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Development and Optimization of a Mathematical Model for Predicting Tensile Strength in Friction Stir Welded Joints of 6082-T6 Aluminum Alloy

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Abstract: Friction Stir Welding (FSW) is a solid-state joining process that uses a rotating tool to generate heat through friction with the material, causing it to soften without reaching the melting point, thus allowing the parts to be securely joined. This technique is particularly significant in industries requiring high mechanical properties, such as applications involving 6082-T6 aluminum alloy. Given the growing industrial importance of this alloy, there is a need to thoroughly investigate the effects of various welding parameters on the mechanica properties of the resulting weld joints. This study aims to develop a mathematical model to analyze the impact of key welding parameters, including spindle speed, welding speed, shoulder penetration depth, and shoulder profile, on the tensile strength of welded joints. The model was constructed using Response Surface Methodology (RSM), providing a means to predict mechanical performance and optimize process variables. The experimental results showed good agreement with the proposed model, with deviations remaining within acceptable limits, thereby demonstrating the model's potential as an effective tool for improving weld quality in industrial applications.

Keywords: Friction stir welding (FSW), 6082-t6 aluminum alloy, Tensile strength, Response surface methodology (RMS), Mathematical modeling.

Introduction

Friction Stir Welding (FSW) is a solid-state welding technique performed using a machine tool, which was conceived, developed, and patented by Wayne Thomas at The Welding Institute (TWI) in the United Kingdom in December 1991. Unlike conventional fusion welding methods, FSW does not involve melting the base materials. Instead, it relies on the frictional heat generated by a rotating, non-consumable tool that plastically deforms and stirs the materials at the joint line, resulting in a high-quality, defect-free weld. This process was initially developed to address the challenges associated with welding high-strength aluminum alloys, particularly those in the AA2xxx and AA7xxx series, which are known for their poor weldability using traditional fusion welding techniques. FSW offers significant advantages in terms of mechanical performance, metallurgical integrity, and environmental impact, making it a widely adopted technique in industries such as aerospace, automotive, and shipbuilding (Thomas et al., 1991; Thomas & Nicholas, 2001).

Initially, research on Friction Stir Welding (FSW) was confined to laboratory-scale experiments. However, due to its numerous advantages over conventional welding processes, FSW has gained widespread popularity in the joining of materials such as aluminum, copper, steel alloys, and others. Its growing adoption is largely attributed to several key benefits, including the formation of a fine recrystallized microstructure, a minimal heat-affected zone (HAZ), excellent dimensional stability, low distortion, and superior mechanical properties in the weld joint. These characteristics have contributed to the global recognition and increasing industrial application of the process (Akbari et al., 2021). Compared to other conventional welding methods such as TIG, MIG, and laser welding, Friction Stir Welding (FSW) offers enhanced material properties. These include improved tensile strength, fatigue resistance, impact resistance, corrosion resistance, and reduced residual stresses, among others (Wakchaure et al., 2018).

Today, Friction Stir Welding (FSW) remains an emerging and evolving trend within the manufacturing sector, particularly in industries focused on high-strength alloys. The ongoing development and optimization of this process are being pursued through various approaches and techniques, primarily by fine-tuning process parameters to enhance weld quality and performance (Sivabalan et al., 2022). The choice between different parameters and performances is the subject of numerous studies and research efforts, aimed at improving the quality of the resulting weld and reducing production costs and lead times.

The multi-objective optimization study of friction stir welding of 6082-T6 aluminum alloy using the hybrid Taguchi-Grey Relational Analysis - ANN method is the objective of the work by Wakchaure K.N. et al (Wakchaure et al., 2018). The objective functions were selected in accordance with the FSW parameters of tool rotational speed, welding speed, and tilt angle. The Taguchi L27 orthogonal array was used to design the experiments using three distinct tools. By simulating the parameters using an artificial neural network (ANN) model well trained with the grey relational grade obtained from GRA, the optimal tool and process parameters for friction stir welding were identified. Similarly, the work of Sivabalan S. et al (Sivabalan et al., 2022) conducted a parametric study in which the process parameters considered were: tool rotational speed in the range of 800–1200 rpm, traverse speed chosen as 100–200 mm/min, and axial force set at 8 kN. The pin profile was selected as a straight cylindrical tool. The study by Mishra R.S. and Jain Sumit (Mishra et al., 2019) also focused on optimizing the individual response of the FSW process using a vertical milling machine on AA 6082-T6, with the aim of obtaining an optimal parameter combination for suitable ultimate tensile strength using Taguchi techniques. The results showed that a rotational speed of 1200 rpm, a welding speed of 30 mm/min, and a threaded cylindrical tool with a shoulder diameter of 16 mm yielded the maximum UTS.

Materials and Methods

A conventional vertical milling machine with a capacity of 5.6 KW and 1800 rpm is used to perform the experiments. The spindle speed (Vr), welding speed (Va), shoulder penetration (PE), shoulder profile (PRE), and the process parameter ranges such as spindle speed and welding speed were taken respectively between 700 rpm and 1500 rpm, and between 48 mm/min and 240 mm/min. The shoulder penetration was gradually increased in five stages, from 0 mm to 0.16 mm. The selected process parameters with their limits, units, and notations are given in Table 1.

Table 1. Process parameter with their range and values at five levels (Gopi et al.,2021)

Process Parameters	Range	level 1 (-2)	level 2 (-1)	level 3 (0)	level 4 (1)	level 5 (2)
Spindle speed or tool rotational speed (Vr)	700 à 1500 tr/min	700	900	1100	1300	1500
feed or welding speed (Va)	48 à 240 mm/min	48	96	144	192	240
Shoulder penetration(PE)	0.0 à 0.16 mm	0	0.04	0.08	0.12	0.16
Shoulder profile (PRE)	-10° à 10°	-10	-5	0	5	10

Table 2. Chemical composition of 6082 alloy (Gopi et al., 2021; Algahtani et al., 2019).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.7 - 1.3	≤ 0.50	≤ 0.10	0.4 - 1.0	0.6 - 1.2	≤ 0.25	≤ 0.20	≤ 0.10

In this study, a composite design was used to construct the experimental plan. Tensile strength (Ts) was chosen as the response variable, while spindle speed (Vr), welding speed (Va), shoulder penetration (PE), and shoulder profile (PRE) were selected as the independent variables. Table 3 summarizes the experimental design used.

Table 3. Design table and experimental value of tensile strength (Gopi et al., 2021).

Test	Vr	Va	PE	PRE	Ts
1	700	48	0	-10	174,874
2	700	96	0,04	-5	180,059
3	700	144	0,08	0	187,953
4	700	192	0,12	5	184,93
5	700	240	0,16	10	177,825
6	900	48	0,04	5	189,189
7	900	96	0,08	10	185,686
8	900	144	0,12	-10	182,088
9	900	192	0,16	-5	183,712
10	900	240	0	0	187,007
11	1100	48	0,08	-5	180,262
12	1100	96	0,12	0	181,885
13	1100	144	0,16	5	192,899
14	1100	192	0	10	195,792
15	1100	240	0,04	-10	191,456
16	1300	48	0,12	10	189,808
17	1300	96	0,16	-10	186,351
18	1300	144	0	-5	189,308
19	1300	192	0,04	0	192,445
20	1300	240	0,08	5	195,578
21	1500	48	0,16	0	178,028
22	1500	96	0	5	181,976
23	1500	144	0,04	10	190,411
24	1500	192	0,08	-10	198,93
25	1500	240	0,12	-5	196,001

Response Surface Methodology (RSM)

Equation (1) was used to fit the experimental tensile strength (Ts) data in order to build the RSM model.

$$\begin{aligned} Y &= A_0 + A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{14}X_1X_4 + A_{23}X_2X_3 \\ &+ A_{24}X_2X_4 + A_{34}X_3X_4 + A_{11}X_1X_1 + A_{22}X_2X_2 + A_{44}X_4X_4 + A_{123}X_1X_2X_3 + A_{124}X_1X_2X_4 \\ &+ A_{134}X_1X_3X_4 + A_{234}X_2X_3X_4 + A_{112}X_1X_1X_2 + A_{113}X_1X_1X_3 + A_{114}X_1X_1X_4 + A_{122}X_1X_2X_2 \\ &+ A_{144}X_1X_4X_4 + A_{223}X_2X_2X_3 \end{aligned} \tag{1}$$

Where X1, X2, X3, and X4 are the values of the independent variables, Y represents the corresponding response variable, A0 is a constant, A1, A2, A3, and A4 are the linear coefficients, A12, A13, A14, A23, A24, and A34 are the interaction coefficients. A11, A22, and A44 are the quadratic coefficients. A123, A124, A134, A234, A112, A113, A114, A122, A144, and A223 are the cubic coefficients. Equation (1) is used to estimate the optimal response variable and the corresponding variables.

Results and Discussion

Modeling using the Response Surface Methodology (RSM) was carried out with the 'Design Expert' software. In this study, the coefficient of determination (R^2) for the response variable represented by tensile strength (Ts) was 0.9939.

Table 4. Fitting statistics of Ts.

Std. Dev.	2,45	R^2	0,9939
Mean	186,98	Adjusted R^2	0,8546
C.V. %	1,31	Predicted R^2	NA[(1)]
		Adeq Precision	10,1614

According to the fit summary, the model is significant for the analysis of tensile strength. The R^2 value is 99.39%, and the adjusted R^2 value is 85.46%. This clearly indicates that the regression model provides a good relationship between the process factors and the response variable.
The RSM model for tensile strength is given by Equation (2).

$$\begin{aligned} Tr = &-1229{,}16617+2{,}53948\,Vr+7{,}91313\,Va+2520{,}60102\,PE-70{,}99142\,PRE \\ &-0{,}013260\,Vr*Va-7{,}58282\,Vr*PE+0{,}139872\,Vr*PRE+20{,}316\,Va*PE \\ &-0{,}251189\,Va*PRE+221{,}03667\,PE*PRE-0{,}001040\,Vr^2-0{,}007188\,Va^2 \\ &-0{,}117344\,PRE^2-0{,}007433\,Vr*Va*PE+0{,}000189\,Vr*Va*PRE \\ &-0{,}216642\,Vr*PE*PRE+0{,}287425\,Va*PE*PRE+4{,}81066.10^{-6}\,Vr^2*Va \\ &+0{,}003728\,Vr^2*PE-0{,}000063\,Vr^2*PRE+8{,}04623.10^{-6}\,Vr.Va^2 \\ &+0{,}000135\,Vr*PRE^2-0{,}036081\,Va^2*PE \end{aligned} \quad (2)$$

The tensile strength (Ts) data predicted by the RSM model were compared with the corresponding experimental tensile strength data (Figure 2). The graph of actual and predicted values for tensile strength demonstrated the predictive capability of the developed model. In this diagram, the points lay on a straight line very close to the actual values, indicating that the errors were uniformly distributed throughout the model, as shown in Figure 2.

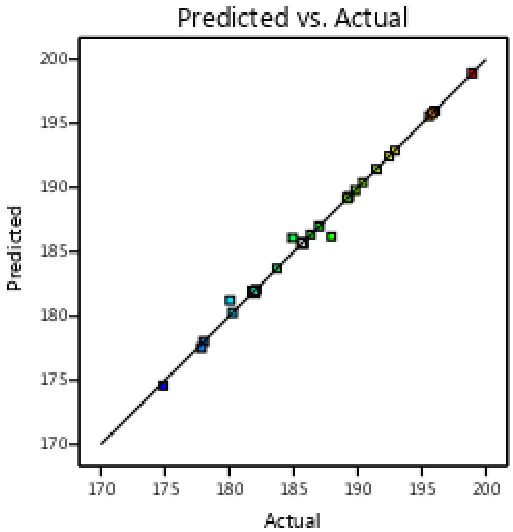

Figure 2. Actual response versus predicted response graph of tensile strength Ts.

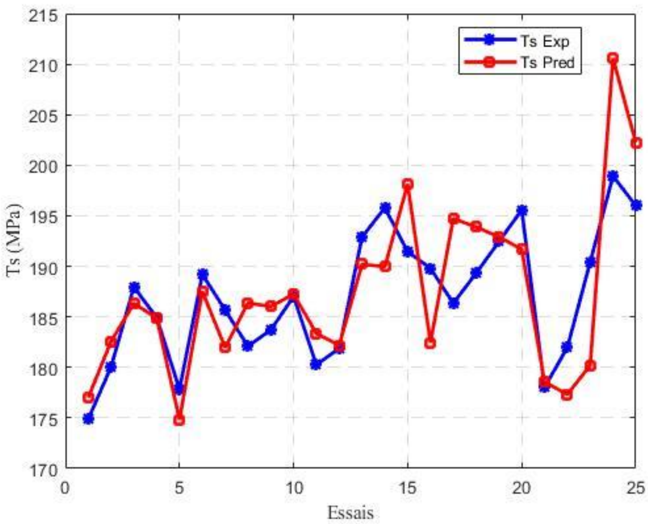

Figure 3. Validation of the tensile strength predicted by RSM.

To demonstrate the effectiveness of the Response Surface Methodology, comparison curves were plotted in Figure 3. The superimposed curves represent a comparison between the experimental values used for the model design and the values predicted by the model for the same machining parameters. Figure 4 shows the effect of factors Vr and Va acting simultaneously on the ultimate tensile strength (Ts), as they increase from their minimum to maximum values, while the third factor (PE) and fourth (PRE) remain constant. Tensile strength increases as Vr increases due to the rise in heat generation. Meanwhile, low heat input was observed at low rotational speeds, indicating a lack of stirring activity, hence poor weld quality. It was also observed that at high rotational speed and low tool traverse speed, a decrease in TS value occurred. This may be due to the effect of excessive heat generation. As shown in Figure 4.

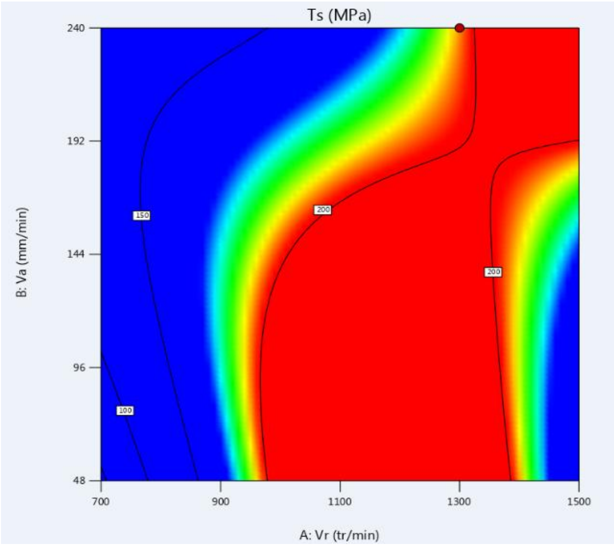

Figure 4. Variation of Ts as a function of factors Vr and Va.

As for the effect of parameters Vr and PE, an increase in the tensile strength value is observed at low to medium rotational speeds with low shoulder penetration. Then, the tensile strength increases as both variables increase together (Figure 5).

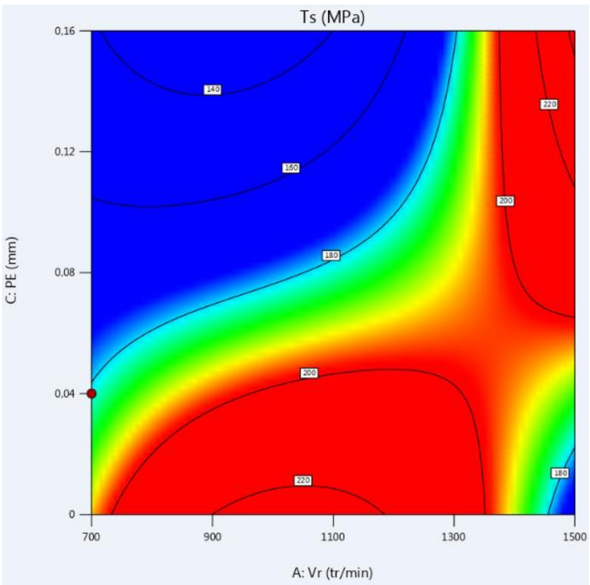

Figure 5. Variation of Ts as a function of factors Vr and PE.

As for the parameters Vr and PRE, it is observed that to achieve high tensile strength, Vr and PRE are proportional, since increasing the rotational speed increases the shoulder angle (i.e., the angle opens outward), and vice versa. At low rotational speeds, a high retention of the resulting heat is required, so this angle acts as a protector of that heat in the welding zone (Figure 6). On the contrary, with the welding speed (Va) and the shoulder angle (PRE), as the welding speed increases, the shoulder angle decreases (i.e., it points inward); as the welding speed decreases, the shoulder angle increases.

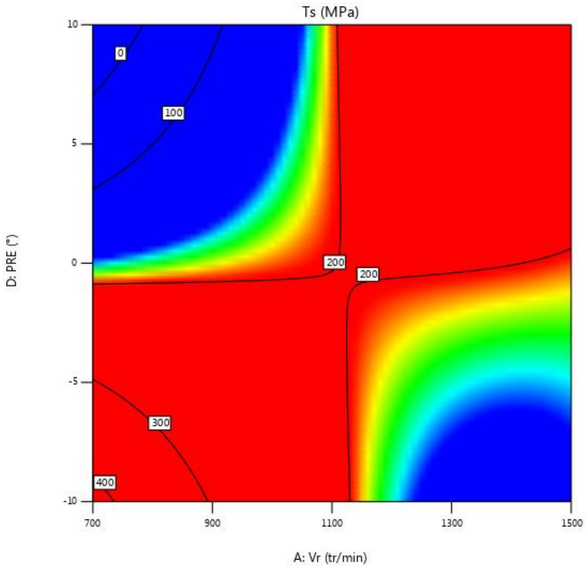

Figure 6. Variation of Ts as a function of factors Vr and PRE.

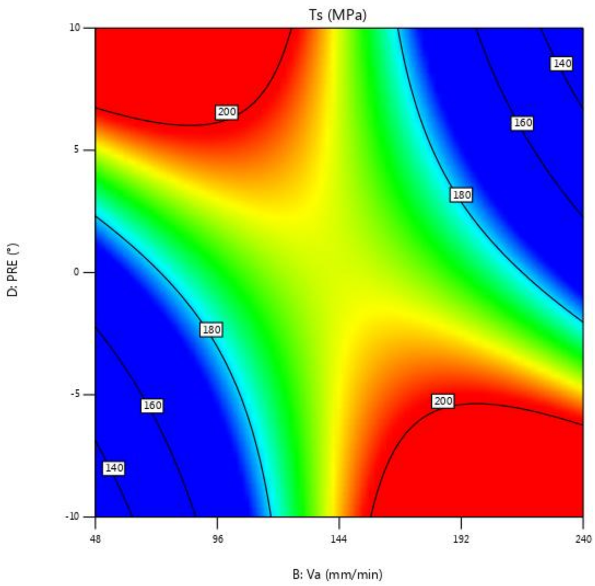

Figure 7. Variation of Ts as a function of factors Va and PRE.

Conclusion

In conclusion, what we have done can be summarized by the following points:

A mathematical model has been presented to study the effect of welding parameters on the tensile mechanical strength of the welded joint in 6082 T6 aluminum alloy. Using Response Surface Methodology (RSM), a mathematical model was developed which offers the possibility to develop an optimization model. It is important to emphasize that the created model shows very low error rates compared to experimental data. The effect of four parameters, namely rotational speed (Vr), feed speed (Va), shoulder penetration (PE), and tool shoulder profile (PRE), was studied. The main objective of this study was to understand and explain the interactions between the four parameters mentioned above, and to highlight the effect of each one on the others regarding the mechanical property of tensile strength of the welded joints.

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

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