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TENSILE-SHEAR-STRENGTH PREDICTION OF FRICTION-MELT-BONDED DISSIMILAR SPOT JOINTS USING RSM

NAPOVED NATEZNO-STRIŽNE TRDNOSTI TORNO VARJENEGA TOČKOVNEGA SPOJA Z UPORABO RSM

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The joining of aluminium (Al) and copper (Cu) is an essential spot weld for renewable energy applications due to its excellent thermal and electrical conductivity. It is challenging to produce a high-quality Al-Cu spot weld using traditional techniques and the durability of a weldment is also uncertain. A new welding technique that is effective and suitable for spot welding Cu and Al is friction-melt-bonding (FMB) spot welding. The process parameters employed during welding have a strong impact on the quality of a weld. The strategy for integrating the FMB process characteristics, such as tool rotational speed and dwell time, into a mathematical model that may be used for predicting the process parameters of dissimilar spot joints, was the focus of this study. The findings showed that the tensile shear fracture load (TSFL) was significantly influenced by the tool's rotational speed and dwell time. Optimization was carried out using the response surface methodology (RSM) to find the best FMB process parameters for making a dissimilar spot weld of AA 6061-Cu.

Keywords: friction melt bonding, renewable energy, dissimilar joints, optimization

Spajanje aluminija in bakra s točkovnim varjenjem je pomembno zaradi njune odlične toplotne in električne prevodnosti. Izdelava visoko kakovostnih spojev Al–Cu s standardnimi postopki varjenja je zahtevno in tudi trajnost takšnih spojev je vprašljiva. Nova tehnika varjenja, to je torno varjenje z gnetenjem (FMB; angl.: friction melt bonded) je učinkovito in primerno za točkovno varjenje bakra in aluminija. Procesni parametri uporabljeni med varjenjem imajo močan vpliv na kakovost varjenega spoja. V raziskavi so kombinirali s pomočjo matematičnega modela procesne parametre postopka FMB, kot sta hitrost vrtenje orodja ter čas zadrževanja in ju uporabili za napoved optimalnih procesnih parametrov točkovnega varjenja dveh različnih materialov. Rezultati raziskave so pokazale, da je natezno-strižna porušna trdnost (TSFL; angl.: tensile shear-fracture load) močno odvisna od hitrosti vrtenja orodja in njegovega časa zadrževanja v stiku obeh kovin. Optimizacijo so izvršili z uporabo metodologije odgovora površine in s tem ugotovili najboljši set procesnih parametrov FMB za točkovno varjenje dveh različnih kovin, to je zlitine na osnovi aluminija vrste AA 6061in bakra.

Ključne besede: torno varjenje z gnetenjem, obnovljiva energija, medsebojno spajanje različnih materialov, optimizacija

1 INTRODUCTION

A potential alternative large-scale renewable energy storage technology is an aluminium battery. Electric motors, batteries, inverters, wiring and charging stations heavily rely on copper. It should be emphasised that the primary uses of spot welding copper (Cu) and aluminium (Al) are in the renewable-energy sector relating to bimetals, bus bars, switchgears, heat sinks, etc.[1–3] Technologies of joining Cu and Al, such as resistance spot welding (RSW), laser-beam welding (LBW) and ultrasonic welding (USW) have been developed. However, dissimilar spot welding is often challenging due to large changes in physical parameters such as the thermal expansion coefficient, melting temperature and the intermetallic-compound (IMC) formations at the weld interface.[4] Low resistivity and improved electrical conductivity are characteristics of Cu and Al. As a result, the time required to make Cu-Al joints by RSW is longer, which could be prohibitively expensive.[5] Furthermore, because of its inherent fusion welding feature, a lot of heat is created, resulting in a lot of deformation.[6]

To overcome the aforesaid challenges, friction melt bonding (FMB), a unique approach that makes use of significant temperature differences between the materials to be bonded as provides a solution to the challenges that occur with the fusion welding process. In FMB, the plates to be joined are stacked one on top of the other and fastened with clamps. The top surface of the plate is pressed up against a flat, revolving tool, which results in a heat production from friction and deformation. The temperature of the top plate rises to almost the melting point of the bottom plate because of the frictional heat produced.[7] The top and bottom plates consequently melt and react locally, generating a joint. According to Chen et al.[8] FMB can generate better dissimilar Ti/Al alloy lap

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joints and can be utilised for spot welding Ti-6Al-4V/2A12-T4 dissimilar alloys. This is a potential method for managing the temperature of the Ti/Al contact and avoiding the development of a thick, brittle Al_3Ti IMC.

A thermal model was developed for joining steel and AA2024–T3 to analyse the thermal cycle and intermetallic growth, and the results show less intermetallic growth in the joints.[9] To better understand the controlled accumulation of IMCs and sensitivity to hot ripping in Al-steel welding with additional interlayers, Mena et al.[10] used FMB. Even so, there is a limited amount of literature on various FMB joints of two plates. There is currently no published study on the use of FMB for spot welding Cu and Al. Mechanical characteristics of the joints are primarily influenced by FMB process parameters such as the tool rotational speed and dwell time. Mechanical qualities of joints must be improved in order to boost the effectiveness of the FMB process. Determining the best welding parameters is a challenging task required to attain a quality weld. Therefore, one such method is the design of experiments (DOE) used for optimising the process parameters for the best weld.[11–14] A powerful statistical technique called the central composite design (CCD) saves significant time and costs while optimising the process, design and product. RSM is a technique that can be utilised to make a series of experiments, creating a mathematical model, determining the ideal set of input parameters, and showing the results as a graph.[11] The CCD can be used to effectively acquire the optimal process response and assess the qualified welding process parameters with the help of the response surface methodology (RSM) and analysis of variance (ANOVA). When fewer components and levels are chosen, the DOE is best suitable for the case. This situation can be made possible by carefully selecting the key process parameters and their ranges based on preliminary tests. Amancio-Filho et al.[15] concluded that the rotational speed and dwell time are significant process parameters used for determining the strength of the friction stir spot welding of AA2024–T3 lap joints. According to Plaine et al.,[14] the dwell time and rotational speed are the two greatest imperative process variables in friction stir spot welding when using an RSM model to determine mechanical properties. This study makes an effort to forecast and optimise FMB process parameters to achieve the highest TSFL for the FMB of dissimilar Al- Cu spot joints.

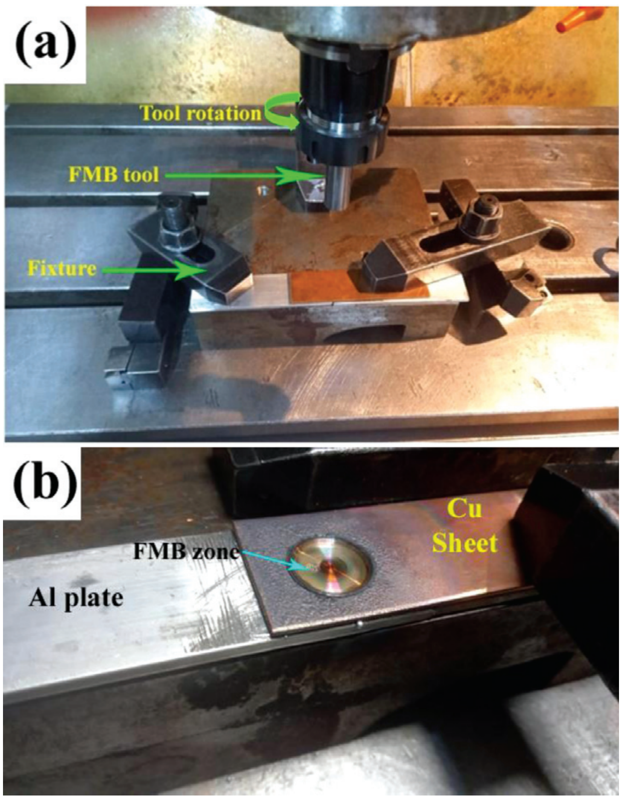

Figure 1: Experimental set-up with: a) tool rotational direction and fixture design and b) FMB processed sample

2 EXPERIMENTAL PART

Dissimilar metals of AA6061–T6 with a composition (in *w*/%) of 96.8 % Al, 0.89 % Zn, 0.91 % Si, 0.65 % Mn, 0.38 % Fe, with few traces of Cu, Ti, Sn, and commercially pure copper were chosen as the investigated materials. The procured AA6061 and Cu had dimensions of (100 × 30 × 4) mm and (100 × 30 × 1.5) mm, respectively. The hardness values of AA6061 and Cu are 102 HV and 100 HV, respectively. The melting points of AA6061 and Cu are 600 °C and 1084 °C, respectively. The tool is made of tungsten carbide that has a 20-mm diameter of the shoulder and no pin. The tool material has a melting point of 2870 °C, and hardness of 2600 HV. The dwell time and rotational speed were considered as the input parameters for this study based on the literature. A plunge depth of 0.5 mm and axial force of 15 kN were kept constant under all the experimental conditions. **Figure 1** shows the experimental set-up and sample processed with FMB.

Table 1 displays the design matrix and the input parameter levels that were ultimately chosen with the use of trial experiments and results. It consists of 13 experimental runs in a 5-centre point and 8-non-centre point configuration. The experimentation was done in accordance with the design matrix. A computerised tensile tester (INSTRON 1195) was used to assess the TSFL after FMB, and the results are shown in **Table 1**.

3 RESULTS

3.1 Mathematical model

The input parameters relate to the output using a regression model that takes the impacts of the input parameters into account. The impacts of the dwell time and rotational speed on the tensile shear fracture load are presented in Equation (1).

Table 1: Process parameters and their levels, design matrix with the experimental and predicted response

Process parameter	Levels				
	–1.41	–1	0	1	1.41
(A) Rotational speed (min^{-1})	1000	1375	1750	2125	2500
(B) Dwell time (s)	50	68	85	103	120
Design matrix					
Trial No.	Rotational speed (min^{-1})	Dwell time level (s)	Tensile shear fracture load (kN)		Error (%)
			Experimental values	Predicted values	
1	–1	–1	5.01	4.96	1.01
2	1	–1	7.03	6.86	2.48
3	–1	1	6.91	6.67	3.60
4	1	1	8	7.89	1.39
5	–1.41	0	5.24	5.47	–4.20
6	1.41	0	8.05	7.68	4.82
7	0	–1.41	5.74	5.64	1.77
8	0	1.41	7.68	7.59	1.19
9	0	0	12.01	11.82	1.61
10	0	0	12.05	11.82	1.95
11	0	0	11.75	11.82	–0.59
12	0	0	11.85	11.82	0.25
13	0	0	12.03	11.82	1.78

Table 2: ANOVA analysis

Source	Sum of squares	Degrees of freedom	Mean square	F-value	P-value	
Model	92.74	5	18.55	380.38	< 0.0001	Significant
A	4.88	1	4.88	100.05	< 0.0001	
B	3.77	1	3.77	77.37	< 0.0001	
AB	0.116	1	0.116	2.38	0.1669	
A^2	47.83	1	47.83	980.83	< 0.0001	
B^2	47.1	1	47.1	965.92	< 0.0001	
Residual	0.3413	7	0.0488			
Lack of Fit	1.53×10^{-9}	3	5.09×10^{-10}	5.97×10^{-9}	1	Not significant
Pure Error	0.3413	4	0.0853			
Cor. Total	93.08	12				
R^2	Adjusted R^2	Predicted R^2	Adequate precision			
0.9963	0.9937	0.9943	45.7412			

$$TSFL = F(A, B) \quad (1)$$

Here,
TSFL – the output (tensile shear fracture load)
A – the rotational speed (min^{-1})
B – the dwell time (s)

The preferred polynomial for the two factors is represented as Equation (2):

$$Y = b0 + b1A + b2B + b11A^2 + b22\,B^2 + b12AB \quad (2)$$

The constant value for the regression model is b0, first-order coefficients are b1 and b2, second-order coefficients are b11 and b22. The interaction coefficient is b12.

Regression analysis and Design Expert 13 software are used to determine the polynomial's coefficient values.

Below are the final developed models as a result of this FMB (Equation (3)):

$$TSFL = 11.82 + 0.7809A + 0.6867B - 2.62A^2 - 2.60B^2 - 0.1703AB \quad (3)$$

3.2 ANOVA analysis for the quadratic model

The appropriateness of the established model was analysed with the help of the analysis of variance (ANOVA) using Design Expert 13. The investigated ANOVA results are given in **Table 2**. The F value of the developed model is significant as it is 380.38.

Lower values of P (less than 0.05) are the indicators for significant terms. For this developed model significant terms are A, B, A^2, B^2. Other terms are insignificant due to a larger value of P (more than 0.1). The F value for the lack of fit is 0.0, which suggests it is significant compared to the absolute error. The R^2, predicted R^2 and

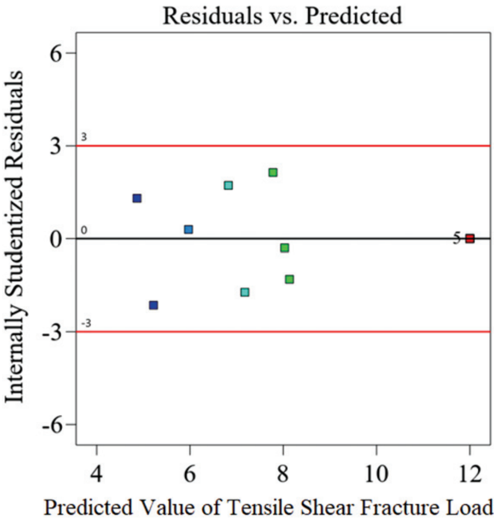

Figure 2: Internally studentized residual values for the predicted values of TSFL of FMB

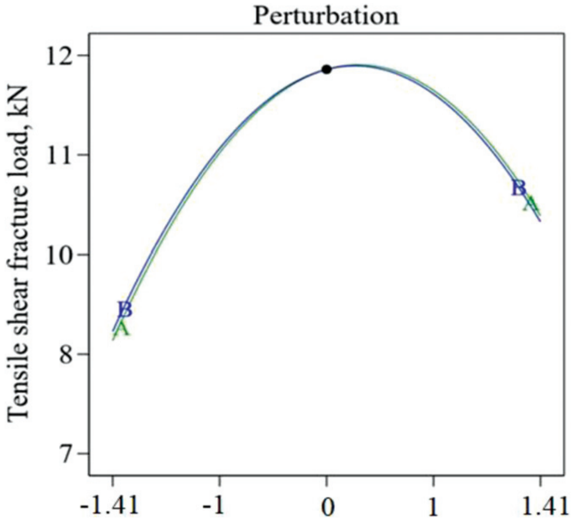

Figure 4: Influence of all the parameters on TSFL of FMB (perturbation plot)

adjusted R^2 values are more than 0.9, indicating that the developed models are adequate. A fair amount of agreement is observed between the predicted and adjusted R^2. Adequate precision is calculated by measuring the signal-to-noise ratio. This ratio must be greater than 4 for a good mathematical model.[13] An adequate precision value of 45.74 show an adequate signal for the developed model. Consequently, these models are utilized to establish the design. The residuals show a random scatter pattern in **Figure 2**, which suggests that the developed models are satisfactory and that no independent or constant variable assumptions have been broken. **Figure 3** compares the expected values of scattered responses to the experimental values, and the fact that it is near the 45-degree line shows that the predicted values and experimental values concur.[14] The perturbation plots from **Figure 4** show how all the parameters have an impact on the tensile shear strength of welded samples. This graph displays the evolution of the output or reaction. While all the input parameters deviate from the reference point, the other values remain constant.

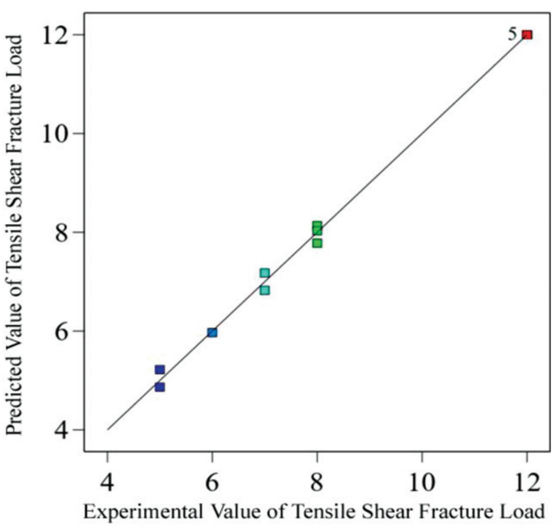

Figure 3: Predicted values versus experimental values for TSFL of FMB

4 DISCUSSION

4.1 Effect of the FMB process parameters

The factors influencing the TSFL of FMB dissimilar spot joints prophesied with the help of developed models are given in **Figure 5**, indicating a common connection between the cause and result.

As seen in **Figure 5a**, the lowest rotational speed (1000 min^{-1}) produces a low TSFL of the FMB. The TSFL increases proportionally with the rotational speed, starting at 1000 min^{-1}, reaching its maximum at 1750 min^{-1}. The TSFL of the joint decreases as a result of the rotational speed continuing to rise above 1750 min^{-1}. The bonded zone is reduced at the lower tool rotational speed due to a low temperature distribution and low heat input. This low heat input produces a weak bonding between the top and bottom plates, so the TSFL is low. It is obvious that the heat input of the FMB increases with the increasing rotational speed. The bonding between the top and bottom plates is destroyed by the additional heat input.[14] The response-surface graphs depicted in **Figure 5a** make it clear that the dwell time affects the TSFL and the TSFL of the FMB of the spot joint is lower with a lower dwell time (50 s). The TSFL increases along with the dwell time after the first 50 s, peaking at 85 s. The TSFL of the spot joint is reduced when the dwell time rises above 85 s. In general, the FMB at a higher dwell time in a spot-welding area produces a short exposure duration, inadequate heat and poor material flow between the plates, making the joint weaker. A higher dwell time is associated with low heat

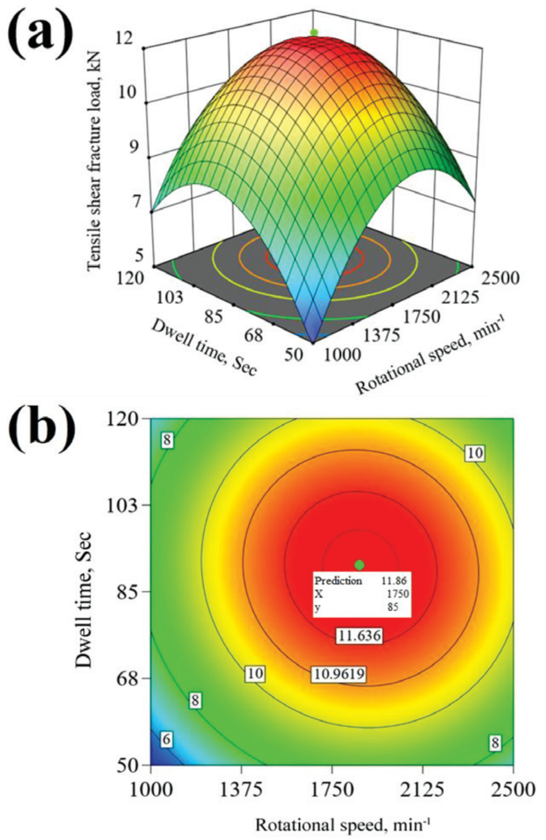

Figure 5: TSFL of FMB: a) response graph and b) contour graph

inputs, resulting in faster cooling rates of the welded joint, hence yielding a lower TSFL.

4.2 Optimizing the FMB parameters

The graphs for the response surface and contour were developed and presented in **Figure 5** to determine the optimum input condition for the best TSFL. These graphs are used to predict the range of experimental conditions for better outputs.[11] The maximum TSFL is calculated from the vertex of the response plot. To graphically depict the area of the ideal parameter settings, a contour plot is developed as shown in **Figure 5b**. Developing these plots is more complex for second-order responses compared to first-order models. Characterizing the response surface close to the specified position is typically required once it has been located. The characterization entails determining if the stationary point is a saddle point, a maximum or minimum response. The easiest way to do this is to look at it through a contour plot. The analysis of a response surface relies heavily on contour plots. The highest possible TSFL value is found to be 11.86 kN, using the analysis of the response surfaces and contour plots (**Figure 5**). A tool rotational speed of 1750 min^{-1} and dwell time of 85 s are the corresponding parameters that produce this maximum value. As long as all of the input parameters have the same degrees of freedom, it is possible to rank the influences of the process parameters on the tensile shear failure load[11] based on their respective F-ratio values shown in **Table 2**. The impact is assumed to be more significant if the F ratio is higher and vice versa. According to the F-ratio results, the rotational speed has the most impact on the tensile shear failure load over the range under consideration in this study, followed by the dwell time.

5 CONCLUSIONS

The following conclusions are derived from this work:

- The correlations between the process parameters for the FMB of dissimilar metals including AA 6061 and Cu were determined using the RSM.
- Response graphs and contour plots were then used to demonstrate the influences of the rotational speed and dwell time on the TSFL of the AA 6061 and Cu joints.
- Both the rotational speed and dwell time exhibited significant influences on the dissimilar spot joining of AA6061 and Cu using FMB.
- The optimum ranges of the rotational speed and dwell time are determined as 1750 min^{-1} and 85 s, respectively, for the FMB of AA6061 and Cu.

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