentation the working range was identified.

During experiments, a tool of an unthreaded tungsten carbide alloy tool (88% WC-12% Co by weight) is employed with flat conical shoulder having shoulder diameter of 18 mm, root and tip pin diameter as 5 mm and 3 mm, and pin length of 2.8 mm is shown in Fig. 2 [14]. The tool material was procured from Sinter Sud Pvt. Ltd., Italy and was given cryogenic heat treatment after machining for enhancing

Fig. 1 Modified vertical milling machine employed for FSW

Table 1 Weld parameters and their levels

Factors	Level 1	Level 2	Level 3
TRS (rpm)	545	765	1070
WS (mm/rev)	20	31.5	50
TA (°)	1	2	3

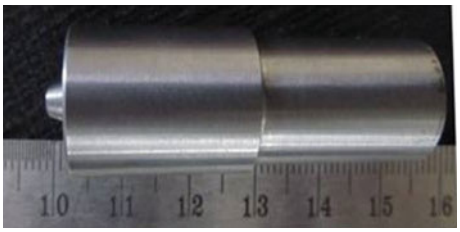
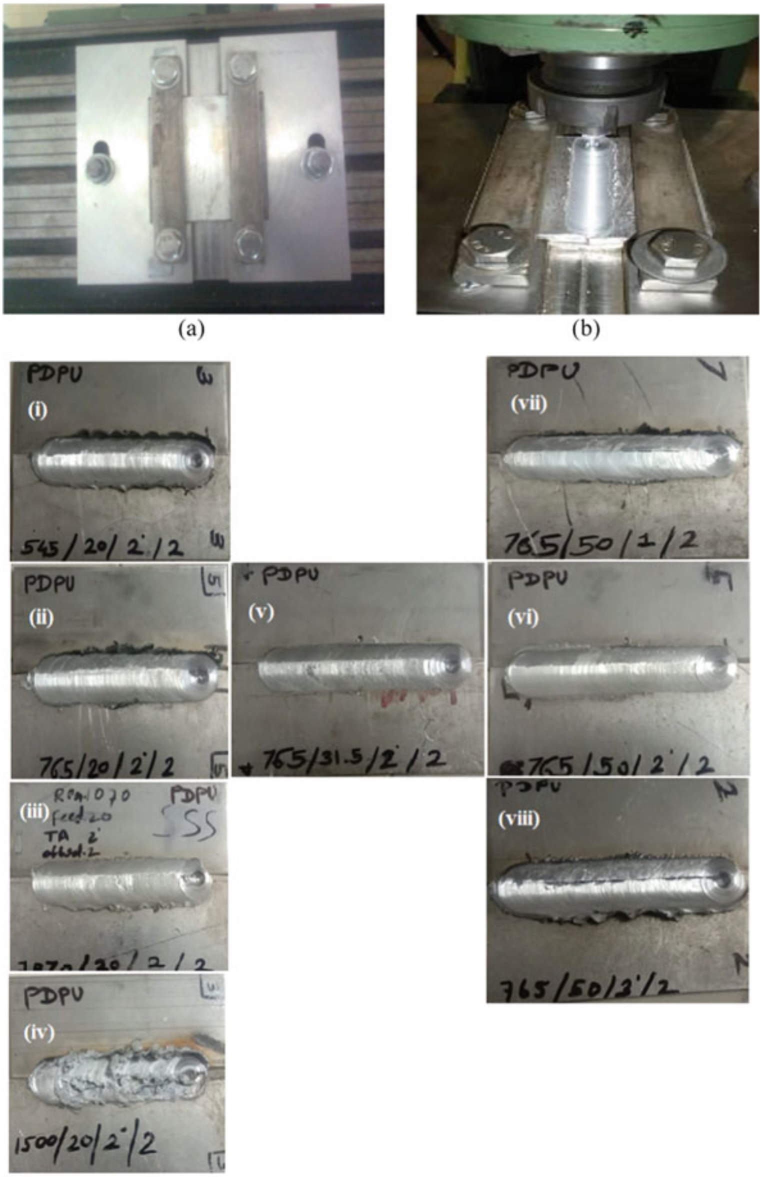


Fig. 2 FSW tool

the hardness. The hardness of the tool was 92.8 HRC, and the torsional resistance was about 2100 N/mm^2. A stainless steel fixture (having dimensions 230 × 195 × 25 mm) was specially designed for the FSW of Al plates [14], as shown in Fig. 3a.



(c)

Fig. 3 **a** FSW Fixture, **b** experimentation during welding and **c** welded samples

Figure 3b, c shows the experimental setup for joining Aluminum and steel alongwith experimentation during welding and FSWed joints at different process conditions. To measure the temperature during the process, two holes were drilled 2 mm away from the nugget zone and two K-type contact thermocouples were inserted in the holes based on past experience, one on the advancing and one on the retreating side (RS). Three tensile specimens were prepared from a joint as per ASTM E8/E8M-11 standard and were tested at Electrical Research & Development Association (ERDA), Baroda with the help of a well-calibrated Universal Testing Machine.

3 Results and Discussion

In order to study the effect of individual process parameter on the joint tensile strength, bottom-up approach [18] was employed by exploring the Table 1. Firstly, TRS was varied keeping WS (20 mm/min) and TA (2°) constant (see Fig. 3ci–iv). Later WS was varied keeping TRS (765 rpm) and TA (2°) constant (see Fig. 3cv, vi). Lastly, TA was varied keeping TRS (765 rpm) and WS (50 mm/min) constant (see Fig. 3cvii, viii) A total eight number of experiments were performed, out of which three conditions showed defective joints (see Fig. 3civ, vii and viii) hence their mechanical properties were not evaluated and not shown in Table 2. The defective joints were produced due to high heat input. The details of process parameters and their corresponding tensile strength are shown in Table 2. All the joints were failed in the weld zone during tensile testing.

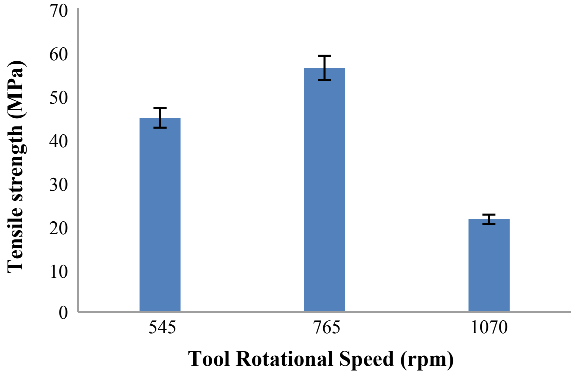
3.1 Effect of Tool Rotational Speed on Tensile Strength

The effect of tool rotational speed on tensile strength is shown in Fig. 4. The maximum joint tensile strength was observed at TRS of 765 rpm WS of 20 mm/min. This can be attributed due to the sufficient heat input in the weld region [13, 15, 19]. Furthermore, welding defects were observed at a higher value of TRS of 1070 rpm due to excessive

Table 2 Tensile strength and peak temperature of Al-Steel FSWed joint

S. No	TRS	WS	TS (MPa)			Avg. TS (MPa)	Peak temp. (°C)	
			Trial 1	Trial 2	Trial 3		RS (steel)	AS (Al)
1	545	20	22.514	16.785	44.647	27.982	328	194
2	765	20	35.13	31.752	56.151	41.011	345	197
3	765	31.5	30.178	42.315	34.115	35.536	298	170
4	765	50	24.457	11.391	9.716	15.188	244	188
5	1070	20	13.102	13.102	21.349	15.851	328	178

Fig. 4 Effect of tool rotational speed on FSWed Al-Steel joint

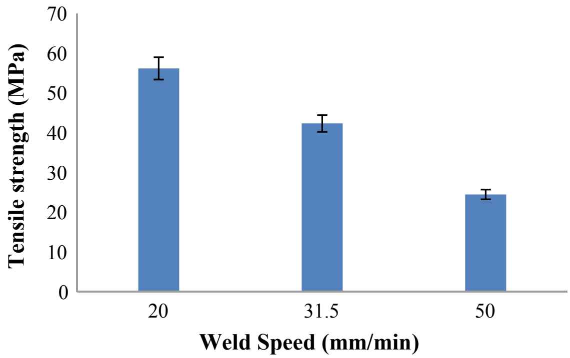


softening of the weld materials. These welding defects are observed due to improper materials flow and mixing [20].

3.2 *Effect of Weld Speed on Tensile Strength*

The weld speed has significant role in the mechanical properties of FSW of Al-steel joints. From Fig. 5, it has been found that increasing the weld speed decreases the tensile strength of the joint. Increasing the weld speed decreases the heat input in which insufficient intermixing of the material take place and thereby weakens the joint.

Fig. 5 Effect of weld speed on FSWed Al-Steel joint



3.3 Effect of Tool Rotational Speed and Weld Speed on Peak Temperature

The effect of tool rotational speed and weld speed on peak temperature of Al-Steel FSWed joint is shown in Table 2. The maximum measured temperature for the aluminium alloy and steel are 345 °C and 197 °C, respectively at constant tool rotational speed and varying weld speed. A similar observation was reported by Chen and Kovacevic [21] in Al-steel joining. Also, increasing weld speed reduces the peak temperature on steel side, but on aluminium side first decrease and then increased. This may be attributed due to availability of time for heat conduction to the aluminium is reduced. It is estimated that the heat input into the steel is ~2 times that of the aluminium alloy at a tool rotational speed of 765 rpm and a weld speed of 20 mm/min by considering thermal properties of the materials. Similarly, results were obtained at constant weld speed and varying tool rotational speed. This may be attributed due to the mechanical mixing and deformation action of the tool pin and an increase in the frictional heat generated under the shoulder. Figure 6 shows the thermal history at TRS 765 rpm and WS 20 mm/min. It can be seen that time to attain maximum temperature above 200 °C is ~30 s whereas for cooling it is ~90 s. The temperature greater than 200 °C was considered due to Al typically recrystallizes between 200 and 300 °C range. The peak temperature and cooling rate, are the most essential parameters at any specific location in the joint during welding, which not only affect the microstructure but also the mechanical properties of welded joint [22].

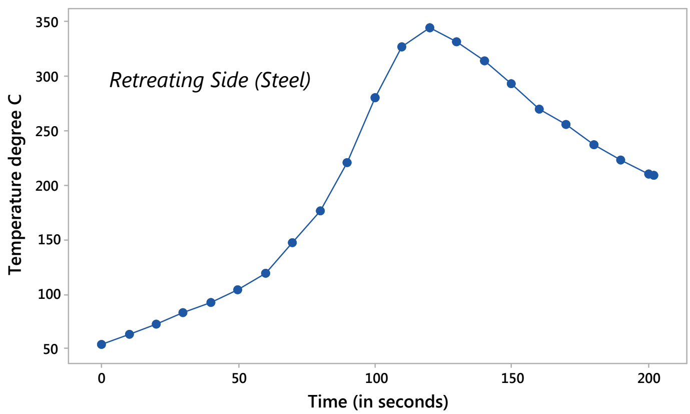


Fig. 6 Temperature history at TRS 765 rpm and WS 20 mm/min

4 Conclusion

In this work, FSW of dissimilar Aluminium (AA6061-T651) alloy and Stainless Steel (SS 304) material was successfully welded. The tool rotational speed and weld speed have a significant effect on tensile strength of the FSWed joint. From the obtained results, it is observed that at TRS of 765 rpm and 20 mm/min, highest tensile strength 41 MPa was obtained. Increasing the weld speed at constant tool rotational speed the tensile strength decreases. Whereas, at constant weld speed and varying tool rotational speed, the tensile strength increases from low to high tool rotational speeds then decreases. Tool rotational speed and weld speed are major FSW process parameters that decides the heat input and thereby the structure and properties of the joints. Microstructural characterization and their correlation with the mechanical properties of FSW of these joints will be carried out as future work.

Acknowledgements The authors would like to thank the authorities of Pandit Deendayal Petroleum University, Gandhinagar for providing the facilities to carry out this work.

References

1. Kusuda Y (2013) Honda develops robotized FSW technology to weld steel and aluminum and applied it to a mass-production vehicle. Ind Rob 40:208–212. https://doi.org/10.1108/01439911311309889
2. Agudo L, Eyidi D, Schmaranzer CH et al (2007) Intermetallic FexAly-phases in a steel/Al-alloy fusion weld. J Mater Sci 42:4205–4214
3. Atabaki MM, Nikodinovski M, Chenier P, Kovacevic R (2013) Welding of aluminum alloys to steels: an overview
4. Rathod MJ, Kutsuna M (2004) Joining of aluminum alloy 5052 and low-carbon steel by laser roll welding. Weld J 83:16–26
5. Shubhavardhan RN, Surendran S (2012) Friction welding to join stainless steel and aluminum materials. Int J Metall Mater Sci Eng 2:53–73
6. Ramachandran KK, Murugan N (2019) Influence of axial force on tensile strength and microstructural characteristics of friction stir buttwelded aluminum alloy/steel joints. Strength Mater 51:300–316. https://doi.org/10.1007/s11223-019-00076-7
7. Dehghani M, Mousavi SAAA, Amadeh A (2013) Effects of welding parameters and tool geometry on properties of 3003-H18 aluminum alloy to mild steel friction stir weld. Trans Nonferrous Met Soc China (English Ed 23). https://doi.org/10.1016/S1003-6326(13)62683-7
8. Tang J, Shen Y (2017) Effects of preheating treatment on temperature distribution and material flow of aluminum alloy and steel friction stir welds. J Manuf Process 29. https://doi.org/10.1016/j.jmapro.2017.07.005
9. Zheng Q, Feng X, Shen Y et al (2016) Dissimilar friction stir welding of 6061 Al to 316 stainless steel using Zn as a filler metal. J Alloys Compd 686:693–701. https://doi.org/10.1016/j.jallcom.2016.06.092
10. Sameer MD, Birru AK (2019) Investigations on microstructural evolutions and mechanical properties of dual-phase 600 steel and AA6082-T6 aluminum alloy dissimilar joints fabricated by friction stir welding. Trans Indian Inst Met 72:353–367. https://doi.org/10.1007/s12666-018-1487-5

11. Mathieu A, Shabadi R, Deschamps A et al (2007) Dissimilar material joining using laser (aluminum to steel using zinc-based filler wire). Opt Laser Technol 39:652–661. https://doi.org/10.1016/j.optlastec.2005.08.014
12. Torkamany MJ, Tahamtan S, Sabbaghzadeh J (2010) Dissimilar welding of carbon steel to 5754 aluminum alloy by Nd:YAG pulsed laser. Mater Des 31:458–465. https://doi.org/10.1016/j.matdes.2009.05.046
13. Bang H, Bang H, Jeon G et al (2012) Gas tungsten arc welding assisted hybrid friction stir welding of dissimilar materials Al6061-T6 aluminum alloy and STS304 stainless steel. Mater Des 37:48–55. https://doi.org/10.1016/j.matdes.2011.12.018
14. Harwani DM, Badheka VJ (2019) Effect of shoulder diameter on friction stir welding of Al 6061 to SS 304. In: Deb D, Balas VE, Dey R (eds) Innovations in infrastructure proceedings of ICIIF 2018, advances in intelligent systems and computing. Springer, Singapore, pp 355–366
15. Ghosh M, Gupta RK, Husain MM (2014) Friction stir welding of stainless steel to Al alloy: effect of thermal condition on weld nugget microstructure. Metall Mater Trans a 45A:854–863. https://doi.org/10.1007/s11661-013-2036-9
16. Bang H, Bijoy MS (2011) Temperature behavior in dissimilar butt joint during TIG assisted friction stir welding. J Korean Weld Join Soc 29:63–71. https://doi.org/10.5781/KWJS.2011.29.5.561
17. Ogawa D, Kakiuchi T, Hashiba K, Uematsu Y (2019) Residual stress measurement of Al/steel dissimilar friction stir weld. Sci Technol Weld Join 24:685–694. https://doi.org/10.1080/13621718.2019.1588521
18. Nadammal N, Kailas SV, Suwas S (2015) A bottom-up approach for optimization of friction stir processing parameters: a study on aluminium 2024-T3 alloy. Mater Des 65:127–138. https://doi.org/10.1016/j.matdes.2014.09.005
19. Mahto RP, Kumar R, Pal SK, Panda SK (2018) A comprehensive study on force, temperature, mechanical properties and micro-structural characterizations in friction stir lap welding of dissimilar materials (AA6061-T6 & AISI304). J Manuf Process 31:624–639. https://doi.org/10.1016/j.jmapro.2017.12.017
20. Ranjan R, Khan AR, Parikh C, et al (2016) Classification and identification of surface defects in friction stir welding: an image processing approach. J Manuf Process 22. https://doi.org/10.1016/j.jmapro.2016.03.009
21. Chen CM, Kovacevic RÃ (2004) Joining of Al 6061 alloy to AISI 1018 steel by combined effects of fusion and solid state welding. 44:1205–1214. https://doi.org/10.1016/j.ijmachtools.2004.03.011
22. Ramanjaneyulu K, Madhusudhan Reddy G, Venugopal Rao A, Markandeya R (2013) Structure-property correlation of AA2014 friction stir welds: role of tool pin profile. J Mater Eng Perform 22:2224–2240. https://doi.org/10.1007/s11665-013-0512-4