The Eurasia Proceedings of Science, Technology,
Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 38, Pages 530-537

IConTES 2025: International Conference on Technology, Engineering and Science

Effect of Friction Stir Welding Parameters on the Evolution of the Welding Temperature

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Abstract: Friction stir welding (FSW) is a permanent joining technique that uses a rotating tool pressed against the two parts to be welded, the rotational movement produces heat that softens the materials and make it malleable whithout reaching the melting point of either the materials parts or the tool in the process, the tool will be then moved in feed motion along the joint to assemble the parts. The welding temperature reached is the key to obtaining a flawless, high-quality weld. İf the welding temperature is too high, it might reduce the mechanical properties or cause cores to collapse. İf the welding temperature is too cold, wormholes could appear due to a bad brew. The purpose of this research is to study the influence of the initial welding parameters, such as rotational speed, feed speed, and the inclination angle of the tool, on the evolution of the maximal temperature reached during the FSW process, to be able to determine optimal reference welding parameters finally. A mathematical model is proposed to help us predict the maximal temperature of the welding joint during the process using the response surface methodology (RSM).

Keywords: Maximal temperature, Welding joint, FSW, Rotational speed

Introduction

Due to their exceptional weight/strength ratios, their corrosion resistance, and good formability, AA3003 aluminum alloys are widely used in various industrial applications including aerospace, shipbuilding, automotive, civil engineering, electronic components, and electrical shielding (Guo et al., 2013; Chen et al., 2023; Çam et al., 2017). There are several approaches to assembling alloys intended for use in these industries. So far, one of the best solutions to fuse two or more pieces of similar or different materials is welding (Shojaei Zoeran et al., 2017; Karami et al., 2016; Eivani & Karimi Taheri, 2007). However, aluminium has characteristics that make it difficult to weld (Yang et al., 2017), because its high thermal conductivity means that it quickly dissipates heat, especially as cracks appear at the end of the solidification process, which is formed at high temperatures, and these oxidise in contact with air, leading to poor joint efficiency. Friction Stir Welding is a process that overcomes the limitations of conventional welds, including the problem of corrosion of the fusion joint due to thermal effects (Pinto et al., 2022; Mishra et al., 2005). The friction-mixing welding (FSW) process depends entirely on the mechanical contact between the tool and the workpiece (Li et al., 2017). Therefore, all process phenomena and outcomes, such as weld geometry and mechanical properties, are governed by the FSW friction system (Hossfeld, 2023; Prabhakar et al., 2023). Chekalil et al have studied the

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

influence of welding parameters, namely the rotational speed Vr, feed speed Va and angle of inclination of the tool θ on the mechanical properties of joints such as yield strength, the stress and resistance to rupture, A mathematical model was proposed to predict the mechanical behavior of the junction using the response surface methodology (RSM). This model is used to determine the optimal values of these parameters, which are responsible for the best performance of the FSW joint.

The optimized values of the parameters that allow to obtain the best mechanical properties of a welded joint correspond to the values of Vr = 1423.93 r/min, Va = 400 mm/ min, and ϴ = 1.2885° (Chekalil et al., 2020). Combinations of the different factors for a better quality of the FSW joint by obtaining a tensile strength of the welded joint equal to 75% of that of the base metal. The quality of the weld joint is also affected by the temperature reached during the FSW process, so it is recommended to have a good control of the temperature when welding, The objective of our study would therefore be to determine the effect of the same welding parameters preceding on the temperature evolution in order to determine the optimal values of Vr, Va and ϴ.

Modelling and Prediction of Maximum Temperature During the FSW Process

This study utilizes an experiment plan to establish a link between the input variables (rotation speed, feed speed, and angle of tool inclination) and the output variable Tmax. To predict the maximum temperature, the Response Surface Methodology (RSM) is used to develop the non-linear model of the thermal cycle of the FSW joint of aluminum alloys (AA 3003). Some results of the experimental study on the effect of the process parameters (rotational speed Vr and feed speed Va) on the evolution of the thermal cycle are presented in Figure 1.

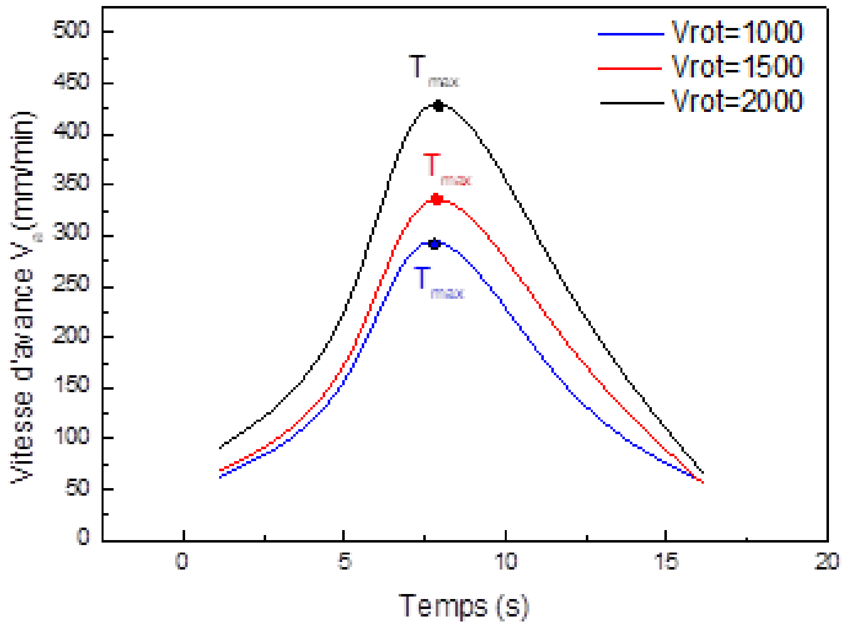

Figure 1. Effect of process parameters on the evolution of the thermal cycle (Va, Vr, and Theta)

The prediction was made by a full factorial plane with three factors, rotation speed Vr, feed speed Va, and tool angle ϴ, at three levels (-1, 0, +1). Table 1 below gives the values of each parameter for each level. The values of these parameters are dictated by machine capacity and premature tool wear

Table 1. Parameter values for each level

Parameters	Low level -1	Central level	High level +1
Rotational speed	1000	1500	2000
Feed speed	200	300	400
Angle of inclination of the tool	0,5	1,5	2,5

The matrix of experiments was determined by MODDE 5.0 software and the use of the experiment plan on 30 samples.

Mathematical Model

The polynomial mathematical model developed for optimization is a second-degree model. The model of the experimenter is quadratic in form:

$$y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{1 \le j \le 3} a_{ij} x_j + \sum_{i=1}^{3} a_{ii} x_i^2 + e \qquad (1)$$

Where is the predicted response value at the center of the experimental domain represents the factor effect, and represents the interaction between the factor andx_j.

The developed mathematical model allows for establishing a relationship between the input parameters (Vr, Va and θ) and the output quantity (T_{max}). The polynomial allows for optimizing the welding temperature to obtain the desired response. To calculate the coefficients of the models, a regression method based on the least squares criterion is used. The mathematical model proposed by MODDE 5.0 is as follows:

$$T_{max} = 213.667 + 39.8889 \times Vr - 14 \times Va + 31.8333 \times \theta - -5.75001 \times Vr.Va - 5.75001 \times Vr.\theta + 0.0833216 \times Va.\theta + 1.99999 \times Vr^2 + 19 \times Va^2 + 34.8333\,\theta^2 \qquad (2)$$

Influence of Welding Parameters on the Maximum Temperature

Influence of Rotational Speed on Maximum Temperature

The values of the coefficients associated with the welding parameters in the mathematical model show the degree of influence of each factor. An example of a prediction is given in Figure 2. It is worth mentioning that it can be used to predict the evolution of maximum temperature as a function of rotational speed (Vr). The central curve represents the predicted values, and the other two curves show the 95% confidence interval of the predicted response.

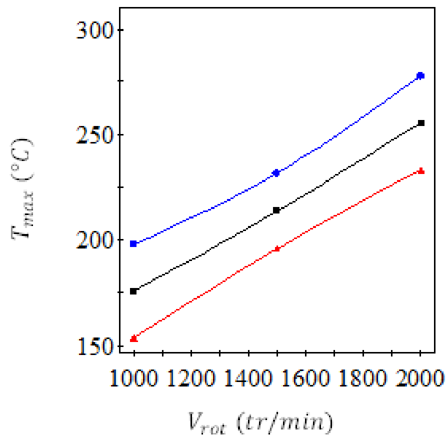

Figure 2. Evolution of maximum temperature as a function of rotational speed (Vr)

The analysis in Figure 2 suggests that an increase in rotational speed Vr leads to a large increase in maximum temperature. Indeed, a 50% increase in the rotation speed leads to an increase of about 48% in the maximum temperature. This temperature is maximum when the speed value is equal to 2000 tr/min. This has the effect of increasing mechanical properties, including hardness, and reducing tunnel and vacuum defects.

Influence of Feed Speed on Maximum Temperature

Concerning the impact of the feed speed, it can be noted that when the feed speed (Va) increases, the maximum temperature (Tmax) gradually decreases in the interval [200- 300mm/min] and then stabilizes around 230°C in the interval [300-400 mm/min]

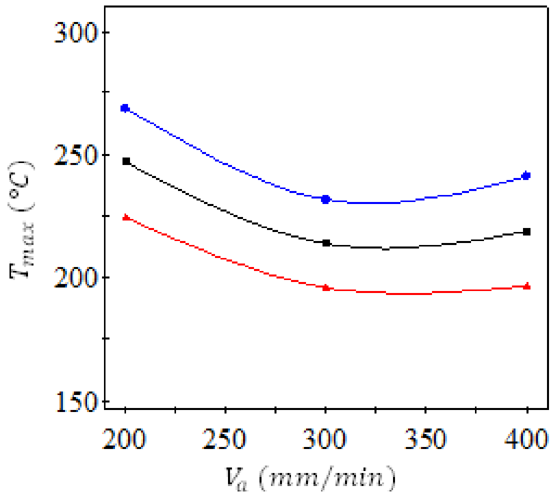

Figure 3. Evolution of the maximum temperature as a function of feed speed

Therefore, it can be concluded that the increase in feed speed induces a slight decrease in maximum temperature (Tmax). Indeed, an increase of 50% in the feed speed leads to a decrease of about 8% in the maximum temperature. It can be assumed that there is a critical feed rate (Va-cr = 300 mm/min) beyond which the temperature is almost independent of this parameter.

Influence of Tool Angle on Maximum Temperature

Figure 4 illustrates the effect of the angle of inclination on the maximum temperature. It is clearly noted that the temperature is constant in the range between 0.5° and 1.5°, beyond the value of 1.5 °, the temperature begins to rise to a maximum value of 275 °C. We find that beyond an angle equal to 1.5, it increases sharply with increasing angle of the tool. Indeed, an increase of 40% in the angle of inclination leads to an increase of about 45% in the maximum temperature.

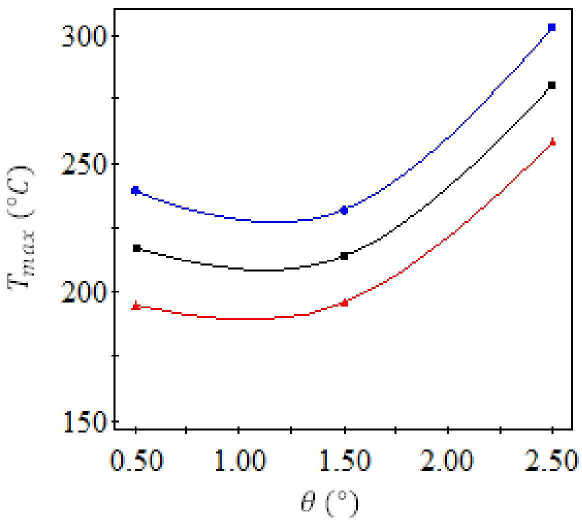

Figure 4. Evolution of the maximum temperature as a function of the angle of inclination of the tool

Effect of Parameter Interactions on Maximum Temperature Response

Interaction Between Tool Angle and Feed Speed

In this analysis step, it was decided to broaden the scope of our study by taking into account the interaction between the two factors. This allows the output parameters to be visualized on a three-dimensional (3D) graph Figure 5; this graph represents the variation of Tmax as a function of both factors θ and Va.

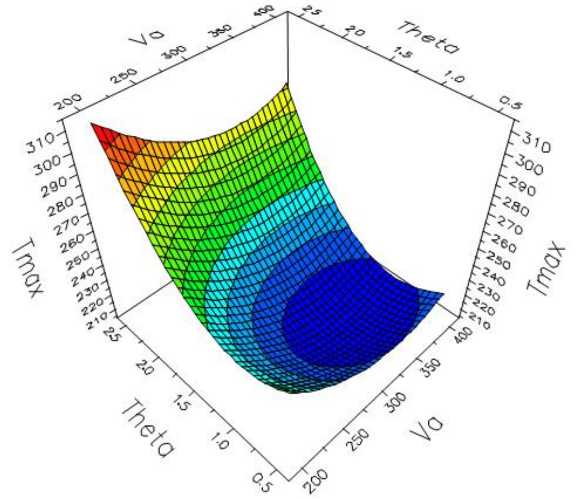

Figure 5. Three-dimensional (3D) variation of Tmax as a function of θ and Va

The curve in Figure 6, commonly referred to as Iso curves, is the projection of the surface onto the plane. This figure shows that the greater the angle of inclination of the tool, the higher the maximum temperature increases to a maximum value of 300°C. Note that this is valid regardless of the speed of feed. On the other hand, the lowest values of Tmax were recorded for the values of Va between [270 and 370mm/min].

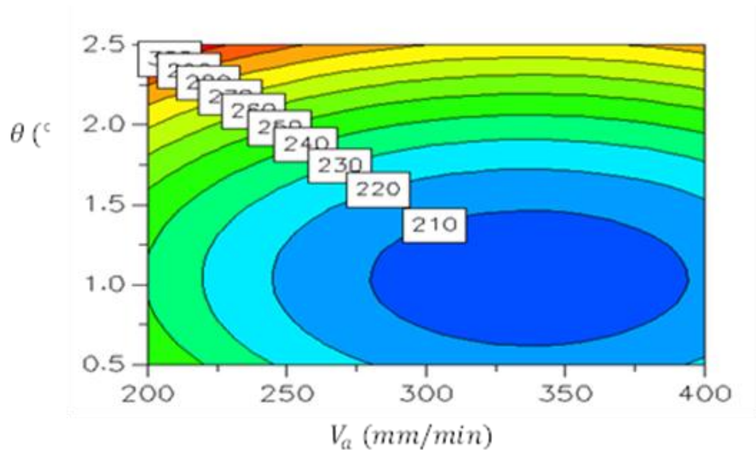

Figure 6. Variation of Tmax as a function of Va and θ

Interaction Between Rotation Speed and Feed Speed

Figure 7. Shows the effect of both factors and acting simultaneously on the maximum temperature (T_{max}), moving from their minimum values to their maximum values while the third factor (θ) is kept constant. The analysis of the graph in this figure suggests that the higher the maximum temperature, also increases to 278 °C, while V_a is between 200 and 230 mm/min. Furthermore, it should also be noted that it can reach values closer to the maximum values for a maximum equal to 400 mm/min and a V_r range between 1650 and 2000 tr/min. On the other hand, low values of are recorded for low values around 1000 tr/min, which is valid regardless of the value of. It should also be mentioned that the maximum temperature values (T_{max}) of the welded joint were obtained for a ratio (V_r/V_a) between 8 and 10. We find that the temperature of the weld depends on the speed of rotation and feed speed. The faster and slower the tool turns, the hotter the weld will be. On the other hand, the slower the tool turns and the faster it moves, the cooler the weld.

All these results were in good agreement with those obtained by Chekalil et al. They studied the effect of the same three parameters on the mechanical behaviour of the FSW welded joint of the aluminium alloy Al3003, They found that the maximum values of mechanical properties are obtained for optimal values of Vr = 1430 r/min, while keeping the value of Va constant and equal to 400 mm/ min.

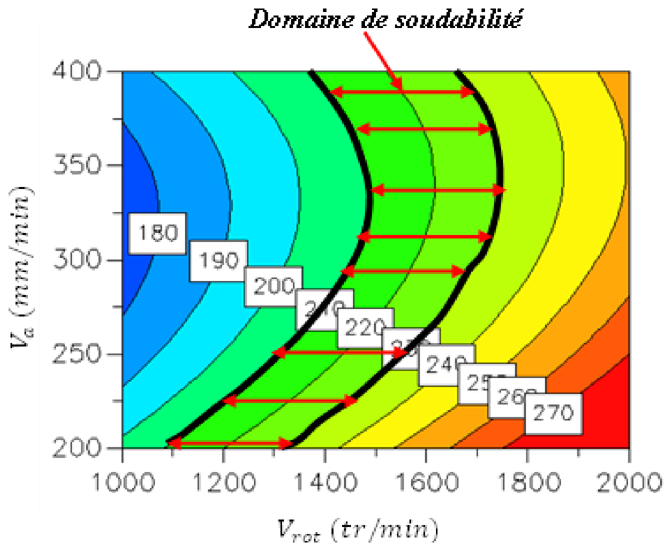

Figure 7. Tmax variation as a function of Vr and Va

Interaction Between the Rotation Speed and the Angle of Inclination of the Tool

This new section aims to present the response area obtained when the value of is kept constant, while varying Vr and θ Figure 8, it can be seen that the maximum temperature takes maximum values in the interaction interval: for θ between 1.8° and 2.5° and between 1600 and 2000 r/min. It should be noted that the best values of the mechanical properties of the weld joint in this range are equal to 80% of those of the base metal. However, low maximum temperature values are recorded for V_r values between 1000 and 1500 r/min, and θ between 0.55° and 1.58°.

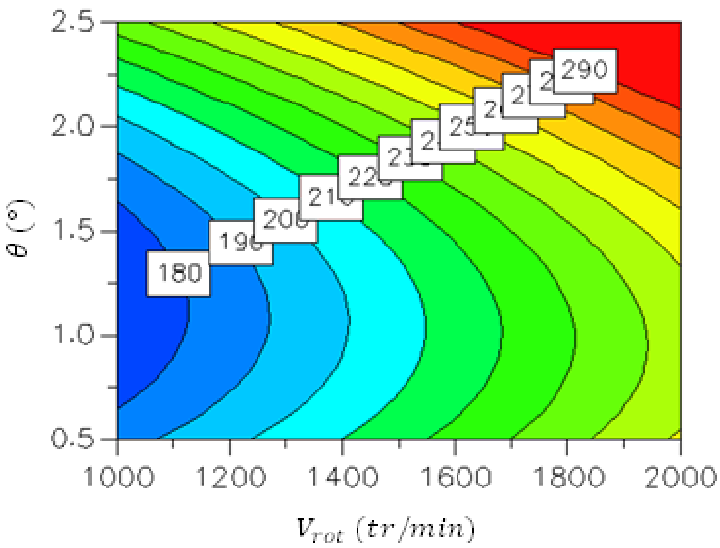

Figure 8. Tmax variation as a function of Vr and θ

Model Validation and Optimization

The validation of the model is carried out by comparing the experimental results with those obtained by the proposed models. Thirty test cases are randomly generated by assigning intermediate values to the process variables, and for each combination, changing the rotation speed (1000-2000 r/min), travel speed (200-400 mm/min), and tool angle (0.5-2.5°). Figure 9 shows a good correlation between the predicted maximum temperature profiles and those of the experiments.

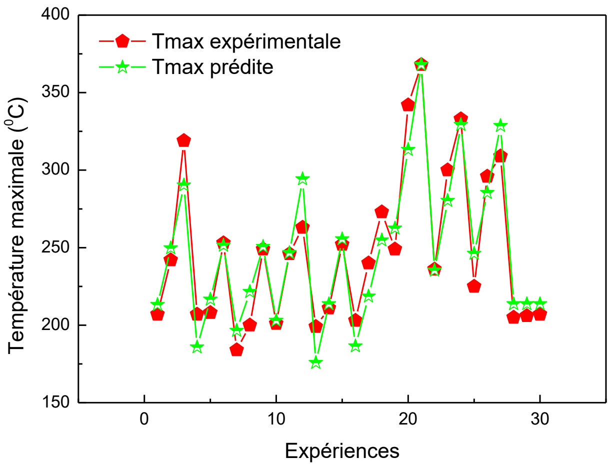

Figure 9. Predicted and experimental maximum temperature values

Conclusion

The model developed by the experimental design approach allowed to obtain a better prediction of the maximum temperature of a welded joint. This model is an effective tool for selecting the optimal parameters of the friction-mixing (FSW) welding process. The most important parameters affecting the evolution of the maximum temperature are in the order: rotation speed, then angle, and finally feed rate. The maximum values of temperature (T_{max}) of the welded joint were obtained for a ratio (V_r/V_a) between 8 and 10.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* There is no funding for this research

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Türkiye on November 12-15, 2025.

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To cite this article:

Amina, B., Abdelkader, M., Ismail, C., & Abdelghani, B. M. (2025). Effect of friction stir welding parameters on the evolution of the welding temperature. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 38,* 530-537.