ADVANCES IN MATERIALS SCIENCE, Vol. 25, No. 4 (86), December 2025

sciendo

DOI: 10.2478/adms-2025-0024

Anna Janeczek[1]*

[1]Institute of Manufacturing and Materials Technology, Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology, Gdansk, Poland

**anna.janeczek@pg.edu.pl*

UNDERWATER FRICTION STIR WELDING OF AA5754 ALUMINUM ALLOY IN SALTWATER ENVIRONMENT: A PRELIMINARY STUDY

ABSTRACT

The Underwater Friction Stir Welding (UFSW) environment was proven to improve mechanical properties of the Friction Stir Welded (FSW) joints. However, carefully selected set of parameters is necessary to succeed. This study presents preliminary results of the research on water salinity level effect on the properties of the AA5754 aluminum alloy joints. For this purpose, the Plackett-Burman design was used. The design of experiment consists of ten attempts with process parameters as variables: welding speed, rotational speed, tool tilt angle and water salinity level. The following tests were proceeded: visual tests, tensile strength tests and fractography analysis. Thus, the response variable was ultimate tensile strength (UTS). Surface defects were found in joints performed with low heat input (i.e. low rotational speed, high welding speed). The highest UTS values – 100% of base metal were obtained for the joint made with process parameters: welding speed - 37.5 mm/min, rotational speed - 1235 rpm, tool tilt angle - 2°, water salinity level - 10%. The fractography of the joint revealed precipitates formation and very small dimples. All of the investigated welding parameters were found to be statistically significant. However, the tool tilt angle was of drastically highest significance. The order of the other process parameters was as following: welding speed, rotational speed and water salinity level.

Keywords: *Underwater Friction Stir Welding; aluminum alloys; water salinity; design of experiment*

INTRODUCTION

The continuously growing interest in Friction Stir Welding (FSW) method results, among other factors, from its environmental and economic advantages. The process does not require the use of additional materials (filler metals), thereby enabling a weight reduction of the welded component which is a desirable factor in the aerospace and automotive industries [1–5]. In recent years, the environmental impact of a given technology has become an important aspect influencing its industrial application. In the case of the FSW method, not only is there no need to use (often harmful) shielding gases, but the welding equipment is also less energy consuming than heat sources used for arc welding which significantly contributes to the reduction of carbon dioxide emissions [6].

Received: 29.09.2025; Received in revised form: 16.12.2025; Accepted: 19.12.2025

Properly selected and correlated process parameters constitute the basis for obtaining joints with high mechanical properties and esthetic surface appearance. The main process parameters for butt joint welding using the FSW method include [7]: rotational speed, welding speed, pin plunge depth into the material and tool tilt angle. The rotational motion of the tool generates friction between the tool and the welded material. Consequently, the rotational speed, correlated with the welding speed, determines the amount of heat input to the material, thereby affecting the degree of its plasticization [8]. The welding speed controls the amount of local heat input [9]. The pin plunge depth determines the degree of mixing of the plasticized material and ensures the formation of a sound joint throughout the entire thickness of the material. In addition, it provides adequate forging pressure exerted by the tool shoulder and prevents excessive flash formation of the plasticized material [10]. Last but not least, a slight change in the tool tilt angle influences the material flow behavior and mixing of the plasticized material [11].

The Underwater Friction Stir Welding (UFSW) process is a modification of the conventional FSW process. Water is used as a cooling medium which, as a result of the ongoing thermomechanical processes and microstructural transformations in the welded material, leads to an improvement in the mechanical properties of FSW joints [12]. The application of cooling results in grain refinement and homogenization of grain size across individual zones of the joint, a reduction in the peak temperature, shortening of the welding thermal cycle, and reduced tool wear [13]. The process is carried out with the base material fully submerged in a water-filled tank [14]. The principle of joint formation is the same as in the standard FSW process.

Researchers indicate the necessity of adjusting the weldability window, i.e., increasing both the rotational speed and the welding speed for the UFSW method compared to the parameters used in the conventional FSW process [15, 16]. Rotational speed and welding speed significantly affect grain refinement and strength-related properties. Consequently, the application of process parameters corresponding to the weldability window of the standard FSW method in the UFSW process leads to the introduction of an insufficient amount of heat for the joint properties to be comparable to or superior to those obtained by conventional FSW [17–19].

To the best authors knowledge, there is no other studies on UFSW of aluminum alloy AA5754. However, there is a limited number of researches on different alloys of 5xxx series. Saravanakumar et al. investigated tools pin profile effect on FSW and UFSW of AA5083 aluminum alloy [20]. They recorded higher UTS values for UFSW than FSW, respectively 295 and 274 MPa for straight hexagonal pin and 275 and 195 MPa for threaded straight pin. They also found the straight hexagonal pin tool to contribute in high mechanical properties of the joints, both FSW and UFSW [20]. Also, Datta et al. compared UFSW and FSW processes on AA5052 aluminum alloy [16]. The researchers noted higher ductility and UTS values as well as grain refinement for UFSW process [16].

There is a limited amount of publications focused on the UFSW joints aluminum alloy performance in salt water. Also, the research incorporates low salinity level – below 10% salinity. Boukraa et al. compared standard FSW method with FSW cooled with Mediterranean seawater (salinity level of Mediterranean seawater is about 3.8%) on AA2017 aluminum alloy) [21]. They noted a 30% lower peak temperature of the process in the UFSW joint compared with the FSW joint. The lower peak temperature is assigned to higher speed of heat dissipation in salt water. The temperature difference also provided narrower thermo-mechanically affected zones (TMAZ) and heat affected zones (HAZ), possibly improving the mechanical properties of the joints. The ultimate tensile strength (UTS) values was higher for UFSW joint (370.8 MPa) in comparison to FSW joint (220 MPa) [21].

Mousaab et al. compared influence of three types of cooling medias: air, water, and salt water of 0.8%, 2%, and 5.8% salinity on mechanical properties of UFSW AA6082-T6 aluminum alloy joints [22]. They concluded that higher salinity level contributes to lowering mechanical properties of the joint, especially ductility and corrosion resistance. The 5.8% salinity also affected in precipitations and grain coarsening. The tensile strength results indicated to lower UTS values (84.7 MPa) for the joints made in water salinity of any level (lowest for 5.8% salinity), compared to water or air cooled (170.47 and 152.47 MPa, respectively) [22].

Based on the literature review, a relatively limited number of studies addressing Submerged Friction Stir Welding (SFSW) performed in media other than water have been identified. Promising results have also been reported with the use of liquid nitrogen, compressed air, carbon dioxide, and dry ice [23–25]. For each type of medium, individual verification of the weldability window and detailed analysis of the thermo-mechanical processes occurring within the joints are required.

The influence of welding parameters on various technological and operational properties of FSW joints has been investigated using statistical and experimental techniques, including Design of Experiment (DoE) and its Taguchi approach, Analysis of Variance, regression analysis, Principal Component Analysis, artificial neural networks, Monte Carlo simulations, Grey Relational Analysis, Statistical Process Control, and multi-objective optimization techniques such as Pareto optimization and desirability function [26–30]. In this paper, due to the large number of factors affecting the UFSW welding process, a fractional Plackett–Burman design was selected for the preliminary experimental stage. The Plackett–Burman design enabled the identification and elimination of statistically insignificant variables as well as facilitated the development of the subsequent main experimental design [31–33].

This paper discusses preliminary investigations on water salinity effect on mechanical properties of UFSW AA5754 aluminum alloy joints. The Plackett-Burman design is used for statistical analysis of the process parameters and its effect on UTS values. The purpose is to assess the feasibility of salt water as a cooling media for FSW joints.

MATERIALS AND METHODS

The investigations were conducted using AA5754 H22 aluminum alloy. Aluminum alloys from the 5xxx series are aluminum–magnesium alloys (AlMg3). Each joint was manufactured from two sheets with dimensions of 170 × 60 × 4 mm. The chemical composition of the alloy is presented in Table 1, while the mechanical properties are listed in Table 2. The chemical composition of the base material was additionally verified using the Positive Material Identification (PMI) method. Furthermore, the base material was subjected to a static tensile strength test in accordance with the ISO 6892-1:2020-05 standard. The analysis of the test results confirmed the identification of the aluminum alloy.

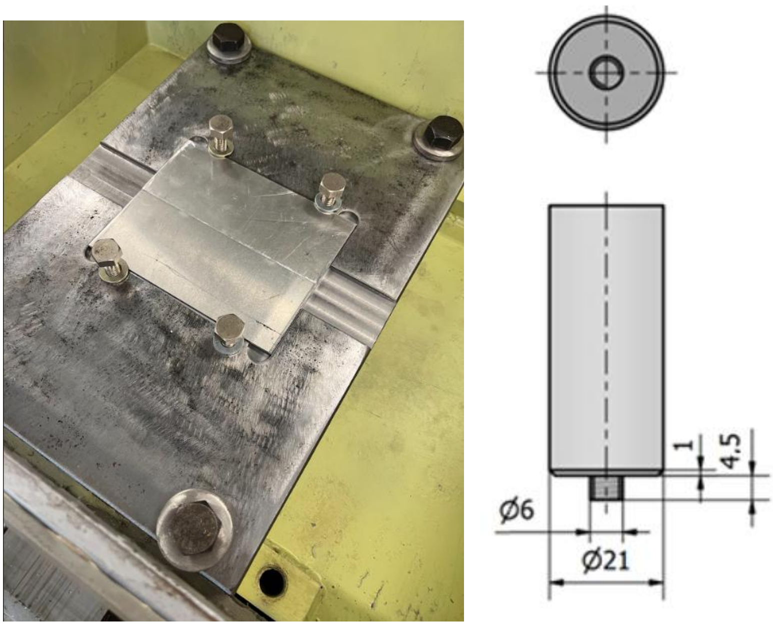
Table 1. *Chemical composition of base material - AA 5754 H22*

	Mg %	Cr %	Fe %	Si %	Cu %	Zn %	Mn %	Al %
Acc. to EN 573-3+A2:2024-06	2.60–3.40	≤0.30	≤0.50	≤0.40	≤0.15	≤0.15	≤0.50	balance
Results of PMI test	2.87	0.04	0.40	0.23	0.05	0.09	0.23	balance

***Table 2.** Mechanical properties of base material - AA 5754 H22*

	UTS MPa	A_{50} %
Acc. to EN 573-3+A2:2024-06	180-250	≥14
Results of tensile strength test	226	24

The welding process was carried out at a workstation mounted on the table of a milling machine (Metal Technics Polska s.c., Sokołów Podlaski). The workstation was designed and manufactured at Gdansk University of Technology. The main component of the workstation is a tank with dimensions of 500 × 400 × 150 mm, which is fixed to the milling machine table. The workstation is presented in Figure 1a. There were no water inlets or outlets in the container during UFSW. The self-developed tool with a cylindrical threaded (M16) pin was used. The welding setup and tool dimensions are presented in Figure 1b. The pin plunge depth was constant for each weld – 3.8 mm. The depth of water measured from the surface of the welded plates was constant—20 mm. The initial water temperature was 23±1 °C.



a) b)

Fig. 1. UFSW welding equipment: a) workstation and plate fixture, b) tool design

The visual tests (VT) were performed in accordance with ISO 17637-2016 [34] standard. The tensile strength tests were performed in accordance with ISO 4136:2022-12 [35]. Two samples were prepared from each joint. The UTS values presented in this paper are average values of two samples. The fractography was performed with an electron microscope Phenom XL (Thermo Fisher Scientific).

DESIGN OF EXPERIMENT

The experimental design was developed using Statistica software (StatSoft Polska), which provides extensive capabilities for statistical data analysis and results visualization [36]. The Plackett–Burman design requires the inclusion of a minimum of seven input variables. The investigated variables were selected based on previous experimental studies and a comprehensive literature review on FSW process and heat treatment of metals in aqueous salt solution [37–40]:

- welding speed (v) [mm/min],
- rotational speed (ω) [rpm],
- tool tilt angle (α) [°],
- water salinity level (s) [%],
- F1, F2, F3 – dummy variables [-].

The number of selected variables was lower than the number required for the Plackett–Burman design. Therefore, three dummy variables, F1, F2, and F3, were introduced. The dummy variables were assigned coded levels of −1, 0, and 1. The UTS, was adopted as the response variable. The levels of the input variables were determined based on previous experimental studies and a literature review [41–45]. Therefore, the Plackett-Burman design consisted of ten joints including one medium sample (no. 9) and one repeated sample (no. 10). The DoE is presented in Table 3.

Table 3. *The Plackett-Burman design*

Sample number	ω rpm	v mm/min	α °	s %	F1	F2	F3
1	475	37.5	0	10	1	-1	1
2	1235	37.5	0	0	1	1	-1
3	475	300	0	10	-1	1	-1
4	1235	300	0	0	-1	-1	1
5	475	37.5	2	0	-1	1	1
6	1235	37.5	2	10	-1	-1	-1
7	475	300	2	0	1	-1	-1
8	1235	300	2	10	1	1	1
9	925	150	1	5	0	0	0
10	1235	37.5	0	0	1	1	-1

RESULTS AND DISCUSSION

The correlation between welding parameters and the amount of heat input was proposed using thermal indices presented in Formula 1 and 2 [46, 47]:

$$HI = \omega / v \quad (1)$$

or

$$\omega^2 / v \quad (2)$$

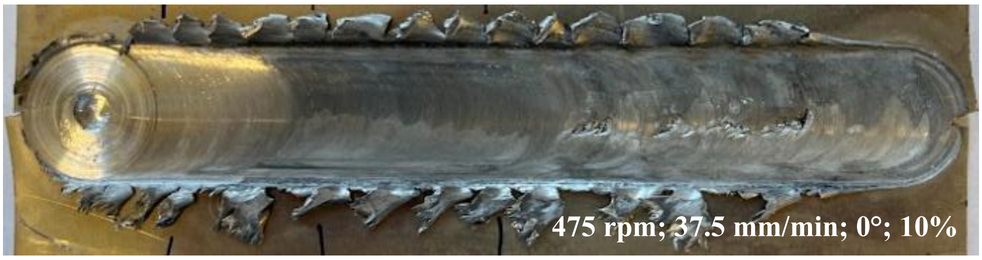
where:
ω - rotational speed [rpm],
v - welding speed [mm/min].

The research results indicate a low degree of dependency within the HAZ and the TMAZ [48]. A slight increase in mechanical properties with increasing values of the ω/v coefficient was also observed. However, it should be acknowledged that the thermal indices do not include tool tilt angle nor the welding environment and its heat dissipation rate. The thermal indices values based on FSW process parameters are presented in Table 4. Also, Figure 2 presents UFSW joints manufactured according to the Plackett-Burman design.

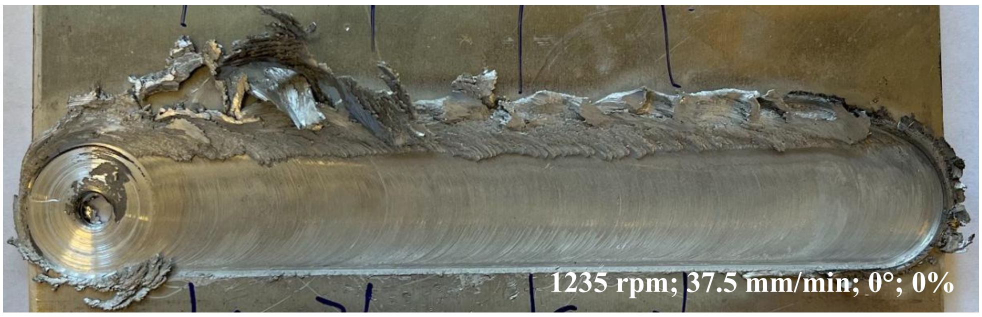
Table 4. *The thermal indices based on process parameters*

Sample number	ω rpm	v mm/min	ω/v r/mm	ω^2/v ratio
1	475	37.5	13	6017
2	1235	37.5	33	40673
3	475	300	2	752
4	1235	300	4	5084
5	475	37.5	13	6017
6	1235	37.5	33	40673
7	475	300	2	752
8	1235	300	4	5084
9	925	150	6	5704
10	1235	37.5	33	40673

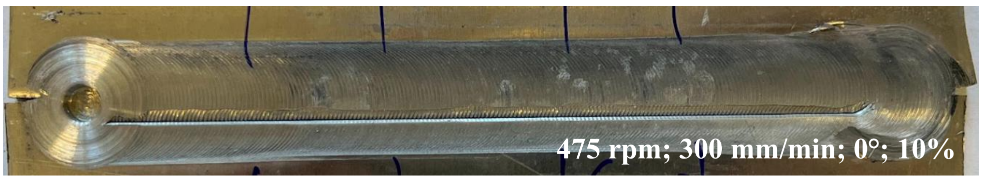
a)



b)



c)



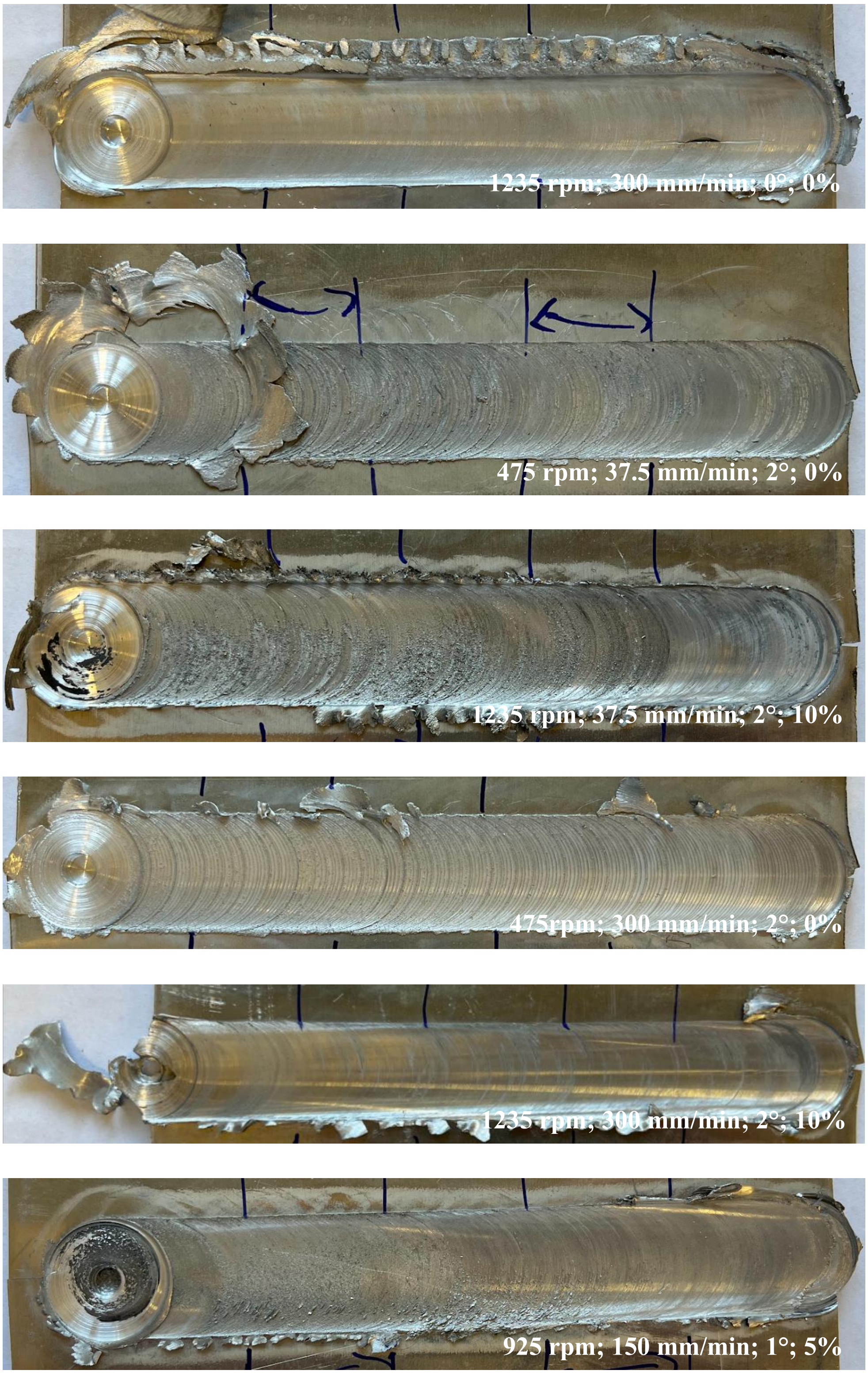


Fig. 2. UFSW joints manufactured according to the Plackett-Burman design: a) 1, b) 2, c) 3, d) 4, e) 5, f) 6, g) 7, h) 8, i) 9

The analysis of the visual inspection results revealed imperfections in the form of incomplete bonding in joints no. 1, 3, and 4. Those were joints made with medium or low values of thermal indices. For example, low rotational speed and high welding speed levels or low rotational speed and 10% water salinity level. In joints no. 1 and 4 the imperfection occurred in the initial section of the joint, whereas in joint no. 3 it was observed along the entire length of the weld. Joints no. 1 and 3 were produced in water with a salinity level of 10% which may have contributed to the lack of proper bonding due to an increased heat dissipation rate. Additionally, joint no. 3 was manufactured at a higher welding speed (300 mm/min) compared to joint no. 1 (37.5 mm/min) which further reduced the amount of heat locally supplied to the welding zone, confirmed by the thermal indices' values.

Joints no. 5, 6, and 9 were characterized by a highly irregular and matte weld surface. Joints no. 5 and 6 were produced at a low welding speed of 37.5 mm/min and a tool tilt angle of 2°. Joint no. 9 was manufactured using medium experimental level process parameters which may be a direct cause of the different surface appearance. It was also observed that weld surfaces produced in water environment with a salinity level of 10% had more of a metallic sheen and were more uniform compared to those produced in water with a salinity level of 0%.

For every joint, some amount of flash was observed. The flash occurred due to the tool pin measurements and its improper fit with the welded material (presented in Figure 1b). A reduced amount of material flash along the joints produced with a tool tilt angle of 2° was also observed. The researches confirm effect of tool tilt angle change on mechanical properties of the weld as well as visual appearance. The study shows that due to the smaller contact area of the tool and the base metal, for tool tilt angle of either 1.5° or 3°, the heat input decreases. Thus, the HAZ and TMAZ decrease in size. However, the joints performed with tool tilt angles of 1.5° and 3° were found inferior to the 0° angle due to the interior defects [49]. Table 5 presents results of the tensile strength tests, including average values of UTS and fracture location (WN – weld nugget, AS – advancing side of the weld) as well as joints efficiency. Figure 3 presents results of the tensile strength tests and Figure 4 presents selected samples after the tests. In order to obtain results from DOE, all of the samples were subjected to the tensile test, despite the visual tests results.

Table 5. *The tensile strength results*

Sample number	UTS MPa	Fracture location	Joint efficiency %
1	93	WN, AS	41
2	210	WN	93
3	44	WN, AS	19
4	95	WN, AS	42
5	222	WN	98
6	227	WN	100
7	201	WN	89
8	199	WN	88
9	185	WN	82
10	201	WN	89

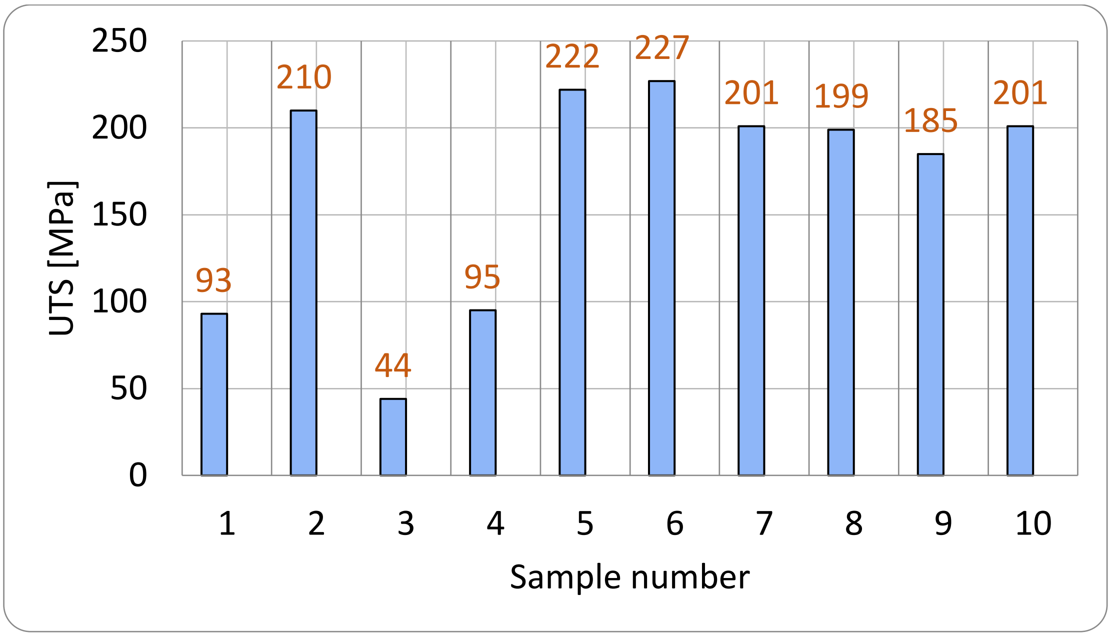
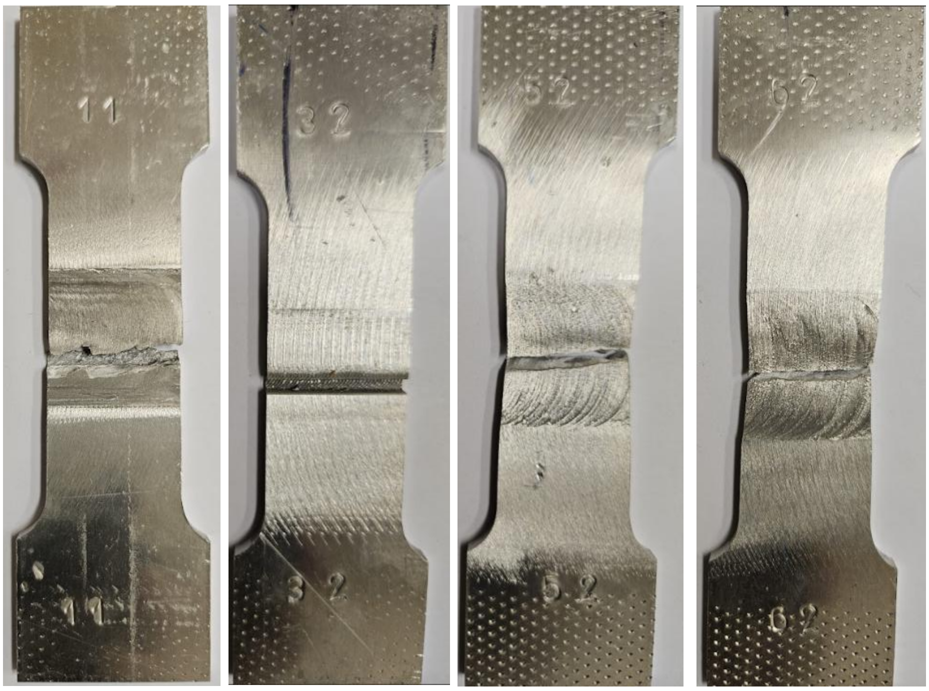


Fig. 3. The tensile strength tests results



a) b) c) d)

Fig. 4. Selected samples after the tensile strength tests: a) 1.1 - 475 rpm; 37.5 mm/min; 0°; 10%, b) 3.2 - 475 rpm; 300 mm/min; 0°; 10%, c) 5.2 - 475 rpm; 37.5 mm/min; 2°; 0% d) 6.2 – 1235 rpm; 37.5 mm/min; 2°; 10%

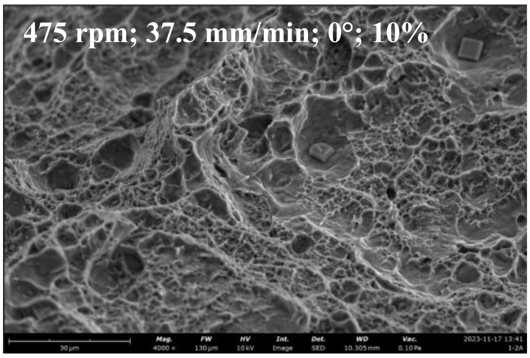
All of the samples fractured in the weld (stirring zone). Three of them (joint no. 1, 3 and 4) fractured in the weld on the advancing side of the joint. With the exception of joints no. 1, 3, and 4, joints exhibited efficiency exceeding 80%. Joints no. 1, 3, and 4 showed defects during the visual inspection stage, which accounted for their reduced UTS values.

Furthermore, the joints with the highest tensile strength values — joints no. 2, 5, and 6 (corresponding to 93%, 98%, and 100% joint efficiency, respectively) — were produced at a low welding speed of 37.5 mm/min, which likely enabled an increased amount of locally generated heat to be introduced into the joined materials. The thermal indices of those three joints had medium (joint no. 5) or high values (joint no. 2 and 6). Rathinasuriyan et al. studied different values of rotational speed and welding speed and its effect on the mechanical properties [50]. The researchers stated that the highest joint efficiency was obtained for the joints made with process parameters: welding speed 30 mm/min and rotational speed 1000 rpm. This provided fine grains structure. Concluding, the correct set of these the parameters is essential for sufficient heat input [50].

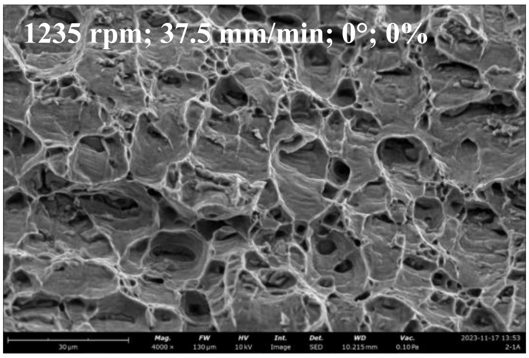
In addition, joints no. 5–8 were manufactured with a tool tilt angle of 2°, which also contributed to higher UTS values compared to joints produced with a tilt angle of 0° (joints no. 1–4). It should be mentioned that joints no. 5-8 were all produced with different values of heat indices. The thermal indices for joint no. 5 and 6 were of medium and high values, whereas for joint no. 7 and 8 of low values. The difference in UTS values was about 21-28 MPa between the joints, thus it indicates the slight correlation between UTS values and thermal indices values. The result is in line with the research of Essa et al. [51]. The researchers compared tool tilt effect on mechanical properties, additionally introducing eccentric tool. They found that, for aligned tool, the UTS was higher for the joint performed with 3° than 0°. However, the correlation was reversed for the eccentric tool. Also, the UTS for the eccentric tool with tilt angle of 0° was the highest of all attempts, stating that it might be the promising method of improving mechanical properties of the FSW joints [51]. No direct effect of changes in water salinity level on the UTS values was observed. Fractography of selected joints, based on the parameters and UTS results, is presented in Figure 5.

For the samples performed in water with salinity level of 10%, crystalline precipitates were detected (Figure 5a and d). The precipitates might be NaCl solution that penetrated to the plasticized material during welding. Larger amount of precipitates was found in joint no. 6, however of smaller sizes than those found in the joint no. 1. Also, very fine dimples were found in the joint no. 6 and, both, fine and large dimples in joint no 1. The diversity of fracture, as well as the large precipitations might be the cause of brittleness and very low UTS results of samples from the joint no. 1. Samples from the joints no. 2, 5, and 9 are characterized by the ductile fracture with uniform dimples as a result of plastic deformation. Although, larger dimples were found in joint no. 9, possibly contributing to lower UTS results. The ductile fracture and large dimples are typical for FSW aluminum alloys joints [52].

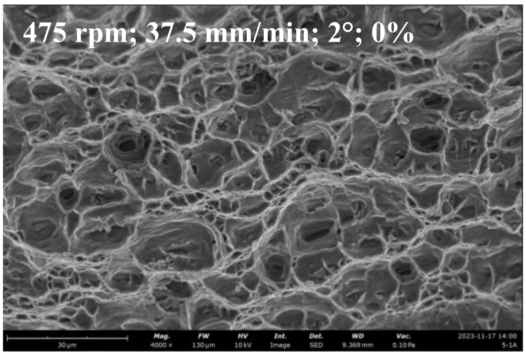
Based on the tensile strength results, a statistical analysis was performed to evaluate the influence of process parameters and welding environment conditions on the joint properties. Figure 6a presents the significance analysis of the effects of all input variables, including the curvature test, using the Pareto charts. Figure 6b shows the standardized Pareto chart after the removal of statistically insignificant variables. As expected, the dummy variables and the curvature test did not exceed the line marking the confidence level. Thus, the dummy variables are not statistically significant. The lack of statistical significance of factors F1, F2, and F3 further confirms the validity of the analyses performed. In turn, the absence of statistical significance of the curvature indicates that the effect of the investigated parameters on UTS is linear.



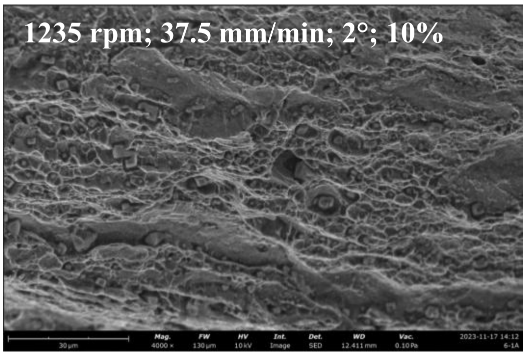
a)



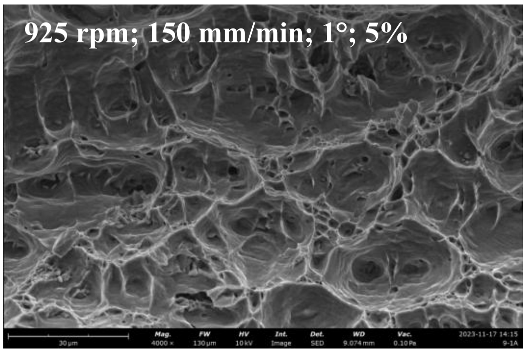
b)



c)



d)



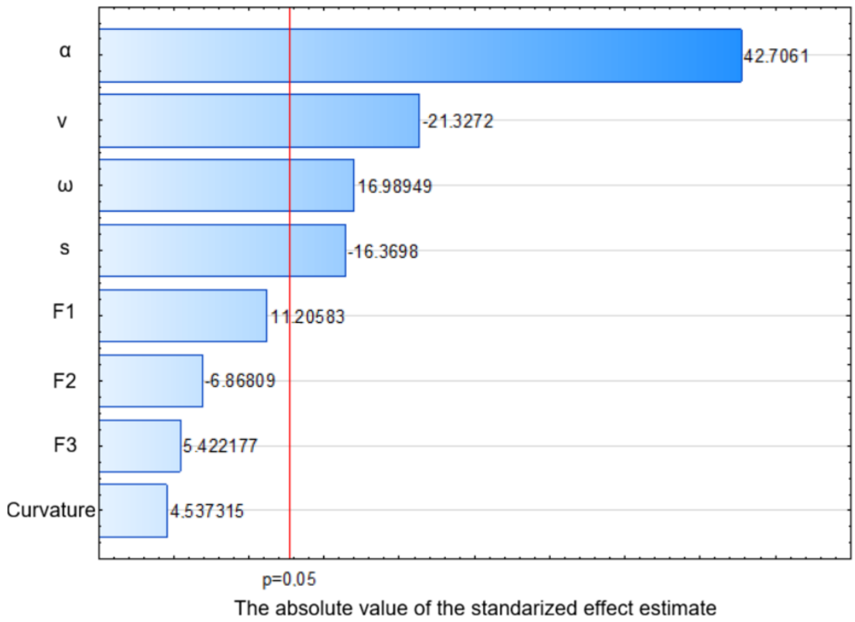
e)

Fig. 5. Fractography of selected samples of UFSW joints: a) 1, b) 2, c) 5, d) 6, e) 9

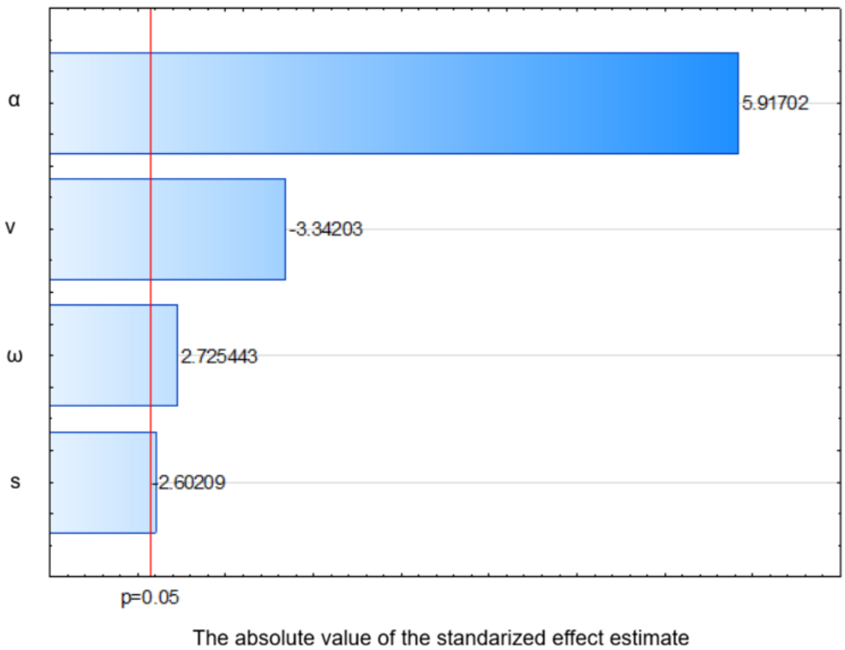
This implies that the main experiments can be conducted in accordance with a two-level experimental design. Additionally, Figure 6c presents a quantitative analysis of the effect significance of the statistically significant variables. Based on the significance analysis of the effects, it was found that all welding parameters are statistically significant (exceeding the confidence level of p=0.05): having a significant impact on the UTS. The tool tilt angle, however, exhibited the highest significance. The quantitative analysis indicates that its significance is approximately twice as high as that of the welding speed. Changing the value from -1 to 1 (from 0° to 2°) results in an effect estimate change by 99.3 MPa, based on the Pareto chart (Figure 6c). Change in the welding speed value results in the effect estimate change by 56.1 MPa. In contrast, the rotational speed and water salinity level showed the lowest significance, changing the effect estimate value by 45.8 MPa and 43.7 MPa, respectively. Kim et al. also used the Plackett-Burman design to estimate the significance of

FSW process parameters – rotational speed (levels 1000 and 1500 rpm), welding speed (levels 300 and 650 mm/min) and tool tilt angle (levels 2 and 3°) [53]. The response values were based on tensile strength, microhardness and fatigue strength. They stated that the most statistically significant parameter was welding speed, then rotational speed, and tool tilt angle at last. However, it should be considered that the tool tilt angle values were of smaller difference than values investigated in this research. The fatigue strength was also most affected by the welding speed, whereas for the microhardness, the tool tilt angle was the most significant parameter [53].

a)



b)



c)

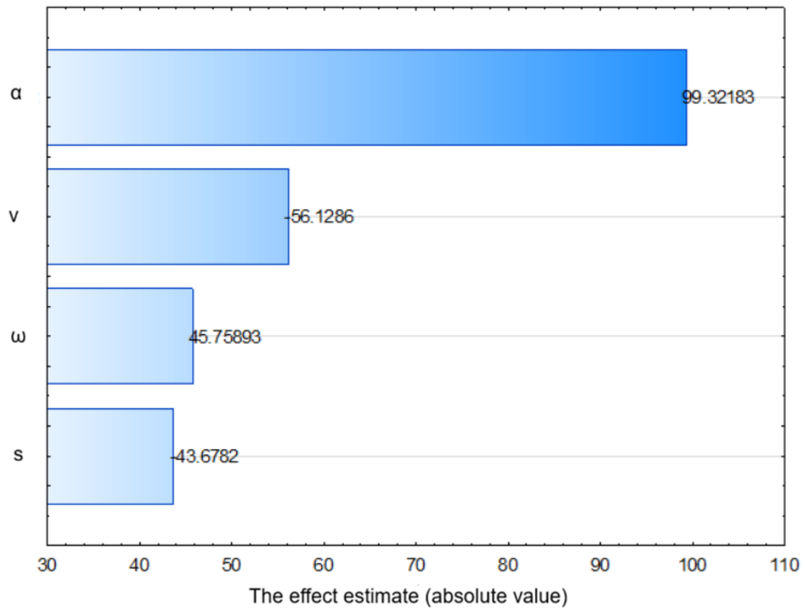


Fig. 6. Results of statistical analysis: a) The Pareto chart - significance analysis of the effects of all input variables, b) the Pareto chart - statistically significant variables, c) quantitative analysis of the effect significance of the statistically significant variables

CONCLUSIONS

The purpose of this paper was to assess the utility of 10% water salinity as a cooling method for FSW process. To the best authors knowledge, there is a very limited amount of research done on this subject. The base material was aluminum alloy AA5754 H22. The Plackett-Burman design was used for the purpose of the research. The DoE consisted of seven input variables: welding parameters (welding speed, rotational speed, tool tilt angle, and water salinity level) and three dummy variables. For performed joint, the visual tests, tensile strength tests and fractography were performed. The response variable was UTS.

The following conclusions were drawn based on the results analysis:

1. The highest statistical significance was noted for the tool tilt angle as the FSW process parameter. The joints made with 2° tilt angle were repeatable and of highest UTS.
2. Statistically, salinity level was least significant. The highest UTS values were obtained for the joint produced in water environment with 10% salinity. However, it affected the material causing precipitates as seen in fractography results.
3. The fractography results indicated that water with 0% salinity level is more prone to develop ductile fracture of the UFSW joints in comparison with 10% salinity level.
4. For welding speed and rotational speed, the best UTS values were obtained for the joints performed with low welding speed (37.5 mm/min) and high rotational speed (1235 rpm). The set of parameters induced high values of thermal indices, enough to produce sound joint.
5. There is a slight linear correlation between ω/v and ω^2/v thermal indices and UTS values. However, it does not refer to all of the attempts in this investigation.
6. Considering low repeatability of the results, extended research should be performed.

ACKNOWLEDGEMENT

The author would like to thank Dariusz Karubin (Gdańsk University of Technology) for technical assistance and support.

Conflicts of Interest

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

REFERENCES

1. Rathinasuriyan C, Pavithra E, Sankar R, Kumar VSS (2021) Current Status and Development of Submerged Friction Stir Welding: A Review. Int J of Precis Eng and Manuf-Green Tech 8:687–701. https://doi.org/10.1007/s40684-020-00187-6
2. Subramanian S, Natarajan E, Khalfallah A, et al (2025) Current Trends and Emerging Strategies in Friction Stir Spot Welding for Lightweight Structures: Innovations in Tool Design, Robotics, and Composite Reinforcement — A Review. Crystals 15:556. https://doi.org/10.3390/cryst15060556
3. Silva WJM, Soares RF, Araújo WM, et al (2025) Mechanical and Metallographic Characterization of Friction Stir Welded EN AW 1200 Aluminum Sheets: Analysis of the Effect of Process Parameters and Pin Geometry. Soldag insp 30:e3010. https://doi.org/10.1590/0104-9224/si30.10
4. Melaku LE, Tomków J (2025) Dissimilar friction stir welding of aluminum to polymer: a review. Int J Adv Manuf Technol 140:2377–2396. https://doi.org/10.1007/s00170-025-16393-y
5. Ahmad T, Lone NF, Khan NZ, et al (2025) Surface properties of friction stir welded dissimilar joints of AA7075 and Mg-WE43 alloys: Effect of positional arrangement. J Magnes Alloy 13:398–413. https://doi.org/10.1016/j.jma.2024.12.022
6. Shrivastava A, Krones M, Pfefferkorn FE (2015) Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum. CIRP J Manuf Sci Technol 9:159–168. https://doi.org/10.1016/j.cirpj.2014.10.001
7. Eslami N, Hischer Y, Harms A, et al (2019) Optimization of Process Parameters for Friction Stir Welding of Aluminum and Copper Using the Taguchi Method. Metals 9:63. https://doi.org/10.3390/met9010063
8. Kilic S, Ozturk F, Demirdogen MF (2025) A comprehensive literature review on friction stir welding: Process parameters, joint integrity, and mechanical properties. J Eng Res 13:122–130. https://doi.org/10.1016/j.jer.2023.09.005
9. Janeczek A, Tomków J, Derazkola HA, et al (2024) Effect of underwater friction stir welding parameters on AA5754 alloy joints: experimental studies. Int J Adv Manuf Technol 134:5643–5655. https://doi.org/10.1007/s00170-024-14485-9
10. Aziz SB, Dewan MW, Huggett DJ, et al (2016) Impact of Friction Stir Welding (FSW) Process Parameters on Thermal Modeling and Heat Generation of Aluminum Alloy Joints. Acta Metall Sin (Engl Lett) 29:869–883. https://doi.org/10.1007/s40195-016-0466-2
11. Zhai M, Wu C, Su H (2020) Influence of tool tilt angle on heat transfer and material flow in friction stir welding. J Manuf Process 59:98–112. https://doi.org/10.1016/j.jmapro.2020.09.038
12. Kosturek R, Torzewski J, Śnieżek L (2024) Study on Underwater Friction Stir Welding of AA7075-T651. Adv Sci Technol Res J 18:191–203. https://doi.org/10.12913/22998624/193529

13. Heidarzadeh A, Javidani M, Mofarrehi M, et al (2021) Submerged Dissimilar Friction Stir Welding of AA6061 and AA7075 Aluminum Alloys: Microstructure Characterization and Mechanical Property. Metals 11:1592. https://doi.org/10.3390/met11101592
14. Chitturi V, Pedapati SR, Awang M (2022) Mathematical Model for Friction Stir Lap Welded AA5052 and SS304 Joints and Process Parameters Optimization for High Joint Strength. Adv Mater Sci 22:5–22. https://doi.org/10.2478/adms-2022-0001
15. Khalaf HI, Al-Sabur R, Abdullah ME, et al (2022) Effects of Underwater Friction Stir Welding Heat Generation on Residual Stress of AA6068-T6 Aluminum Alloy. Materials 15:2223. https://doi.org/10.3390/ma15062223
16. Datta R, Kumar Gupta S, Bhargava M (2023) Comparison of underwater friction stir welded and conventional friction stir welded AA 5052 alloys based on the mechanical, formability and microstructure behaviour. Materials Today: Proceedings S221478532304779X. https://doi.org/10.1016/j.matpr.2023.09.108
17. El-Sayed MM, Shash AY, Abd-Rabou M, ElSherbiny MG (2021) Welding and processing of metallic materials by using friction stir technique: A review. J Adv Join Process 3:100059. https://doi.org/10.1016/j.jajp.2021.100059
18. Sucharitha M, Ravi Sankar B, Umamaheswarrao P (2020) A Review on Submerged Friction Stir Welding of Light Weight Alloys. IOP Conf Ser: Mater Sci Eng 954:012014. https://doi.org/10.1088/1757-899X/954/1/012014
19. Wahid MohdA, Khan ZA, Siddiquee AN (2018) Review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties. Trans Nonferrous Met Soc China 28:193–219. https://doi.org/10.1016/S1003-6326(18)64653-9
20. Saravanakumar R, Sirohi S, Pandey SM, et al (2024) Attributes of FSW and UWFSW butt joints of armour grade AA5083 aluminium alloy: Impact of tool pin profile. Heliyon 10:e38351. https://doi.org/10.1016/j.heliyon.2024.e38351
21. Boukraa M, Chekifi T, Madani T, et al (2025) Enhancing Friction Stir Welding Performance for 2017AA Alloy through Cooling with Mediterranean Seawater. Exp Tech 49:189–201. https://doi.org/10.1007/s40799-024-00751-8
22. Mousaab BM, Eddine CMND, Yazid AF, et al (2025) Experimental investigation of the impact of aqueous salinity on the performance of underwater friction stir welding. Int J Adv Manuf Technol 141:5447–5456. https://doi.org/10.1007/s00170-025-16928-3
23. Iwaszko J, Kudła K (2022) Evolution of Microstructure and Properties of Air-Cooled Friction-Stir-Processed 7075 Aluminum Alloy. Materials 15:2633. https://doi.org/10.3390/ma15072633
24. Liu XC, Li WT, Zhou YQ, et al (2023) Multiple effects of forced cooling on joint quality in coolant-assisted friction stir welding. J Mater Res Technol 25:4264–4276. https://doi.org/10.1016/j.jmrt.2023.06.248
25. Su Y, Zhou M, Li W, et al (2025) Microstructural evolution and mechanical behavior of TA5 titanium alloy joint in low-temperature friction stir welding with various cooling rates. Eng Fail Anal 176:109667. https://doi.org/10.1016/j.engfailanal.2025.109667
26. Myśliwiec P, Kubit A (2025) Integrated multiobjective optimization of RFSSW parameters for AA2024-T3 using ANOVA machine learning and NSGA II. Sci Rep 15:38029. https://doi.org/10.1038/s41598-025-21941-3
27. Saravanakumar R, Rajasekaran T, Pandey C (2023) Optimisation of underwater friction stir welding parameters of aluminum alloy AA5083 using RSM and GRA. Proc Inst Mech Eng, Part E: J Process Mech Eng 237:2334–2348. https://doi.org/10.1177/09544089221134446

28. D S, P S, Babu S D D, Roy V (2024) Optimization of parameters and formulation of numerical model employing GRA–PCA and RSM approach for friction stir welded Ti–6Al–4V alloy joints. Mater Res Express 11:056511. https://doi.org/10.1088/2053-1591/ad48e3

29. Zhang Z, Xiao YH, Liu CK, Li JY (2024) Experimental and numerical studies of relationship between microstructures and mechanical properties in friction stir welding under water. J Mater Sci 59:19716–19733. https://doi.org/10.1007/s10853-024-10357-5

30. Lacki P, Derlatka A, Więckowski W, Adamus J (2024) Development of FSW Process Parameters for Lap Joints Made of Thin 7075 Aluminum Alloy Sheets. Materials 17:672. https://doi.org/10.3390/ma17030672

31. Esch P, Klocke F, Bauernhansl T, Schneider M (2021) Methodic development of laser micro structured cutting tools with microscale textures for AW7075 aluminum alloy using a Plackett–Burman screening design. CIRP J Manuf Sci Technol 32:188–195. https://doi.org/10.1016/j.cirpj.2020.06.008

32. Wang J, Chen X, Yang L (2022) Reliability-based multi-objective optimization incorporating process–property–performance relationship of double-pulse MIG welding using hybrid optimization strategy. Struct Multidisc Optim 65:148. https://doi.org/10.1007/s00158-021-03103-x

33. Fydrych D, Świerczyńska A, Tomków J (2013) Diffusible Hydrogen Control in Flux Cored Arc Welding Process. KEM 597:171–178. https://doi.org/10.4028/www.scientific.net/KEM.597.171

34. ISO 17637:2017-02 - Non-destructive testing of welds — Visual testing of fusion-welded joints

35. ISO 4136:2022-12 - Destructive tests on welds in metallic materials — Transverse tensile test

36. Jonda ES, Fydrych D, Łatka L, Myalska-Głowacka H (2024) The Use of Cluster Analysis to Assess the Wear Resistance of Cermet Coatings Sprayed by High Velocity Oxy-Fuel on Magnesium Alloy Substrate. Adv Sci Technol Res J 18:216–227. https://doi.org/10.12913/22998624/188877

37. Aghajani Derazkola H, Kordani N, Aghajani Derazkola H (2021) Effects of friction stir welding tool tilt angle on properties of Al-Mg-Si alloy T-joint. CIRP J Manuf Sci Technol 33:264–276. https://doi.org/10.1016/j.cirpj.2021.03.015

38. Kosturek R, Torzewski J, Wachowski M, Śnieżek L (2022) Effect of Welding Parameters on Mechanical Properties and Microstructure of Friction Stir Welded AA7075-T651 Aluminum Alloy Butt Joints. Materials 15:5950. https://doi.org/10.3390/ma15175950

39. Uday KN, Rajamurugan G (2023) Influence of process parameters and its effects on friction stir welding of dissimilar aluminium alloy and its composites – a review. J Adhes Sci Technol 37:767–800. https://doi.org/10.1080/01694243.2022.2053348

40. Pizetta Zordão LH, Oliveira VA, Totten GE, Canale LCF (2019) Quenching power of aqueous salt solution. Int J Heat Mass Transf 140:807–818. https://doi.org/10.1016/j.ijheatmasstransfer.2019.06.036

41. Chandra PC, Mondal AK, Nirsanametla Y, et al (2025) Impact of Tool Plunge Depth, Tool Tilt Angle, and Tool Offset on Microstructure, Mechanical Properties, and Fracture Morphology of Friction Stir Welded Pure Copper Butt Joints. J of Materi Eng and Perform 34:22021–22038. https://doi.org/10.1007/s11665-025-10840-3

42. Sabry I, Singh VP, Alkhedher M, et al (2024) Effect of rotational speed and penetration depth on Al-Mg-Si welded T-joints through underwater and conventional friction stir welding. J Adv Join Process 9:100207. https://doi.org/10.1016/j.jajp.2024.100207

43. Alfattani R, Yunus M, Mohamed AF, et al (2021) Assessment of the Corrosion Behavior of Friction-Stir-Welded Dissimilar Aluminum Alloys. Materials 15:260. https://doi.org/10.3390/ma15010260

44. Venugopal V, Pratap Singh V, Kuriachen B (2023) Underwater friction stir welding of marine grade aluminium alloys: A review. Mater Today Proc S221478532304052X. https://doi.org/10.1016/j.matpr.2023.07.182

45. Lipińska M (2023) Microstructure and Mechanical Properties of the Joints from Coarse- and Ultrafine-Grained Al-Mg-Si Alloy Obtained via Friction Stir Welding. Materials 16:6287. https://doi.org/10.3390/ma16186287

46. Abbasi Gharacheh M, Kokabi AH, Daneshi GH, et al (2006) The influence of the ratio of "rotational speed/traverse speed" (ω/v) on mechanical properties of AZ31 friction stir welds. Int J Mach Tools and Manuf 46:1983–1987. https://doi.org/10.1016/j.ijmachtools.2006.01.007

47. Fu R, Zhang J, Li Y, et al (2013) Effect of welding heat input and post-welding natural aging on hardness of stir zone for friction stir-welded 2024-T3 aluminum alloy thin-sheet. Mater Sci and Eng A 559:319–324. https://doi.org/10.1016/j.msea.2012.08.105

48. Li Y, Zhou Z, Yin L, et al (2023) Thermal Cycling, Microstructure, and Mechanical Properties of Al-Mg-Si-Cu Alloy Bobbin Tool Friction Stir Welded Joints Based on Thermal Index. Coatings 13:1607. https://doi.org/10.3390/coatings13091607

49. Abdullah ME, M. Rohim MN, Mohammed MM, Derazkola HA (2023) Effects of Partial-Contact Tool Tilt Angle on Friction Stir Welded AA1050 Aluminum Joint Properties. Materials 16:4091. https://doi.org/10.3390/ma16114091

50. Rathinasuriyan C, Puviyarasan M, Sankar R, Selvakumar V (2024) Effect of process parameters on weld geometry and mechanical properties in friction stir welding of AA2024 and AA7075 alloys. J Alloy Metall Syst 7:100091. https://doi.org/10.1016/j.jalmes.2024.100091

51. Essa ARS, Aboud ARK, Ahmed MMZ, et al (2025) Friction stir welding of aluminum alloy 6082-T6 using eccentric shoulder tools to eliminate the need for tool tilting. Sci Rep 15:8801. https://doi.org/10.1038/s41598-025-91065-1

52. Kosturek R, Ślęzak T, Torzewski J (2024) Structural Integrity of AA7075-T651 UWFSW Joints. Adv Mater Sci 24:98–110. https://doi.org/10.2478/adms-2024-0025

53. Kim W-K, Won S-T, Goo B-C (2010) A study on mechanical characteristics of the friction stir welded A6005-T5 extrusion. Int J Precis Eng Manuf 11:931–936. https://doi.org/10.1007/s12541-010-0113-1