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A NEW TOOLING APPROACH FOR FRICTION STIR WELDING OF THIN SHEET AA2024-T3 - OPTIMIZATION OF WELDING PARAMETERS

Abstract: In this study a new ceramics tools with different groove distributions were designed and manufactured in order to enrich technological storage of joining thin-wall structures and obtain sound joint with high quality of Alclad AA2024-T3 alloy of 0.5 mm in thickness. Four types of tools were tested, without grooves, with 1, 2 and 6 grooves. The tools are made of two materials. The straight shank is made from tungsten carbide and tool body made from ceramics strengthened with whiskers. The influence of technological parameters on the strength of FSW joints was tested by the Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) method. The least durable weld is produced by a tool without grooves. The single and double flute tool produces a good quality weld over a wide range of tool speeds. It has been shown that the grooves on the tool shoulder significantly affect the quality of the obtained FSW joint.

Keywords: aluminium alloy AA2024-T3, ANOVA, ceramic tools, friction stir welding, FSW tool geometry, joining of thin sheets, RSM

1. Introduction

Friction stir welding (FSW) is a solid-state welding technique that has evolved as a solution for joining different metal sheets especially dissimilar materials that are difficult to weld. It is currently used as an alternative to riveting for e.g. the assembly of airplane fuselages (Takhakh & Hussein, 2021). FSW uses a rotary pin to locally mix the materials of the two sides of the joint below the melting point temperature (Thomas et al., 1995). Thus, the formation of welding defects such as hot cracking is prevented (Węglowski, 2018). Friction stir welding is a continuous, hot shear, autogenous process involving non-consumable

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rotating tool of harder material than the substrate material (Ahmed et al., 2021). Fig. 1 explains the working principle of FSW process.

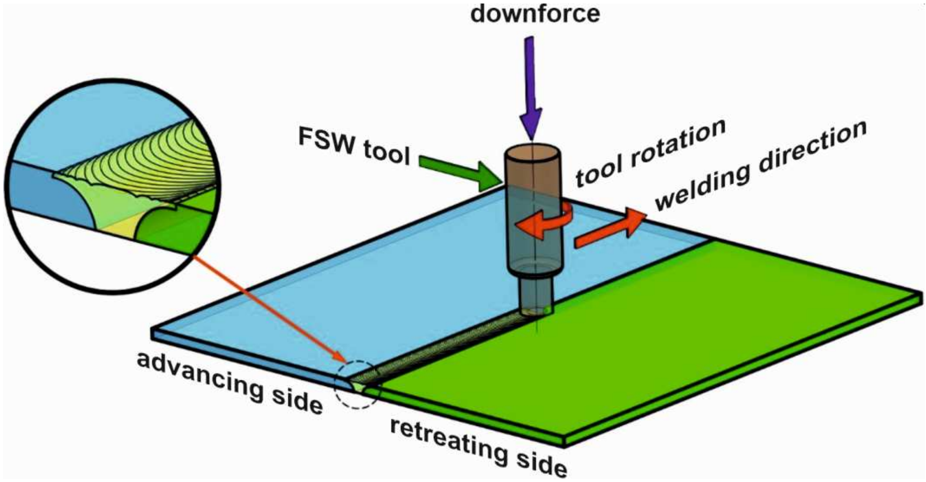


Fig. 1. Schematic representation of FSW principle

In order to increase the efficiency of FSW welding, many different tool variants are being developed. Both the tool material and the tool geometry are subjected to modification. Tool material should be wear-resistant under high thermal stress (Kumar & Kailas, 2008). Tool shoulder plays a key role in generation of surface friction and rise of workpiece temperature. Tool pin generates stirring and therefore materials in processed zone experience sever plastic deformation. Flowing and recrystallisation in processed zone occurs with tool rotation and linear movement. This results in creation of a fine equiaxed microstructure (Elangovan & Balasubramanian, 2007; Zhang et al. 2020).

In this paper, the mechanical properties (tensile strength) of the samples of welded 2024-T3 aluminum alloy sheets were investigated to determine the best rotational speed and welding speeds. The work determines the optimal parameters using one of the optimized methods to ensure proper welding performance based on tensile strength, study the obtained optimal parameters of mechanical properties and performance using the design of experiments (DOE) technique and development of models. It can help designers and engineers to achieve perfect welding. ANOVA techniques were used to identify the relevant factors influencing the ultimate tensile strength (UTS).

2. Material and experimental procedure

The initial material used in this work is a cold-rolled commercial AA2024-T3 aluminum alloy sheet with the 0.5 mm in thickness Alclad covered. In this investigation, the joining region are carefully cleaned prior to welding. After polished by abrasive paper and cleaning with acetone, several weld plates were subjected to FSW along the rolling direction. The blank sheet dimensions were 180×100 mm (Fig. 2). The FSW experiments were carried out using special prepared CNC milling machine MAKINO PS95 and the welding tools (Fig. 3). Cylindrical tool made from whisker-reinforced ceramic with geometrical features and process inputs are reported in Table 1.

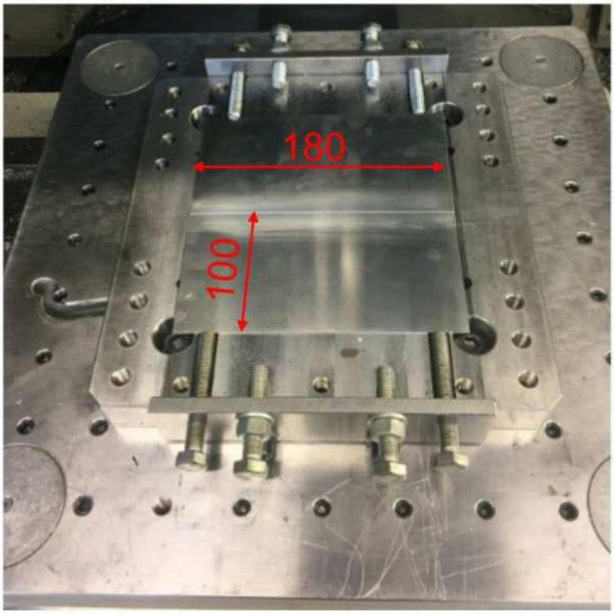


Fig. 2. View of workpiece material installed on fixture device

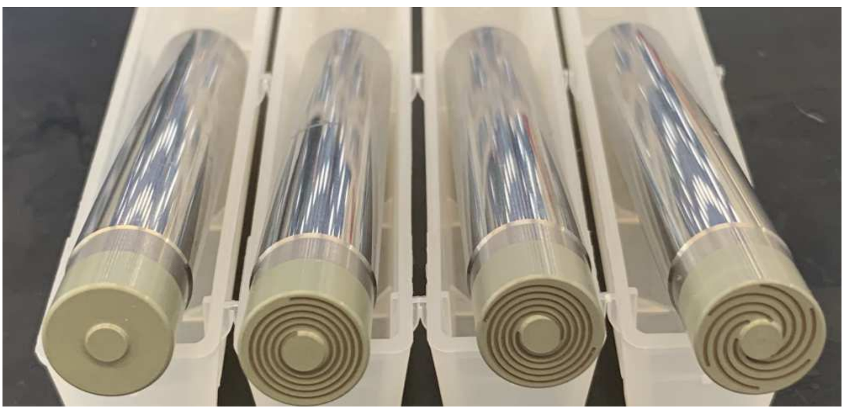
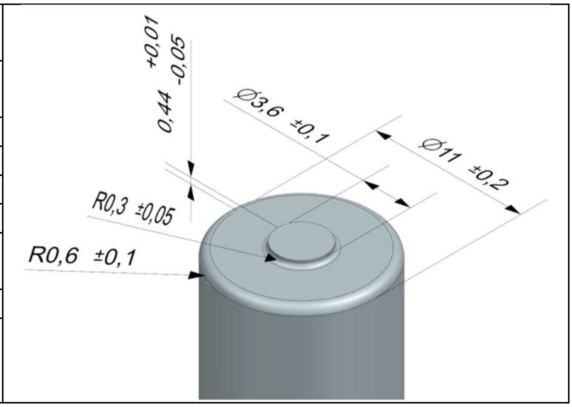


Fig. 3. Different type of shoulder profile of FSW tools with and without groves

Table 1. Inputs used for the experimental set-up of FSW

Tool material	whisker-reinforced ceramics	
Shoulder diameter D	11 mm	
Pin diameter d	3.6 mm	
Pin height	0.44 mm	
Pin profile	cylindrical	
Shoulder profile	flat	
D/d ratio of the tool	3.05	
Dwell time	1 s	
Penetration depth (tool offset)	0.03 mm	

Tool worked without a tilt angle, perpendicular to the surface of the welded material. The butt joint configuration was prepared to produce the joints. Welding has been done on the 180 mm long section.

A research plan was prepared for the experiment. Design-Expert software by Stat-Ease, Inc. was used. The range for technological parameters was determined for the rotational speed from 1000 to 2000 rpm and the welding speed from 200 to 1000 mm/min (Fig. 4). The last factor was the number of spiral grooves on the tool face. On this basis, a matrix of technological parameters was created. The set of parameters is shown in Fig. 5. Several regression models have been tested. The best results were obtained for the CUBIC model (Table 2).

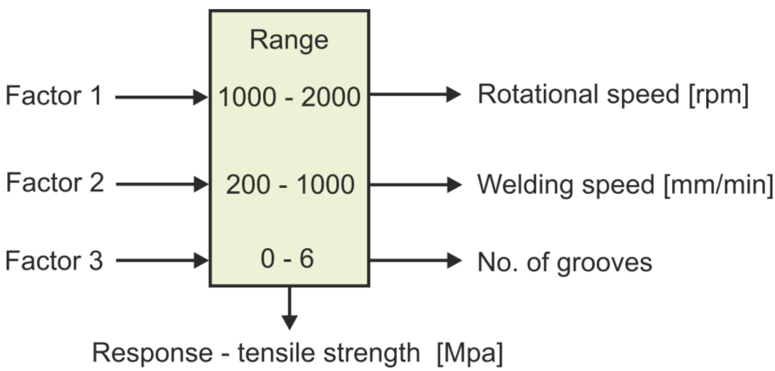


Fig. 4. Ranges of changes in welding parameters

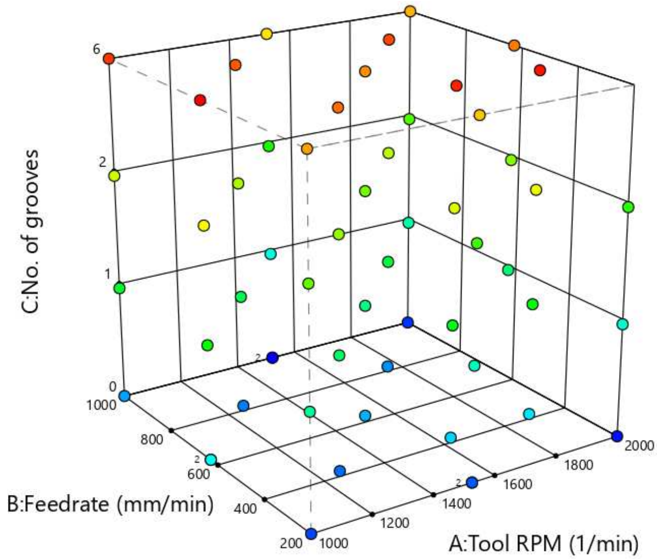


Fig. 5. Matrix of welding parameters

Table 2. Various regression models for the FSW experiment

Source	**Model p-value**	**Lack of fit p-value**	**Adjusted R^2**	**Predicted R^2**	**Recommenda-tion**
Design Model	< 0.0001	0.5185	0.6001	0.5637	
Linear	< 0.0001	0.4064	0.4838	0.4091	
2FI	0.0138	0.5060	0.5908	0.4649	
Quadratic	0.0007	0.6467	0.6961	0.5697	Suggested
Cubic	0.0291	0.8023	0.7843	0.3346	Suggested
Quartic	0.2486	0.9016	0.8279	-1.8351	Aliased

Obtained FSW joints were the basis to make specimens for tensile tests. The mechanical properties of the joints were measured during tensile testing. Tensile specimens dimension and a method of preparing was shown on Fig. 6. Static tensile test was performed in accordance with PN-EN ISO 6892-1:2009. The tensile tests were carried out on an Zwick/Roell Z 100 universal testing machine, at room temperature. An extensometer with a gauge length of 50 mm was used for strain data acquisition. The results, given by the nominal stress vs. nominal strain curves, were evaluated in terms of the ultimate tensile strength, yield strength (YS) and ultimate elongation (UE) in percentage. In the purpose of verifying the repeatability of the results each tested samples was repeated at least three times. From each joined metallic plate was cut three samples from the beginning, middle and end of a weld and then the measured values were averaged.

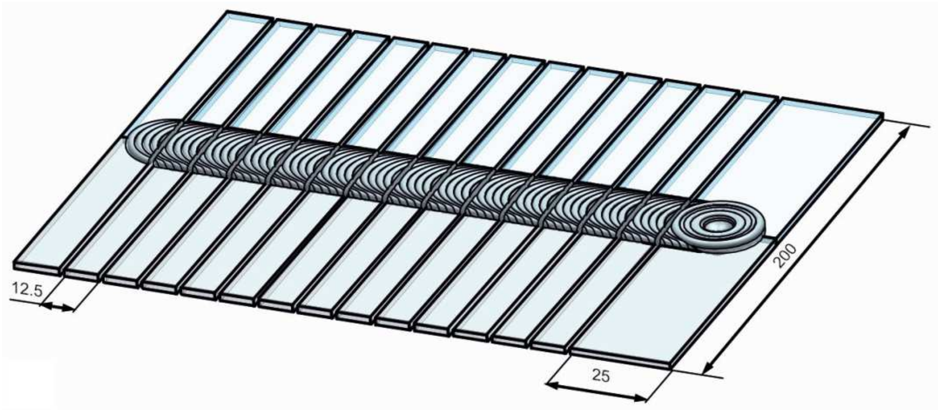


Fig. 6. Geometry of specimens for uniaxial tensile testing (dimension are in mm)

Backward elimination regression model were developed. As an input factors tool rotation per minute, feedrate and number of grooves were selected. Factors were coded -1 for lower and +1 for high limit. Number of grooves was set as categoric 4 levels: 0, 1, 2, 6 (Table 3).

Table 3. Input factors used in experiments

Factor	Name	Units	Type	Min.	Max.	Coded Low	Coded High	Mean	Std. Dev.
A	Tool rotational speed	1/min	Num.	1000	2000	-1 ↔ 1000	+1 ↔ 2000	1500.34	360.59
B	Feed rate	mm/min	Num.	200	1000	-1 ↔ 200	+1 ↔ 1000	586.21	294.66
C	Number of grooves		Categoric	0	6			Levels:	4.00

3. Results

Ultimate tensile strength test results have been taken into account as the response. Performed analysis of variation (ANOVA) and cubic model were selected with regard to fit summary of different models. Then applied backward eliminator algorithm which removes insignificant input factors with p-value less than 0.1 but with hierarchical agreement. Table 4 presents ANOVA for Reduced Cubic Model of UTS. The Model F-value of 19.24 means that model is significant and only a 0.01% chance that this large values could result due to noise. P-value for factors is less than 0.05 which means that model is significant.

Table 4. ANOVA for UTS response for reduced CUBIC model

Source	Sum of Squares	df	Mean Square	F-value	p-value	Signifi-cance
Model	7.572E+05	9	84137.06	19.24	< 0.0001	significant
A-Tool RPM	77165.40	1	77165.40	17.65	0.0001	
B-Feedrate	3.532E+05	1	3.532E+05	80.77	< 0.0001	
C-No. of grooves	1.050E+05	3	35011.94	8.01	0.0002	
AB	1.234E+05	1	1.234E+05	28.22	< 0.0001	
A^2	66868.44	1	66868.44	15.29	0.0003	
B^2	31448.21	1	31448.21	7.19	0.0101	
B^3	41593.47	1	41593.47	9.51	0.0034	
Residual	2.055E+05	47	4372.23			
Lack of Fit	1.881E+05	44	4275.25	0.7378	0.7312	not significant
Pure Error	17383.84	3	5794.61			
Cor Total	9.627E+05	56				
Std. Dev.	66.12			R^2		0.7865
Mean	199.82			Adjusted R^2		0.7457
C.V. %	33.09			Predicted R^2		0.6928
				Adeq Precision		16.7052

Obtained R^2 value is 0.7865 for the UTS model means that it's 78.65% able to predict response values. Predicted $R^2 = 0.7457$ and adjusted $R^2 = 0.6928$ are with an acceptable agreement. Precision ratio higher than 4 indicates adequate signal so the model can be applied to operate design space. The equation, which is consistent with the experimental model and describes UTS, is given in Equation (1) with the coded factors:

$$\begin{aligned} \mathrm{UTS} = 204.38 - 56.68 \times \mathrm{A} - 227.56 \times \mathrm{B} - 59.98 \times \mathrm{C}[1] \\ + 43.82 \times \mathrm{C}[2] + 35.38 \times \mathrm{C}[3] + 87.29 \times \mathrm{AB} \\ - 79.58 \times \mathrm{A}^2 + 59.09 \times \mathrm{B}^2 + 135.42 \times \mathrm{B}^3 \end{aligned} \quad (1)$$

The modified CUBIC model was subjected to a convergence analysis. The following analyzes were performed: externally studentized residuals, predicted vs. actual analysis and Cook's Distance analysis (Vahdati et al., 2020). The obtained results are shown in Fig 7.

The RSM (Eshghi & Lee, 2019) analysis shows the influence of the welding parameters on the strength of the FSW joint (UTS) depending on the used tool and welding parameters (Figs. 8 and 9). The best results were achieved for the C1 and C2 tools. The parameters from the red areas of the graphs correspond to the best strength of the FSW joint. It can be seen that for all tools variants, an increase in the welding speed causes a reduction in the mechanical properties of the FSW joint. Tool without any shoulder modification (C0) produces a FSW joint with the lowest mechanical properties.

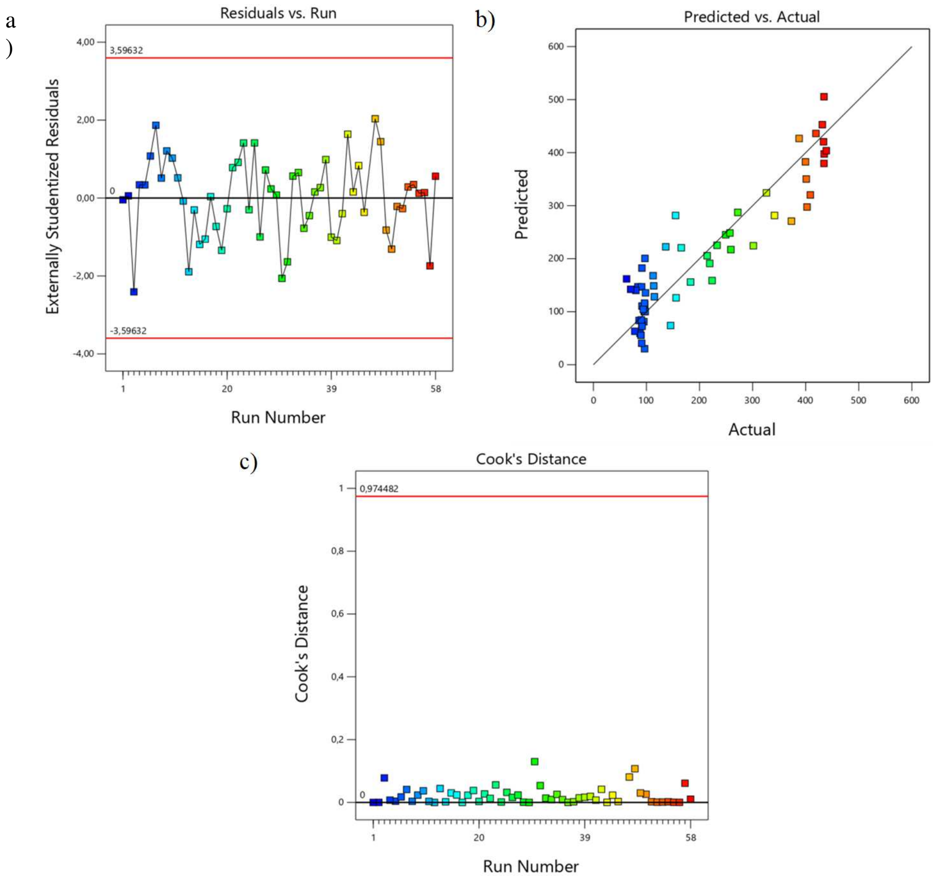


Fig. 7. Analysis of the convergence of the adopted model: a) Externally Studentized Residuals; b) Predicted vs. Actual analysis; c) Cook's distance

For the obtained experimental data, optimization of welding parameters was performed using the hill climbing method. The following optimization criterion was used: rotation speed and welding speed within the scope of the experiment, any tool, UTS max in the range up to 400 ÷ 470 MPa (Fig. 10). As a result of optimization, using the welding parameters of 1000 rpm and 200 mm/min for the tool C1, it is possible to make FSW joints with the best mechanical properties close to the parent material.

a)
b)

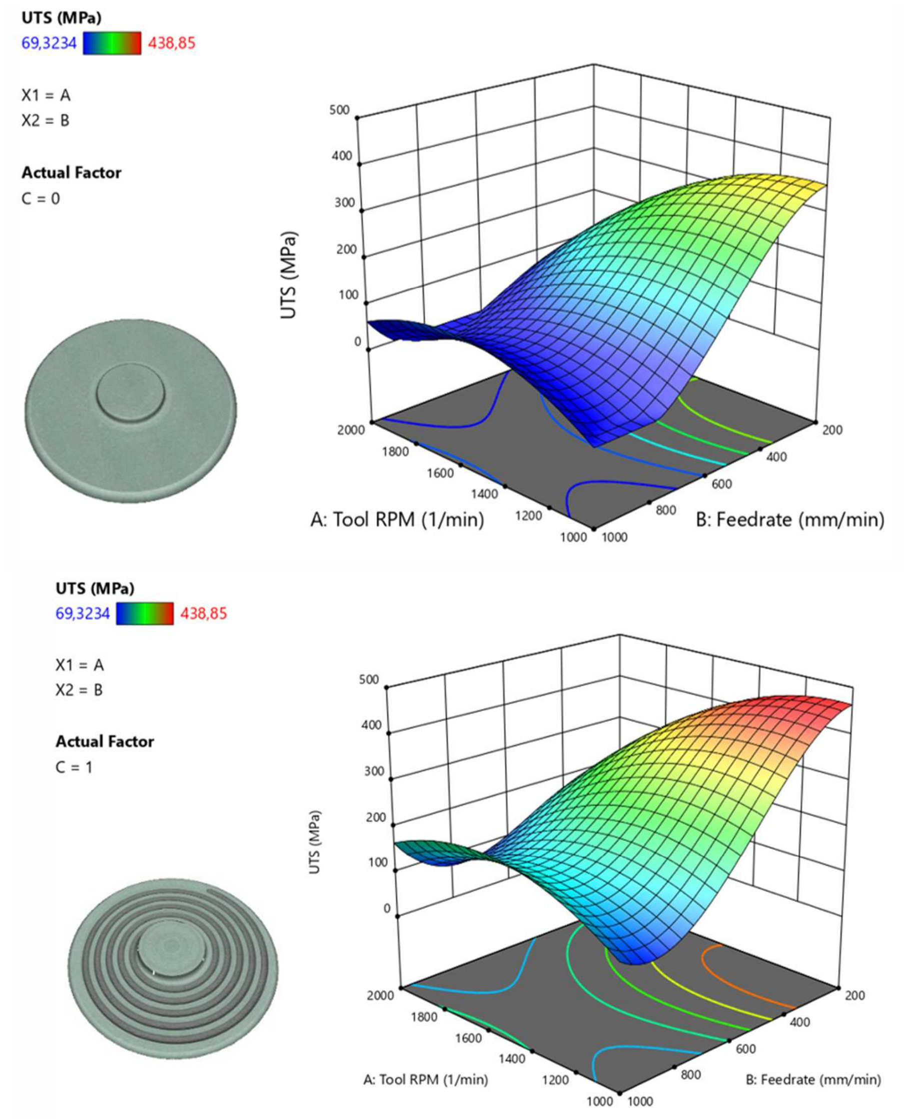


Fig. 8. Response surface plots presenting the interaction between tool rotational speed and feed rate affecting the UTS for a) flat and b) grooved shoulder (number of grooves: 1)

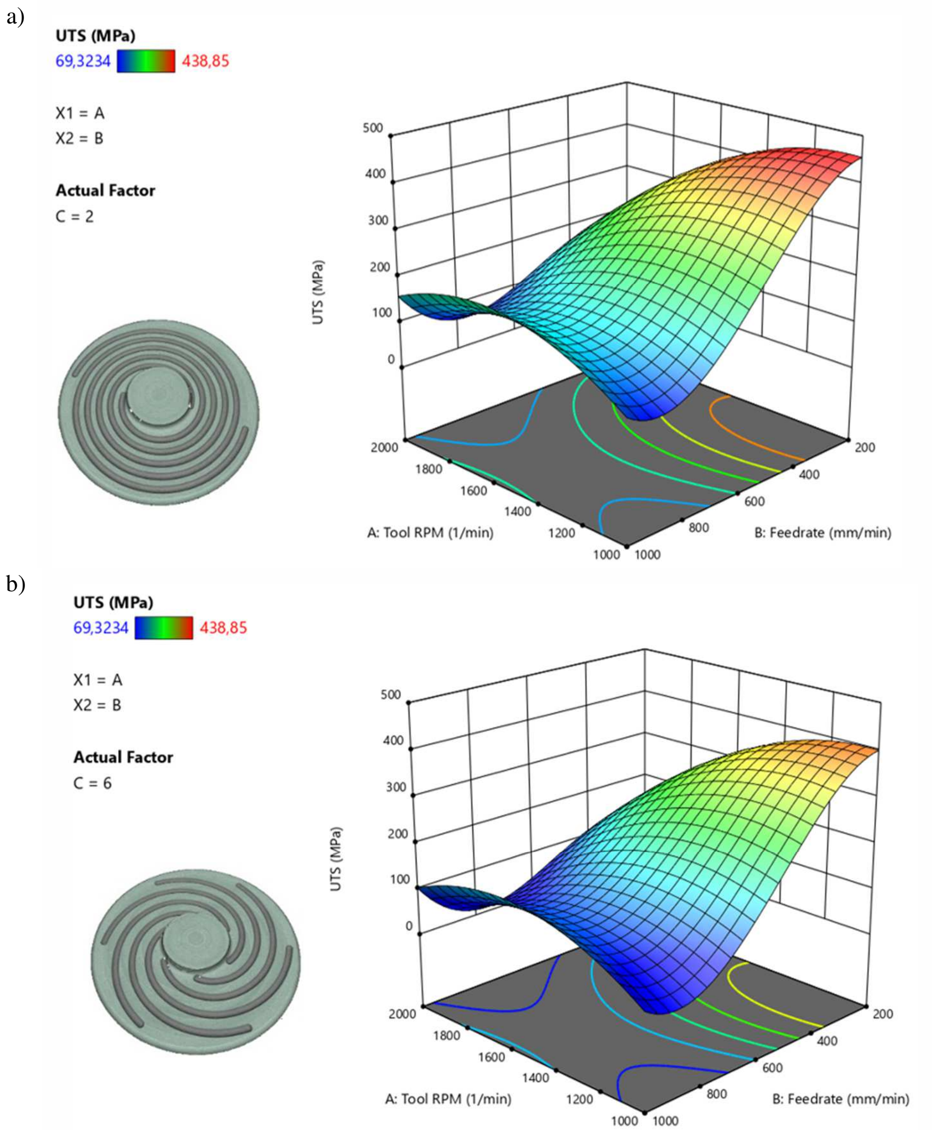
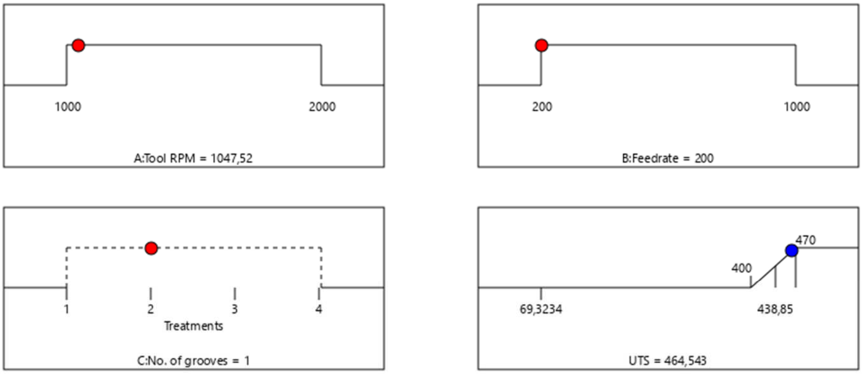


Fig. 9. Response surface plots presenting the interaction between tool rotational speed and feed rate affecting the UTS for grooved shoulder with number of groves: a) 2 and b) 6

a)



b)

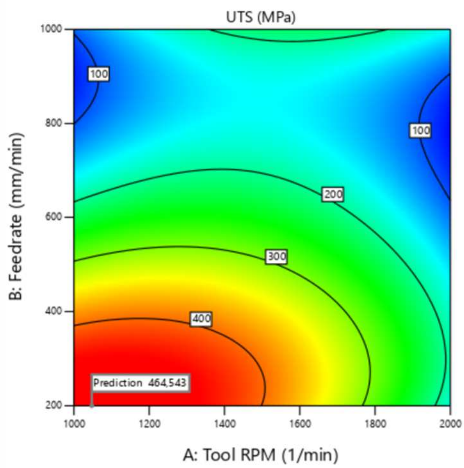
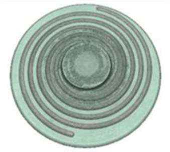
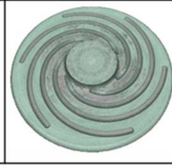


Fig. 10. Hill Climbing optimalization results for FSW process: a) optimization criteria with an indication of the best parameters, b) optimisation results

The tool made of tool whiskers reinforcement ceramics fully meets the expectations regarding the implementation of the FSW process. Tool ceramics are characterized by low thermal conductivity which allows to shorten the dwell time significantly. Another advantage of this approach is high resistance to abrasion and mechanical loads. The manufacturing process of an FSW tool is typical for the manufacture of cutting tools. No problems were encountered in this regard. Moreover, ceramic tools do not shown any signs of wear (Table 5). The geometry of the tool shoulders significantly improves the quality of the weld. A single concentric helix has been shown to help produce the best joint.

Table 5. Tool wear test performed after 10 m of welds

Number of grooves	0	1	2	6
New tools				
Tool used (approx. 10 m of weld)				

The applied technological parameters of FSW welding allowed for the preparation of regression models with a relatively high convergence of nearly 80% as evidenced by the performed diagnostics of the CUBIC model. Application advanced statistical analyzes to select the optimal technological parameters for welding AA2024-T3 alloy sheets of 0.5 mm in thickness. The results of the experiment confirmed these assumptions.

4. Conclusions

A new tooling approach was proposed for the FSW process based on tool ceramics. The methods used to optimize the technological parameters of the FSW process significantly improved the quality of the obtained joints. Modifying the tools shoulder geometry improves the mechanical properties of the FSW joint and is an important factor for tools design. The following conclusions can be drawn:

- The use of a whisker-reinforcement ceramic tool enables the production of high-quality FSW joints with a strength exceeding 95% compared to the parent material.
- The geometry of the helical grooves on the face of the tool greatly affects the quality of the FSW joint.
- The reduced CUBIC model was characterized by the coefficient of determination $R^2 = 0.7865$.
- For the parameters: 1000 rpm and 200 mm/min and the C1 tool, the best joint was obtained, the strength of which is similar to parent material.
- After realizing approx. 10 m of weld with each tool, no signs of tool wear were observed.

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NOWE PODEJŚCIE NARZĘDZIOWE DO ZGRZEWANIA TARCIOWEGO CIENKICH BLACH AA2024-T3 - OPTYMALIZACJA PARAMETRÓW ZGRZEWANIA

Streszczenie

W pracy zaprojektowano i wykonano nowe narzędzia ceramiczne o różnym rozkładzie rowków w celu wzbogacenia technologii łączenia konstrukcji cienkościennych i uzyskania wysokiej jakości połączenia blach ze stopu aluminium AA2024-T3 Alclad o grubości 0,5 mm. Przetestowano cztery typy narzędzi, bez rowków, z 1, 2 i 6 rowkami. Narzędzia wykonano z dwóch materiałów. Część chwytową wykonano z węglika wolframu, a korpus narzędzia z ceramiki wzmocnionej whiskerami. Wpływ parametrów technologicznych na wytrzymałość złączy FSW badano metodami analizy powierzchni odpowiedzi (RSM) oraz analizy wariancji (ANOVA). Najmniej trwałą spoinę wytworzyło narzędzie bez rowków. Narzędzie z pojedynczym i podwójnym rowkiem zapewniło dobrej jakości spoinę w szerokim zakresie prędkości obrotowych narzędzia. Wykazano, że rowki na kołnierzu narzędzia istotnie wpływają na jakość uzyskanego połączenia FSW.

Słowa kluczowe: stop aluminium AA2024-T3, ANOVA, narzędzia ceramiczne, zgrzewanie tarciowe z przemieszaniem, gemetria narzędzia do zgrzewanie tarciowego z przemieszaniem, łączenie cienkich blach, RSM

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