Acta Materialia Transylvanica 8/1. (2025) 23–27.
DOI: Hungarian: https://doi.org/10.33923/amt-2025-01-05
English: https://doi.org/10.33924/amt-2025-01-05

Tool Development for Friction Stir Welding of Aluminium Alloys

Emese KOZÁK,[1] Zsolt Ferenc KOVÁCS [2]

[1] John von Neumann University, GAMF Faculty of Engineering and Computer Science, Department of Innovative Vehicles and Materials, Kecskemét, Hungary. kozak.emese@nje.hu

[2] John von Neumann University, GAMF Faculty of Engineering and Computer Science, Department of Innovative Vehicles and Materials, Kecskemét, Hungary.

Abstract

In recent years, the demand for aluminium and aluminium alloys has increased due to their favourable properties. The properties of aluminium alloys are almost the same as structural steel, but their weight is approximately one third. Technological developments have made it possible to weld metals that are difficult to weld with traditional fusion welding, such as aluminium alloys, using Friction Stir Welding (FSW). This article briefly introduces the FSW procedure and its application. During this research, 5053 aluminium alloys were welded with the mentioned technology, for which customized FSW tools were used. These tools were made with 3D printing technology, which ensured the manufacturing of complex geometries. After welding, the pieces were subjected to the following material tests: visual inspection, tensile tests, hardness tests and metallographic analysis.

Keywords: *friction stir welding, FSW tool, aluminium, material testing.*

1. Introduction

Friction stir welding (FSW) is a solid-state welding process in which the joint is formed without melting the base materials [1].]. Its basic principle is that a rotating tool is used that penetrates the fixed workpieces to be welded. The shoulder of the tool generates frictional heat, which causes a local decrease in the strength of the workpieces, thereby softening the material. During this stage, the rotating tool moves along the joint line, stirring the plastically deformed material, and upon cooling, a solid-state bond is formed between the workpieces [2, 3, 4].

The main parts of the tool are shown in Fig. 1. Since the illustration from source [5] showed the basic design of the FSW tool with a conceptual error, it has been corrected and republished accordingly.

Variables during the process include the materials to be welded, their quality, thickness, and the number of dissimilar materials to be joined. Technological parameters include the tool inclination angle, transverse speed, rotational speed, axial force applied to hold the tool in the material, and in some cases the presence or absence of cooling. Key factors in tool design include the tool material, shoulder diameter, and pin geometry, diameter, and length [6, 7, 8, 9].

Additive manufacturing, one of the most dynamically developing manufacturing technologies, also plays an important role in this research. While FSW tools are typically produced by machining (subtractive manufacturing), additive manufacturing becomes an attractive option when the tool requires complex pin and shoulder

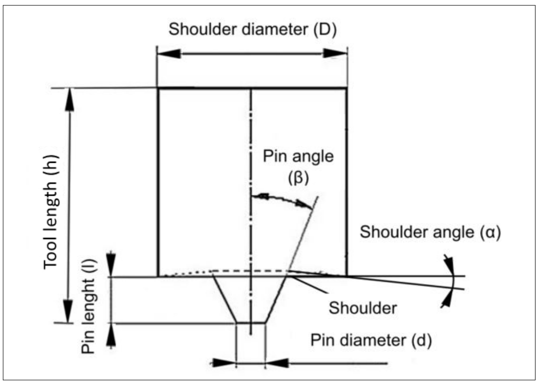


Fig. 1. *Simplified schematic of the FSW tool.* [5]

geometries that are difficult or impossible to machine. Additive manufacturing enables the production of such complex shapes and also brings economic benefits.

2. Design of the FSW tool

Additive manufacturing of metal parts allows for faster and more cost-effective production of complex geometries compared to traditional machining, including friction stir welding. Additive manufacturing has so far mainly appeared in friction stir welding by welding additively manufactured workpieces together [10]. Therefore, this research can be considered pioneering, as it is the first study in Hungary on the use of additively manufactured friction stir welding tools.

The design was primarily based on the workpieces to be welded – in this case, two 4 mm thick aluminium plates. The plate thickness determines the length of the pin, which cannot be equal to or greater than the material thickness. The pin should be slightly shorter to avoid full penetration. Consequently, the pin length was set to 3,7 mm.

The shoulder diameter significantly influences the formation of the weld. For aluminium alloys, the shoulder diameter is typically 2,5 to 3 times the pin diameter. The shoulder diameter affects both the weld width and the amount of frictional heat generated.

In this study, all tools were designed with a shoulder diameter of D = 20 mm. However, future work should include testing different shoulder diameters under the same process parameters. The overall tool length was h = 15 mm in all cases, which provides a suitable clamping length and cost-effectiveness in production.

The pin diameter and geometry, as well as the shoulder face and profile, were varied between tools to improve material flow during welding (Fig. 2).

3. Description of Welding Experiments

The base material was aluminum alloy 5053, with specimen dimensions of 50 × 90 × 4 mm. The goal of the research was to identify, under fixed welding parameters, the most suitable tool geometry based on destructive and non-destructive testing of the weld quality.

A total of 15 welds were performed at a constant rotational speed of 1000 min^{-1}, using three different traverse speeds. The tool tilt angle was 0°, and no cooling was applied (Table 1.).

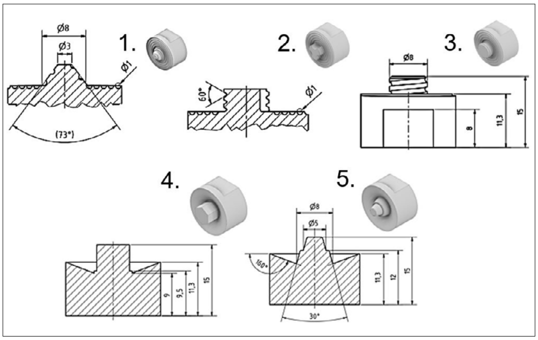


Fig. 2. *Designed FSW tools from 1 to 5 with dimensions.*

Table 1. *Technological parameters of the welding process*

Number of Measurements	Tool Name	Feed v_f (mm/min)
1.	1.	80
2.		125
3.		170
4.	2.	80
5.		125
6.		170
7.	3.	80
8.		125
9.		170
10.	4.	80
11.		125
12.		170
13.	5.	80
14.		125
15.		170

During welding, the plates were positioned in the same plane, and the joint was formed along their contacting edges. Due to the spiral tool design, the spindle rotated counterclockwise (M4 direction) during welding to ensure proper material flow consistent with the tool geometry. The experimental setup is shown in Fig. 3.

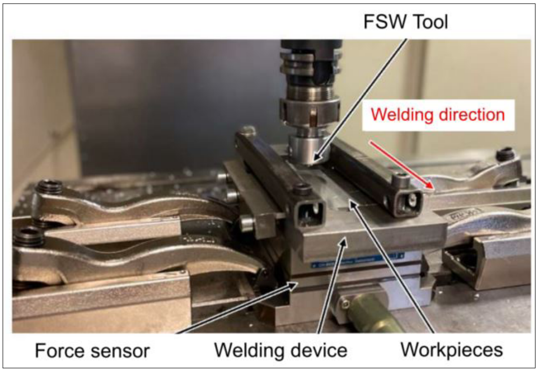
4. Material testing

This chapter summarizes the procedure and results of the evaluation of welded samples. The welds were examined visually, as well as by tensile testing, hardness testing, and metallographic analysis.

4.1. Welding quality by visual inspection

The welds made with tools 1 and 3 are particularly noteworthy.

With tool 1, at a transverse speed of 80 mm/min, the tool "plowed" the material, resulting in insufficient material mixing and poor weld formation. At a speed of 125 mm/min, the quality of the joint improved significantly, but at higher speeds, tunnel-type porosity defects appeared (**Fig. 4**).



For tool 3, welds were successfully created in all three experiments, although the surface roughness varied. A transverse speed of 80 mm/min produced a rougher surface, while increasing the speed produced smoother welds. However, defects observed at the beginning of the weld are indicative of internal tunnel porosity (**Fig. 5**).

4.2. Welding quality by tensile test

For transverse tensile tests, three specimens (10 mm wide) were cut from each welded sample. The nominal specimen width was 8 mm and the total length was 98 mm, resulting in a total of 36 specimens, 33 of which were tested at different transverse speeds. The tests were performed using an Instron 4482 tensile testing machine.

The highest tensile strengths were measured for specimens 1/125 and 3/125. The summarized results are shown in **Table 2**.

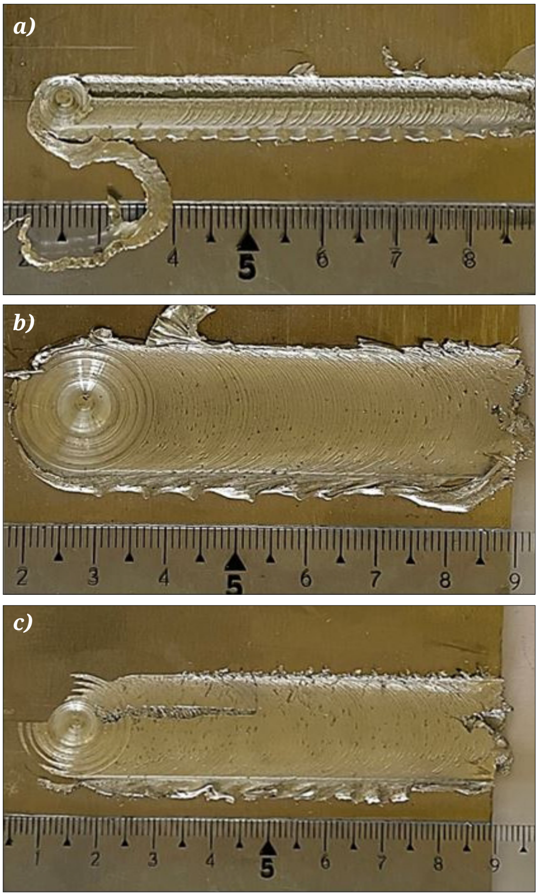


Fig. 4. *Top view of welds produced with Tool 1: a) 80 mm/min; b) 125 mm/min; c) 150 mm/min*

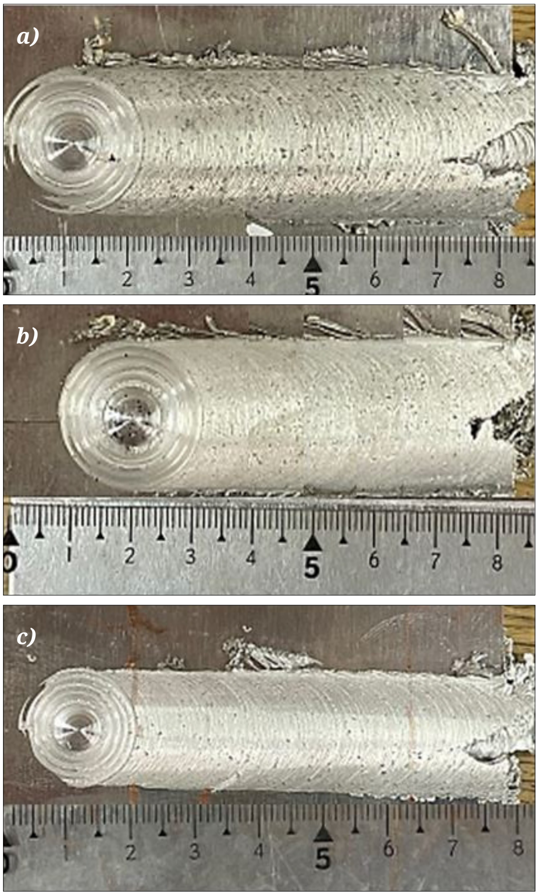


Fig. 5. *Top view of welds produced with Tool 3: a) 80 mm/min; b) 125 mm/min; c) 150 mm/min*

2. táblázat. *A szakítóvizsgálat eredményei (részlet)*

Próbatest	Max. terhelés (N)	Megnyúlás max. terhelésnél (mm)	Szakítószilárdság (MPa)
1/125a	6869	10,76	215
1/125b	6946	11,63	212
1/125c	6870	10,76	224
3/125a	6111	7,51	186
3/125b	7060	11,99	215
3/125c	7109	13,18	214

4.3. Welding quality by metallographic examination

The cold-embedded samples were sanded in three stages with 320, 600 and 1200 grit sandpaper and then examined under a microscope for internal defects.

Different sizes of defects were found in each weld. The lowest defect incidence was observed in the 1/125 and 3/125 welds (**Fig. 6** and 7).

4.4. Welding quality by hardness testing

Vickers hardness measurements were performed on the mounted samples using a Struers Duramin-100 tester. The measurements were carried out on the 1/125 and 3/125 specimens, which had shown the best performance in earlier tests. The applied load was 9.81 N.

Since the welded plates were made of identical material, the hardness values were expected to be nearly uniform across the measured points, with slightly higher hardness within the weld zone. Measurements were taken along the crown side from the retreating to the advancing side (**Fig. 8** and 9) **[2]**.

5. Conclusion

Of the results, welds made with tools 1 and 3 at a travel speed of 125 mm/min were the most promising. These tools should be further tested with different welding parameters, such as different tool inclination angles (1–3°).

The spiral grooves on the tool improved material flow during mixing.

Further research should also investigate concave shoulder designs to empirically determine the optimal shoulder angle that promotes favorable weld formation.

For tool 2, vertical grooves on the pin should be avoided under the test conditions, as this configuration did not give satisfactory results at any travel speed. However, further experiments are recommended, adjusting the groove geometry to ensure material flow along them during welding.

Acknowledgements

The project number 2024-2.1.1-EKÖP-2024-00008 was implemented with the support of the Ministry of

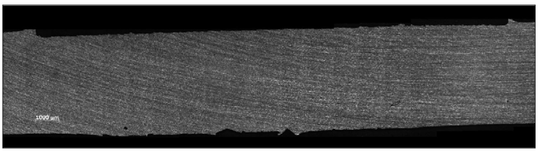


Fig. 6. *Cross-section of specimen welded by tool 1 at a feed rate of 125 mm/min.*

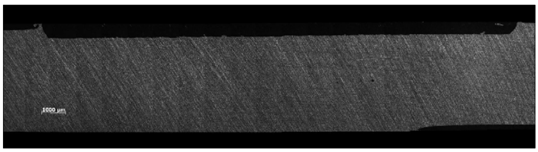


Fig. 7. *Cross-section of specimen welded by tool 3 at a feed rate of 125 mm/min.*

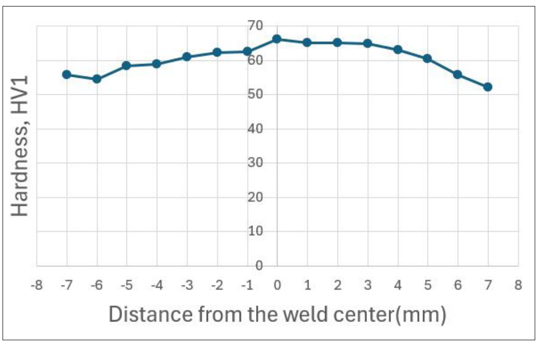


Fig. 8. *Hardness measurement of the sample welded by tool 1 at a feed rate of 125 mm/min.*

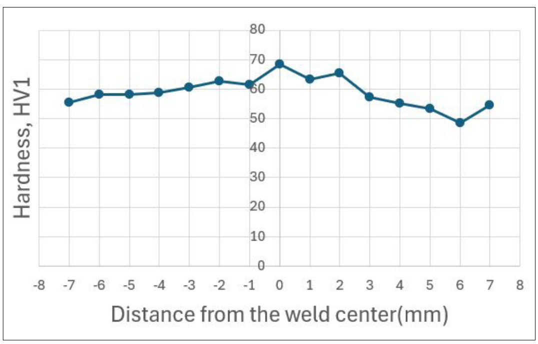


Fig. 9. *Hardness measurement of the sample welded by tool 3 at a feed rate of 125 mm/min.*

Culture and Innovation from the National Research Development and Innovation Fund, financed by the 2024-2.1.1-EKÖP application program.

References

[1] Michael H., Stefan B., Sven S.: *Influence of surface roughness of tools on the friction stir welding process.* Journal of Welding and Joining, 32/6. (2014) 22–28. https://doi.org/10.5781/JWJ.2014.32.6.22

[2] Kovács Zs. F., Hareancz F.: *A kavaró dörzshegesztés alkalmazási lehetőségei alumínium kompozitok esetén.* Gradus, 8/1. (2021) 294–298. https://doi.org/10.47833/2021.1.ENG.011

[3] Singh Bharat Raj: *A Hand Book on Friction Stir Welding.* LAP Lambert Academic Publishing, UK, 2012. 3–7, 69, 72–74, 90–104. https://doi.org/10.13140/RG.2.1.5088.6244

[4] Kilic S., Ozturk F., Demirdogen M. F.: *A comprehensive literature review on friction stir welding: Process parameters, joint integrity, and mechanical properties.* Journal of Engineering Research, 13/1. (2025) 122–130. https://doi.org/10.1016/j.jer.2023.09.005

[5] Bilici M. K.: *Effect of tool geometry on friction stir spot welding of polypropylene sheets.* Express Polymer Letters, 6/10. (2012) 805–807. https://doi.org/10.3144/expresspolymlett.2012.86

[6] Kovács Zs. F.: *Acéllemez kavaró dörzshegesztése.* Hegesztés Technika, XXXIV/1. (2023) 51–53.

[7] Mugada K. K., Kumar A.: *Role of Tool Shoulder End Features on Friction Stir Weld Characteristics of 6082 Aluminum Alloy*. Journal of The Institution of Engineers (India), Series C, 100 (2019) 343–350. https://doi.org/10.1007/s40032-018-0451-9

[8] Tarasov S., Amirov A., Chumaevskiy A., Savchenko N., Rubtsov V. E., Ivanov A., Moskvichev E., Kolubaev E.: *Friction Stir Welding of Ti-6Al-4V Using a Liquid-Cooled Nickel Superalloy.* Tool Technologies, MDPI, 10/118. (2022) 1–2, 13–14. https://doi.org/10.3390/technologies10060118

[9] Abolusoro O. P., Akinlabi E. T., Kailas S. V.: *Impact of tool profile on mechanical behavior and material flow in friction stir welding of dissimilar aluminum alloys.* Materialwissenschaft Werkstofftechnic, 51. (2020) 729–730. https://doi.org/10.1002/mawe.202000002.

[10] Javadi M. S., Ehteshamfar M. V., Adibi H.: *A comprehensive analysis and prediction of the effect of groove shape and volume fraction of multi-walled carbon nanotubes on the polymer 3D-printed parts in the friction stir welding process.* Polymer Testing, 117. (2023), 107844. https://doi.org/10.1016/j.polymertesting.2022.107844.