

# Development of mathematical models for predicting mechanical properties of dissimilar DP600 steel and AZ31B magnesium alloy friction stir welds

Kapil B. Pipavat <sup>1,2</sup>, Hirenkumar I. Joshi <sup>3\*</sup>, G. D. Acharya <sup>4</sup>

<sup>1</sup> Research Scholar, Gujarat Technological University, Ahmedabad - 382424, India

<sup>2</sup> Sir Bhavsinhji Polytechnic institute, Bhavnagar - 364002, India

<sup>3</sup> Government Engineering college, Rajkot - 360005, India

<sup>4</sup> Atmiya University, Rajkot - 360005, India

\*Corresponding Authors

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## ABSTRACT

This study presents the development of mathematical models for predicting the mechanical properties of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welded joints. A General Full Factorial Design was employed by considering rotational speed, welding speed, and tool offset as process parameters. Ultimate tensile strength (UTS), yield strength (YS), microhardness (HV), and percentage elongation (%E) were selected as response variables. Second-order polynomial regression models were developed using Python, and their adequacy was evaluated through ANOVA. The developed models exhibited high predictive capability with  $R^2$  values greater than 0.94 for all responses. The optimum welding condition was obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm, producing a maximum UTS of 185.708 MPa, YS of 130.506 MPa, microhardness of 207.9 HV, and elongation of 4.508%. The results indicated that rotational speed and tool offset positively influenced the mechanical properties, whereas welding speed showed a comparatively negative effect. The close agreement between experimental and predicted values confirmed the reliability of the developed mathematical models for predicting and optimizing the mechanical performance of dissimilar friction stir welded joints.

**Keywords:** friction stir welding; DP600 steel; AZ31B magnesium alloy; mathematical modeling; polynomial regression; ANOVA; full factorial design.

## INTRODUCTION

The increasing demand for lightweight and fuel-efficient transportation systems has encouraged the integration of lightweight alloys with advanced high-strength steels in automotive and aerospace structures. Among the available joining technologies, friction stir welding (FSW) has emerged as an effective solid-state welding process capable of producing high-quality joints while eliminating defects commonly associated with conventional fusion welding techniques [1], [2], [3], [4].

DP600 steel is extensively used in automotive applications because of its high strength and excellent crashworthiness, whereas AZ31B magnesium alloy is attractive for lightweight structural applications due to its low density and high specific strength. The combination of these materials offers significant potential for weight reduction; however, their joining remains challenging because of differences in melting temperature, thermal properties, and the immiscible nature of the Fe-Mg system [5][6][7][8].

Several studies have demonstrated the feasibility of joining magnesium alloys to steel using FSW. Abe et al. [5] reported successful joining of AZ31B magnesium alloy and steel with joint strengths approaching 70% of the magnesium base metal strength. Kasai et al. [6] showed that aluminium present in magnesium alloys promotes the formation of Fe-Al interfacial compounds, improving joint performance. Further investigations by Joo [7] and Wang et al. [8] highlighted the critical influence of welding conditions and interfacial reactions on the mechanical properties of steel-magnesium dissimilar joints.

In parallel, mathematical modeling techniques such as design of experiments (DOE), response surface methodology (RSM), regression analysis, and ANOVA have been widely employed to predict the mechanical properties of friction stir welded joints [1], [2], [3], [4] [9], [10], [11], [12], [13]. These approaches enable the establishment of relationships between process parameters and weld performance while reducing the number of experimental trials required for optimization.

The usefulness of statistical experimental design and regression-based modelling extends beyond welding applications. Joshi and Acharya [14] employed response surface methodology to develop predictive relationships between multiple design parameters and stress responses, with model adequacy evaluated using ANOVA and coefficients of determination. In a related study, Joshi and Acharya [15] applied a Taguchi L25 orthogonal array to systematically examine five design variables and developed regression equations for predicting stress responses. These studies demonstrate the broader applicability of DOE-based regression modelling for quantifying parameter effects and developing predictive engineering models [14], [15].

Although several predictive models have been developed for aluminium alloys, copper alloys, and aluminium based dissimilar joints, limited research has focused on mathematical modeling of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welds. Therefore, the present study aims to develop mathematical models for predicting ultimate tensile strength, yield strength, microhardness, and percentage elongation of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welds using a general Full Factorial Design approach. The adequacy of the developed models was evaluated through regression analysis and analysis of variance (ANOVA).

## EXPERIMENTAL DETAILS

### Materials

DP600 dual-phase steel and AZ31B magnesium alloy sheets with dimensions of 100 mm × 50 mm × 3 mm were used as the base materials in this study. DP600 steel was selected because of its high strength and excellent crashworthiness, whereas AZ31B magnesium alloy was chosen due to its low density and high specific strength, making it suitable for lightweight structural applications. Prior to welding, the mating surfaces were cleaned and degreased using acetone. The sheets were arranged in a butt-joint configuration with DP600 steel on the advancing side (AS) and AZ31B magnesium alloy on the retreating side (RS) for clockwise tool rotation.

### Experimental Set-up

Friction stir welding was performed using a vertical milling machine equipped with a non-consumable tungsten carbide (WC) tool. The tool consisted of an 18 mm shoulder diameter and a tapered cylindrical pin with a bottom diameter of 5 mm, tip diameter of 3 mm, and pin length of 2.8 mm. A tool tilt angle of 2° was maintained throughout the welding process.

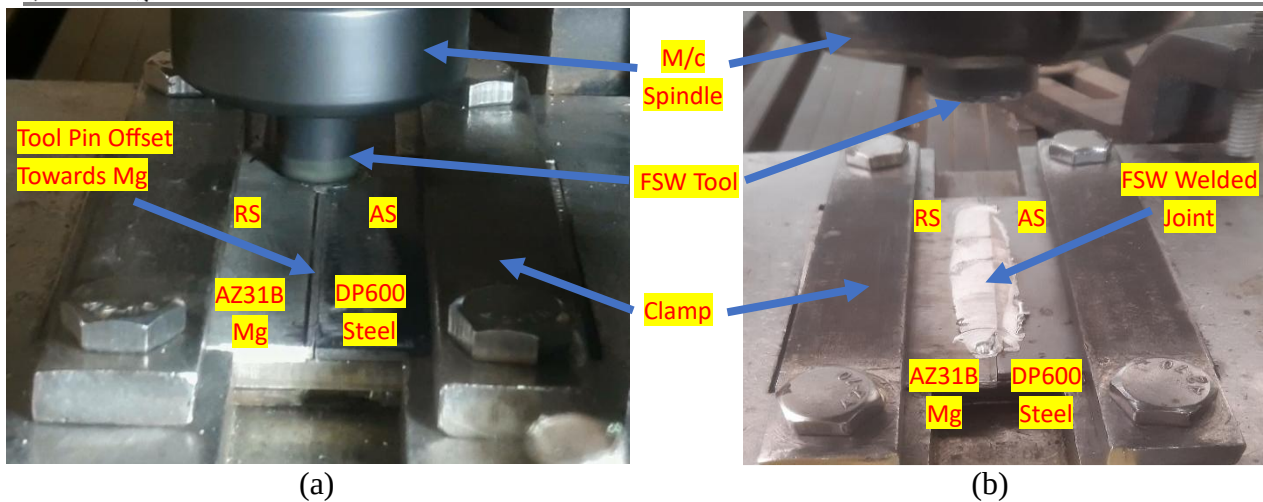


Fig. 1. (a) Experiment Set-up, (b) FSW Welded Joint

Fig. 1. Friction stir welding experimental arrangement for dissimilar DP600 steel and AZ31B magnesium alloy joints: (a) experimental set-up and (b) friction stir welded joint.

The experimental arrangement and a representative welded joint are shown in Fig. 1. During welding, the tool pin was offset towards the magnesium side to improve material flow and interfacial bonding. The workpieces were rigidly clamped using a specially designed fixture to ensure stable welding conditions. Three process parameters, namely rotational speed (545-765 rpm), welding speed (31.5-50 mm/min), and tool offset (1.0-1.5 mm), were selected as input variables for the experimental investigation.

After welding, the joints were visually inspected and subjected to radiographic examination. Defect-free welds were used for mechanical characterization. Tensile testing was conducted according to ASTM E8 standards to determine ultimate tensile strength, yield strength, and percentage elongation, while Vickers microhardness measurements were performed across the weld region.

## Experimental Design - General Full Factorial Design

### Selection of Process Parameters and Levels

Tool rotational speed (N), welding speed (V), and tool offset towards the magnesium side (O) were selected as the process parameters for the present investigation, as they significantly influence heat generation, material flow, and joint properties during friction stir welding. Based on preliminary trials and literature review, each parameter was studied at two levels, as presented in Table 1.

Table 1. Process parameters and levels.

| Factor | Parameter              | Low Level (-1) | High Level (+1) |
|--------|------------------------|----------------|-----------------|
| N      | Rotational Speed (rpm) | 545            | 765             |
| V      | Welding Speed (mm/min) | 31.5           | 50              |
| O      | Tool Offset (mm)       | 1.0            | 1.5             |

### Experimental Matrix

A General Full Factorial Design with three factors and two levels was employed to investigate the effect of process parameters on the mechanical properties of the welded joints. The design generated eight experimental

runs ( $2^3 = 8$ ), enabling the evaluation of both main and interaction effects of the selected variables. The experimental matrix used for conducting the welding trials is presented in Table 2.

The experimental results obtained from these trials were used to develop mathematical models for predicting ultimate tensile strength, yield strength, microhardness, and percentage elongation of the dissimilar friction stir welded joints.

## RESULTS AND ANALYSIS

### Experimental Results

The experimental results obtained from the eight friction stir welding trials are presented in Table 2. The ultimate tensile strength (UTS), yield strength (YS), microhardness (HV), percentage elongation (%E), and joint efficiency (%JE) were found to vary with the selected welding parameters.

The maximum UTS, YS, microhardness, elongation, and joint efficiency of 185.708 MPa, 130.506 MPa, 207.9 HV, 4.508%, and 72.83%, respectively, were obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm (Experiment No. 6). The minimum UTS of 110.612 MPa was observed for Experiment No. 3. The experimental data presented in Table 2 were subsequently used for the development of mathematical models and ANOVA analysis.

Table 2. DOE - Mechanical Characterization Results (UTS, YS, HV, % Elo, % JE)

| Ex No. | Rotational Speed | Welding Speed | Tool Offset to Mg | Tensile Strength UTS | Yield Strength | Micro Hardness | Elongation | Joint Efficiency |
|--------|------------------|---------------|-------------------|----------------------|----------------|----------------|------------|------------------|
|        | (RPM)            | (mm/min)      | (mm)              | (Mpa)                | (Mpa)          | (HV)           | (%)        | (%)              |
| 1      | 545              | 31.5          | 1                 | 125.284              | 91.919         | 177.5          | 3.054      | 49.13            |
| 2      | 545              | 31.5          | 1.5               | 169.498              | 125.177        | 190.7          | 4.118      | 66.47            |
| 3      | 545              | 50            | 1                 | 110.612              | 88.480         | 156.2          | 2.948      | 43.38            |
| 4      | 545              | 50            | 1.5               | 138.409              | 109.395        | 190.3          | 3.297      | 54.28            |
| 5      | 765              | 31.5          | 1                 | 168.283              | 120.770        | 189.9          | 3.771      | 65.99            |
| 6      | 765              | 31.5          | 1.5               | 185.708              | 130.506        | 207.9          | 4.508      | 72.83            |
| 7      | 765              | 50            | 1                 | 130.186              | 102.547        | 185.2          | 3.193      | 51.05            |
| 8      | 765              | 50            | 1.5               | 177.992              | 129.045        | 200.4          | 4.268      | 69.80            |

### Development of Mathematical Model

Mathematical models were developed to predict the mechanical properties of dissimilar DP600 steel–AZ31B magnesium alloy friction stir welded joints using the experimental data presented in Table 2. The data were analyzed using Python in the Google Colab environment. Rotational speed (N), welding speed (V), and tool offset (O) were considered as the input process parameters, while ultimate tensile strength (UTS), yield strength (YS), microhardness (HV), and percentage elongation (%E) were selected as response variables.

A second-order polynomial regression model was employed to establish the relationship between the process parameters and the responses. The general form of the developed mathematical model is expressed as:

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon \quad \dots(1)$$

where Y is the response variable, while  $x_i$  are factors or process variables. In Eq. (1), terms in  $x_i$  are linear, terms in  $x_i^2$  are quadratic and terms in  $x_i x_j$  are product terms;  $\beta_0$ ,  $\beta_i$ ,  $\beta_{ii}$ , and  $\beta_{ij}$  are constant coefficients while  $\varepsilon$  is residual random error.

## Development of Mathematical Model for ultimate tensile strength (UTS)

### Regression Model for UTS

The developed polynomial regression model relating ultimate tensile strength (UTS) to rotational speed (N), welding speed (V), and tool offset (O) is expressed as:

$$UTS = 0.0008 + 0.2613 (N) + 0.0155 (V) + 8.0071 (O) - 0.0000 (NV) - 0.0308 (NO) + 0.7548 (VO) \quad \dots(2)$$

The developed model incorporates linear, quadratic, and interaction terms to capture the influence of welding parameters on tensile strength. The coefficient of determination ( $R^2$ ) obtained for the model was 0.9498, indicating that approximately 94.98% of the variation in tensile strength can be explained by the selected process parameters. The adjusted  $R^2$  value of 0.6489 further confirms the adequacy of the developed regression model.

### ANOVA for UTS Model

Analysis of Variance (ANOVA) was performed to evaluate the statistical significance of the developed UTS model. The ANOVA results are presented in Table 3. The model exhibited an  $R^2$  value of 0.9498, indicating a strong correlation between the experimental and predicted tensile strength values. The minimum p-value obtained from the ANOVA analysis was 0.2624, corresponding to the welding speed parameter. Although the limited number of experimental runs resulted in relatively higher p-values, the model demonstrated satisfactory predictive capability for the investigated process parameter range.

Table 3. ANOVA for UTS

|          | sum_sq   | df | F        | PR (>F)  | $R^2$   | Adjusted $R^2$ | Min P-Value |
|----------|----------|----|----------|----------|---------|----------------|-------------|
| N        | 1378.009 | 1  | 5.0337   | 0.266924 | 0.94984 | 0.64889        | 0.262368    |
| V        | 1432.453 | 1  | 5.23258  | 0.262368 |         |                |             |
| O        | 30.16248 | 1  | 0.11018  | 0.79597  |         |                |             |
| $N^2$    | 11.38925 | 1  | 0.041604 | 0.871906 |         |                |             |
| $V^2$    | 53.48542 | 1  | 0.195376 | 0.735044 |         |                |             |
| $O^2$    | 30.1584  | 1  | 0.110165 | 0.795982 |         |                |             |
| N V      | 0.000338 | 1  | 1.23E-06 | 0.999293 |         |                |             |
| N O      | 5.74605  | 1  | 0.02099  | 0.908405 |         |                |             |
| V O      | 24.37416 | 1  | 0.089036 | 0.815394 |         |                |             |
| Residual | 273.7566 | 1  |          |          |         |                |             |

The ANOVA results indicate that rotational speed and welding speed contributed more significantly to the tensile strength response compared to tool offset and interaction effects. Therefore, the developed regression equation can be effectively used for predicting the ultimate tensile strength of dissimilar friction stir welded joints within the selected experimental domain.

### Response Surface and Effects of Process Parameters

The interaction effects of rotational speed, welding speed, and tool offset on ultimate tensile strength (UTS) were analyzed using 3D response surface plots, 3D scatter plots, and contour plots, as shown in Figs. 2–4.

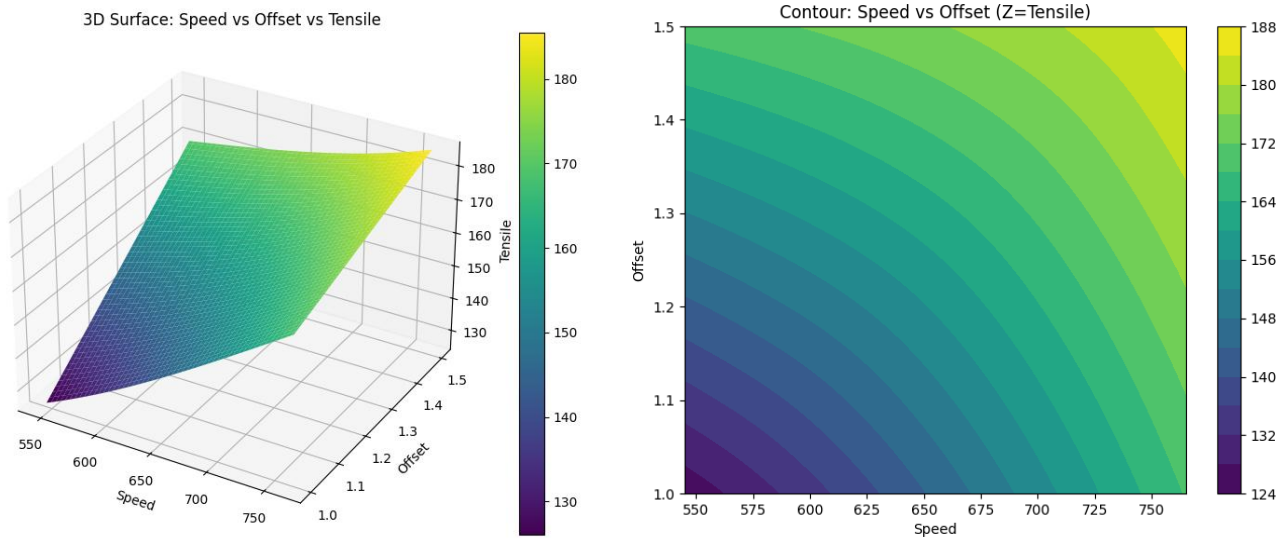


Fig. 2. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and tool offset on ultimate tensile strength.

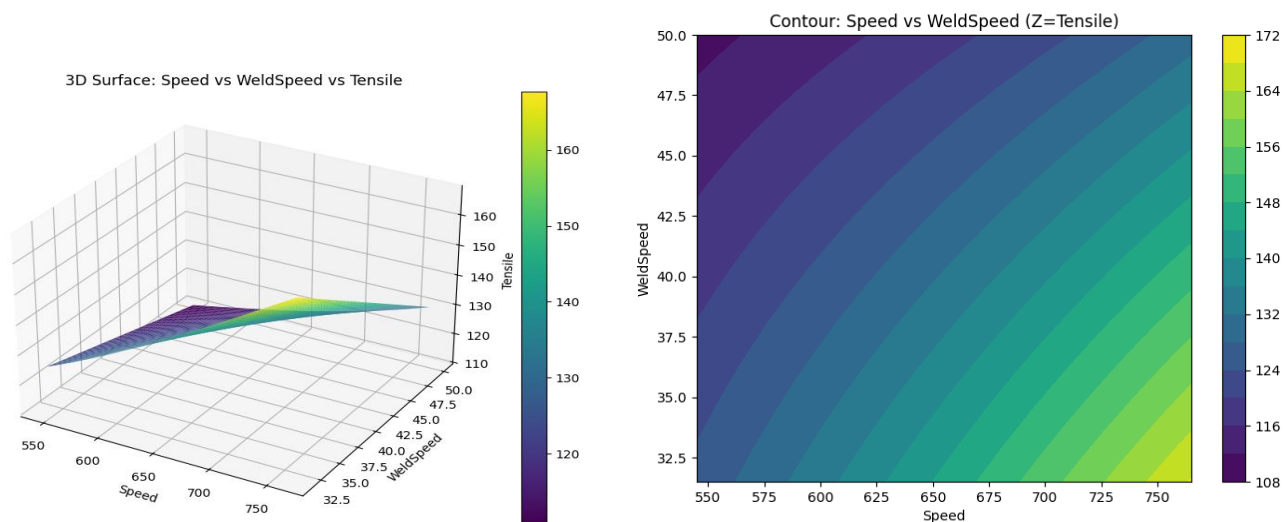


Fig. 3. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and welding speed on ultimate tensile strength.

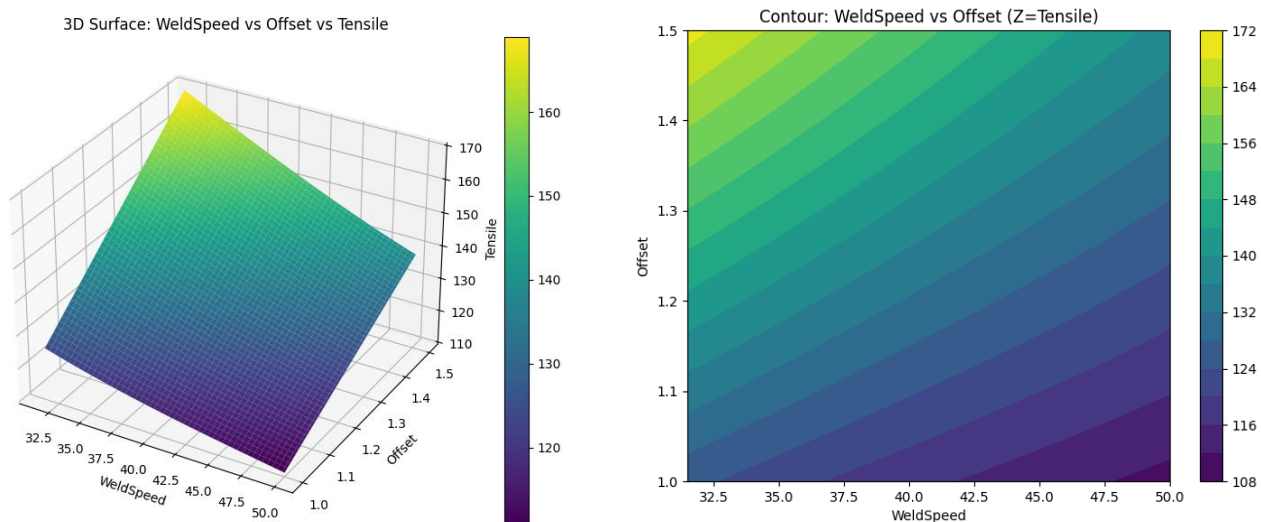


Fig. 4. (a) 3D response surface plot and (b) contour plot showing the combined effect of welding speed and tool offset on ultimate tensile strength.

The 3D scatter plots validate the experimental trends predicted by the regression model, while the contour plots identify the optimum parameter region. The maximum UTS was obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm, which is consistent with the experimental results.

## Development of Mathematical Model for Yield Strength (YS)

### Regression Model for YS

The developed regression equation for predicting yield strength is given by:

$$YS = 0.0006 + 0.1847 (N) + 0.0111 (V) + 12.2595 (O) - 0.0001 (NV) - 0.0815 (NO) + 0.2389 (VO) \quad \dots(3)$$

The developed model yielded an  $R^2$  value of 0.9453 and an adjusted  $R^2$  value of 0.6171, indicating satisfactory agreement between the experimental and predicted yield strength values.

### ANOVA for YS Model

Analysis of Variance (ANOVA) was performed to evaluate the adequacy of the developed regression model. The ANOVA results (Table 4) revealed that the model exhibited a coefficient of determination ( $R^2$ ) of 0.9453, demonstrating that 94.53% of the variation in yield strength can be explained by the selected process parameters. The minimum p-value obtained was 0.2316, corresponding to welding speed, indicating that rotational speed and welding speed contributed more significantly to the yield strength response than the remaining model terms.

Table 4. ANOVA for YS

|       | sum_sq   | df | F        | PR(>F)   | $R^2$  | Adjusted $R^2$ | Min P-Value |
|-------|----------|----|----------|----------|--------|----------------|-------------|
| N     | 688.6258 | 1  | 6.503364 | 0.237908 | 0.9453 | 0.61708        | 0.231567    |
| V     | 730.6623 | 1  | 6.900356 | 0.231567 |        |                |             |
| O     | 70.70677 | 1  | 0.667753 | 0.56384  |        |                |             |
| $N^2$ | 0.015912 | 1  | 0.00015  | 0.992196 |        |                |             |

|                |          |   |          |          |  |  |  |
|----------------|----------|---|----------|----------|--|--|--|
| V <sup>2</sup> | 7.089217 | 1 | 0.06695  | 0.838811 |  |  |  |
| O <sup>2</sup> | 70.7019  | 1 | 0.667707 | 0.563851 |  |  |  |
| N V            | 0.026796 | 1 | 0.000253 | 0.989874 |  |  |  |
| N O            | 40.22597 | 1 | 0.379893 | 0.648358 |  |  |  |
| V O            | 2.440945 | 1 | 0.023052 | 0.904075 |  |  |  |
| Residual       | 105.8876 | 1 |          |          |  |  |  |

Overall, the ANOVA results confirm that the developed regression model is capable of predicting the yield strength of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welded joints within the investigated parameter range.

### Response Surface and Effects of Process Parameters

The interaction effects of rotational speed, welding speed, and tool offset on yield strength were analyzed using 3D response surface plots and contour plots, as shown in Figs. 5–7.

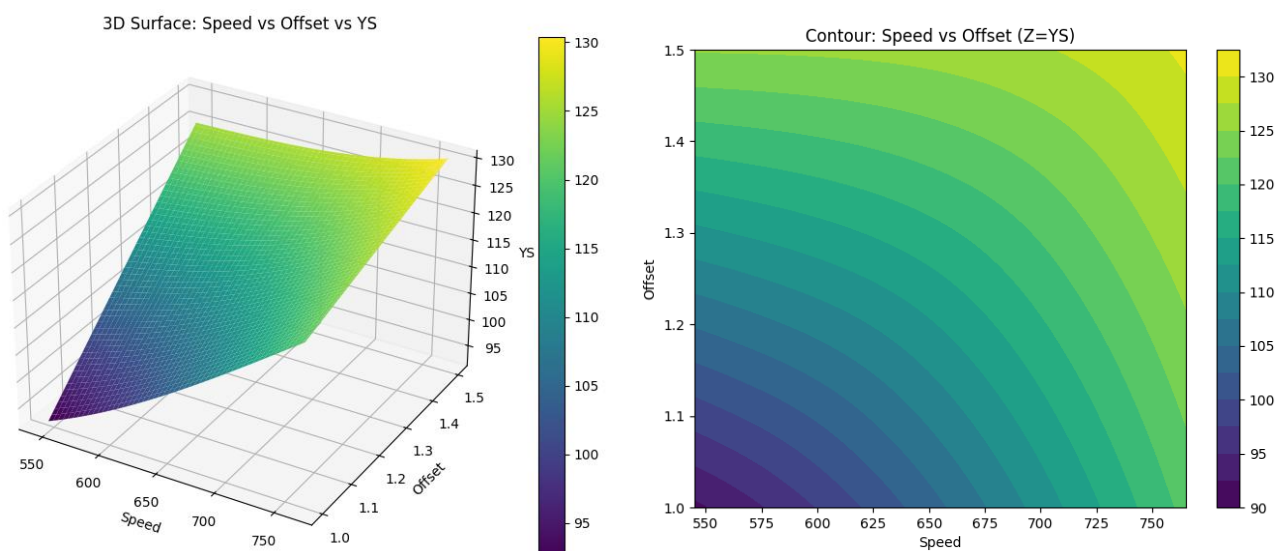


Fig. 5. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and tool offset on yield strength.

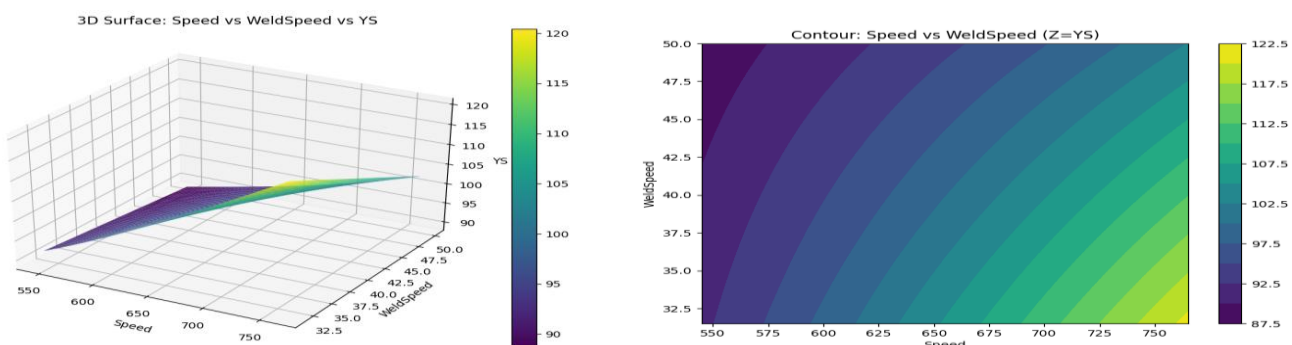


Fig. 6. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and welding speed on yield strength.

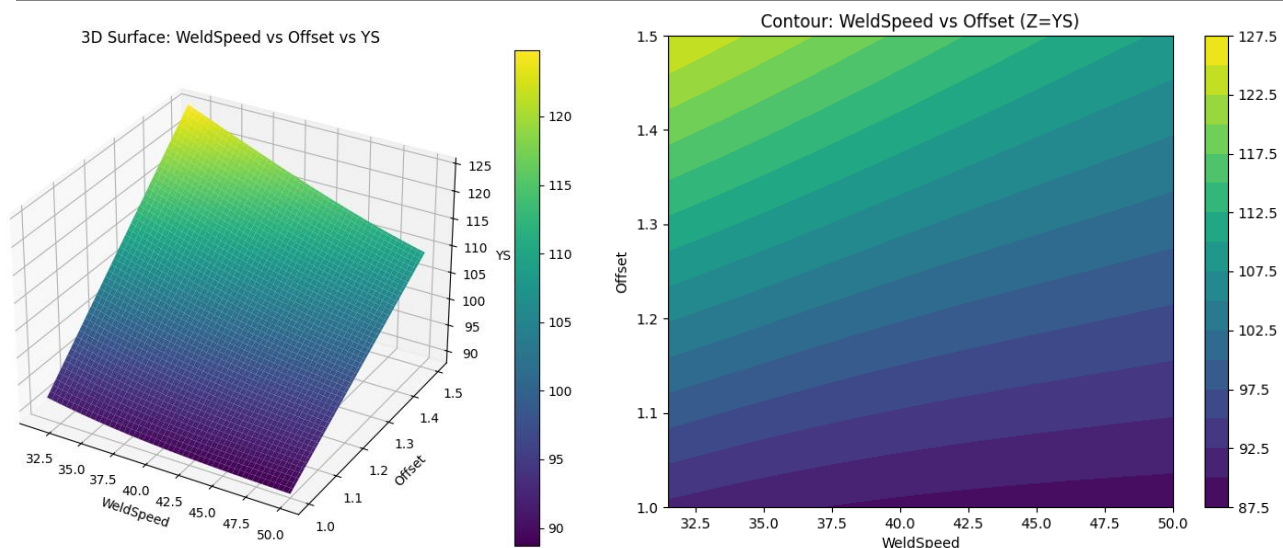


Fig. 7. (a) 3D response surface plot and (b) contour plot showing the combined effect of welding speed and tool offset on yield strength.

The contour plots further identify the optimum parameter region corresponding to high rotational speed, low welding speed, and large tool offset. The maximum yield strength was obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm, which is consistent with the experimental observations.

### Development of Mathematical Model for Microhardness (HV)

The experimental microhardness values obtained from the friction stir welded joints were used to develop a predictive mathematical model. A second-order polynomial regression analysis was performed using Python in the Google Colab environment to establish the relationship between the selected welding parameters and the microhardness response.

### Regression Model for Microhardness

The developed regression equation for predicting microhardness is given by:

$$\text{Hardness} = 0.0014 + 0.4472 (N) + 0.0268 (V) + 5.8436 (O) + 0.0012 (NV) - 0.0641 (NO) + 0.9784 (VO) \dots(4)$$

The developed model exhibited an  $R^2$  value of 0.9585 and an adjusted  $R^2$  value of 0.7094, indicating excellent agreement between the experimental and predicted microhardness values.

### ANOVA for Microhardness Model

Analysis of Variance (ANOVA) was performed to evaluate the adequacy and significance of the developed model. The ANOVA results (Table 5) revealed that the model possessed a coefficient of determination ( $R^2$ ) of 0.9585, indicating that 95.85% of the variation in microhardness could be explained by the selected welding parameters. The minimum p-value obtained was 0.0813, suggesting that rotational speed and welding speed had a relatively greater influence on the microhardness response compared to the remaining model terms.

Table 5. ANOVA for Microhardness

|   | sum_sq   | df | F       | PR(>F)   | $R^2$   | Adjusted $R^2$ | Min P-Value |
|---|----------|----|---------|----------|---------|----------------|-------------|
| N | 4037.877 | 1  | 57.5104 | 0.083466 | 0.95848 | 0.70935        | 0.081299    |

|                |          |   |          |          |  |  |  |
|----------------|----------|---|----------|----------|--|--|--|
| V              | 4258.499 | 1 | 60.65266 | 0.081299 |  |  |  |
| O              | 16.06474 | 1 | 0.228806 | 0.715961 |  |  |  |
| N <sup>2</sup> | 166.7444 | 1 | 2.374896 | 0.366439 |  |  |  |
| V <sup>2</sup> | 68.01707 | 1 | 0.968749 | 0.505053 |  |  |  |
| O <sup>2</sup> | 16.05991 | 1 | 0.228737 | 0.715998 |  |  |  |
| N V            | 11.28125 | 1 | 0.160676 | 0.757299 |  |  |  |
| N O            | 24.85125 | 1 | 0.35395  | 0.658334 |  |  |  |
| V O            | 40.95125 | 1 | 0.583258 | 0.584784 |  |  |  |
| Residual       | 70.21125 | 1 |          |          |  |  |  |

The high R<sup>2</sup> value confirms that the developed regression model can effectively predict the microhardness of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welded joints within the investigated parameter range.

### Response Surface and Effects of Process Parameters

The interaction effects of rotational speed, welding speed, and tool offset on microhardness were analyzed using 3D response surface plots and contour plots, as shown in Figs. 8-10.

Figure 8 indicates that microhardness increased with increasing rotational speed and tool offset. Figure 9 shows that higher rotational speed and lower welding speed resulted in improved hardness values. Similarly, Figure 10 reveals that microhardness increased significantly with increasing tool offset, while a marginal reduction was observed with increasing welding speed.

The contour plots further identify the optimum parameter region corresponding to high rotational speed, low welding speed, and large tool offset. The maximum microhardness was obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm, which is consistent with the experimental observations.

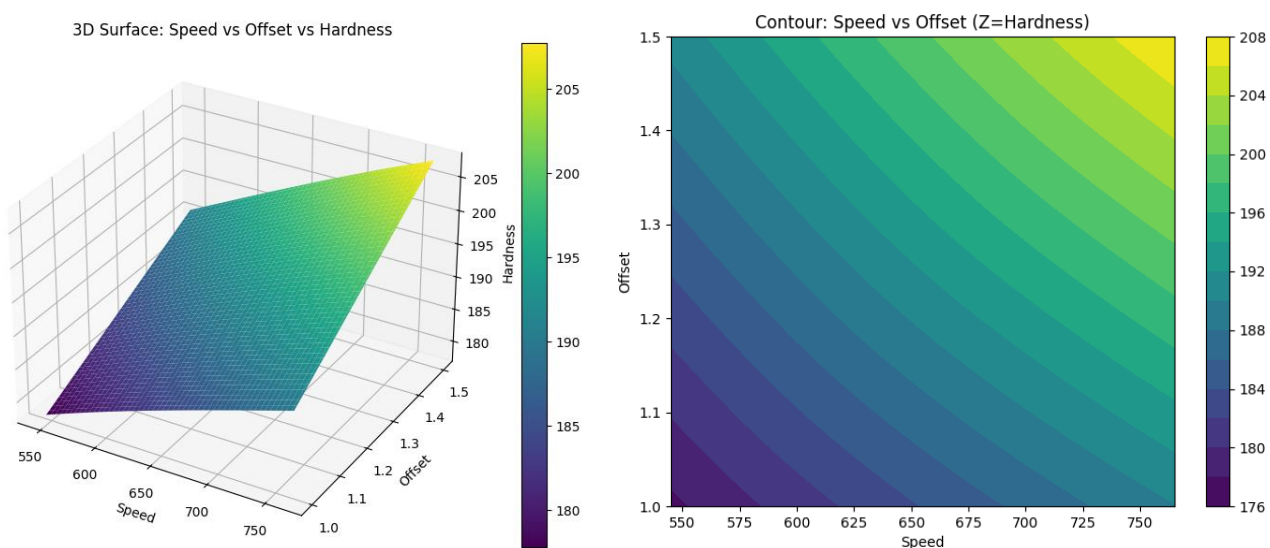


Fig. 8. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and tool offset on microhardness.

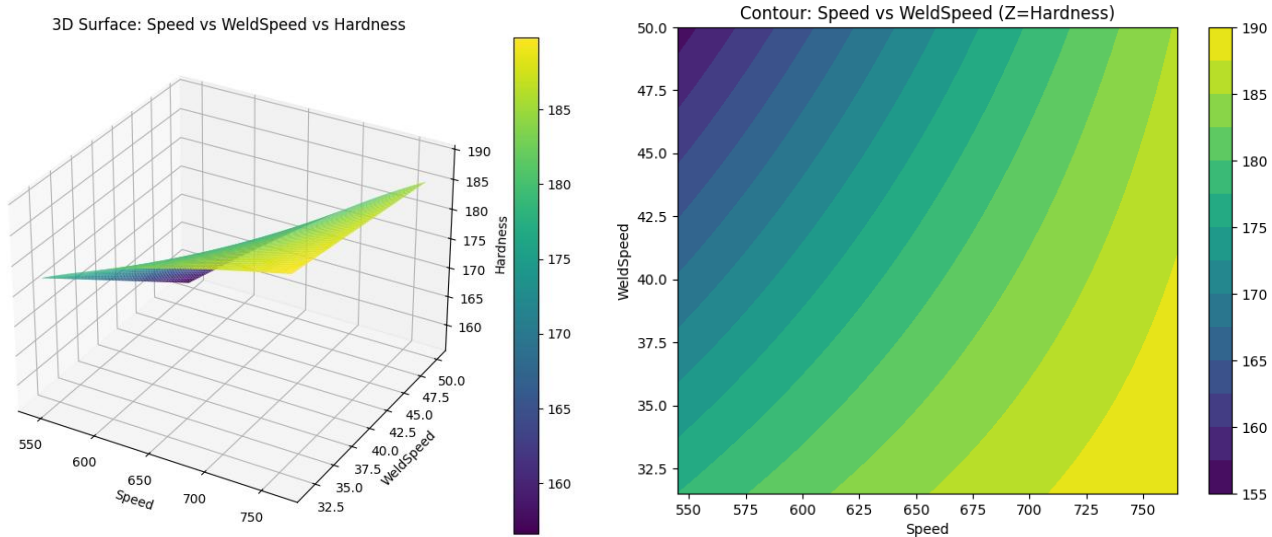


Fig. 9. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and welding speed on microhardness.

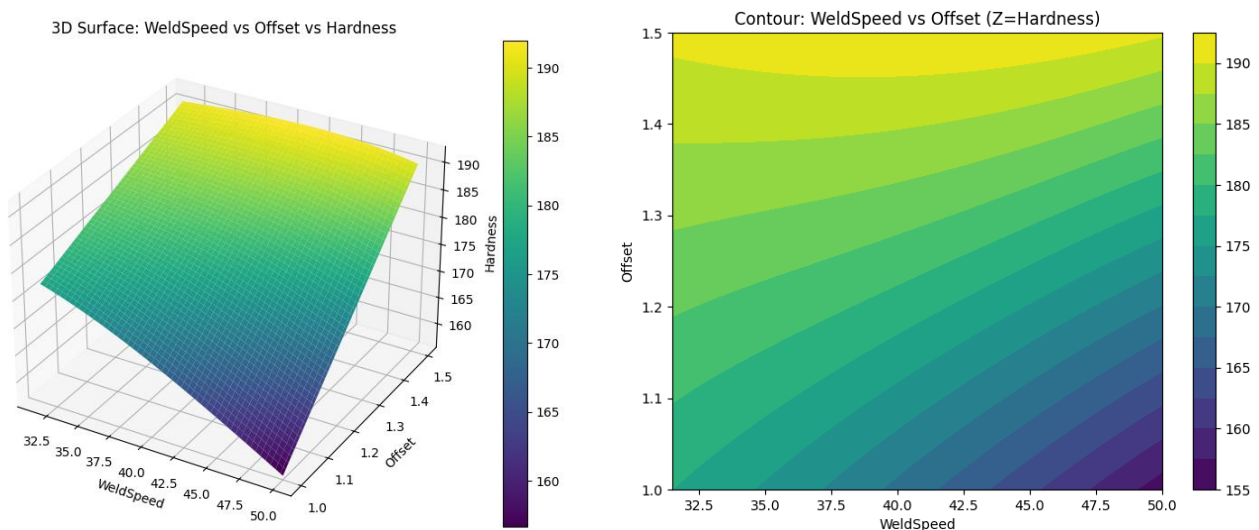


Fig. 10. (a) 3D response surface plot and (b) contour plot showing the combined effect of welding speed and tool offset on microhardness.

### Development of Mathematical Model for Percentage Elongation (%E)

The experimental elongation values obtained from the friction stir welded joints were used to develop a predictive mathematical model. A second-order polynomial regression analysis was performed using Python in the Google Colab environment to establish the relationship between the selected welding parameters and the percentage elongation response.

### Regression Model for Percentage Elongation

The developed regression equation for predicting percentage elongation is given by:

$$\text{Elongation} = 0.0000 + 0.0067 (N) + 0.0004 (V) + 0.1731 (O) + 0.0000 (NV) + 0.0018 (NO) - 0.0204 (VO) \dots (5)$$

The developed model exhibited an  $R^2$  value of 0.9453 and an adjusted  $R^2$  value of 0.6170, indicating satisfactory agreement between the experimental and predicted elongation values.

## ANOVA for Percentage Elongation Model

Table 6. ANOVA for Percentage Elongation

|                | sum_sq   | df | F        | PR(>F)   | R <sup>2</sup> | Adjusted R <sup>2</sup> | Min P-Value |
|----------------|----------|----|----------|----------|----------------|-------------------------|-------------|
| N              | 0.894536 | 1  | 6.454033 | 0.238732 | 0.94528        | 0.61697                 | 0.230669    |
| V              | 0.964562 | 1  | 6.959263 | 0.230669 |                |                         |             |
| O              | 0.014099 | 1  | 0.10172  | 0.803452 |                |                         |             |
| N <sup>2</sup> | 0.068643 | 1  | 0.495256 | 0.609603 |                |                         |             |
| V <sup>2</sup> | 0.00059  | 1  | 0.004258 | 0.958519 |                |                         |             |
| O <sup>2</sup> | 0.014096 | 1  | 0.101704 | 0.803466 |                |                         |             |
| N V            | 0.001485 | 1  | 0.010715 | 0.934335 |                |                         |             |
| N O            | 0.0199   | 1  | 0.143578 | 0.769416 |                |                         |             |
| V O            | 0.017766 | 1  | 0.128182 | 0.781126 |                |                         |             |
| Residual       | 0.138601 | 1  |          |          |                |                         |             |

Analysis of Variance (ANOVA) was performed to evaluate the adequacy and significance of the developed model. The ANOVA results (Table 6) revealed that the model possessed a coefficient of determination ( $R^2$ ) of 0.9453, indicating that 94.53% of the variation in elongation could be explained by the selected welding parameters. The minimum p-value obtained was 0.2307, suggesting that rotational speed and welding speed had a relatively greater influence on elongation compared to the remaining model terms.

The high  $R^2$  value confirms that the developed regression model can effectively predict the elongation of dissimilar DP600 steel–AZ31B magnesium alloy friction stir welded joints within the investigated parameter range.

## Response Surface and Effects of Process Parameters

The interaction effects of rotational speed, welding speed, and tool offset on elongation were analyzed using 3D response surface plots and contour plots, as shown in Figs. 11-13.

Figure 11 indicates that elongation increased with increasing rotational speed and tool offset. Figure 12 shows that higher rotational speed and lower welding speed resulted in improved elongation values. Similarly, Figure 13 reveals that elongation increased significantly with increasing tool offset and decreased with increasing welding speed.

The contour plots further identify the optimum parameter region corresponding to high rotational speed, low welding speed, and large tool offset. The maximum elongation was obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm, which is consistent with the experimental observations.

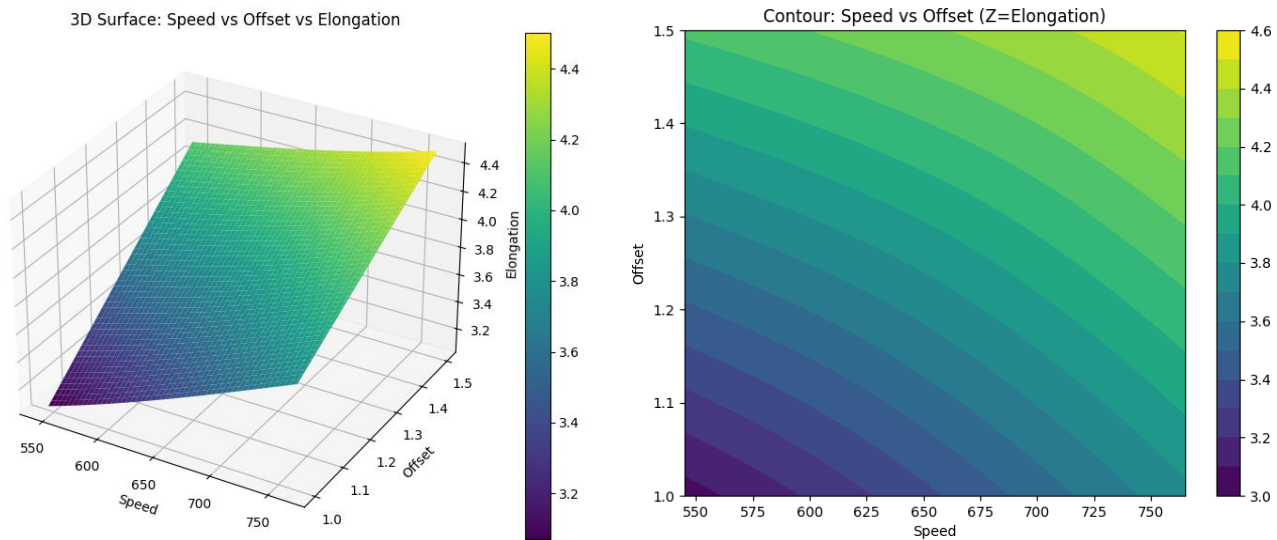


Fig. 11. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and tool offset on percentage elongation.

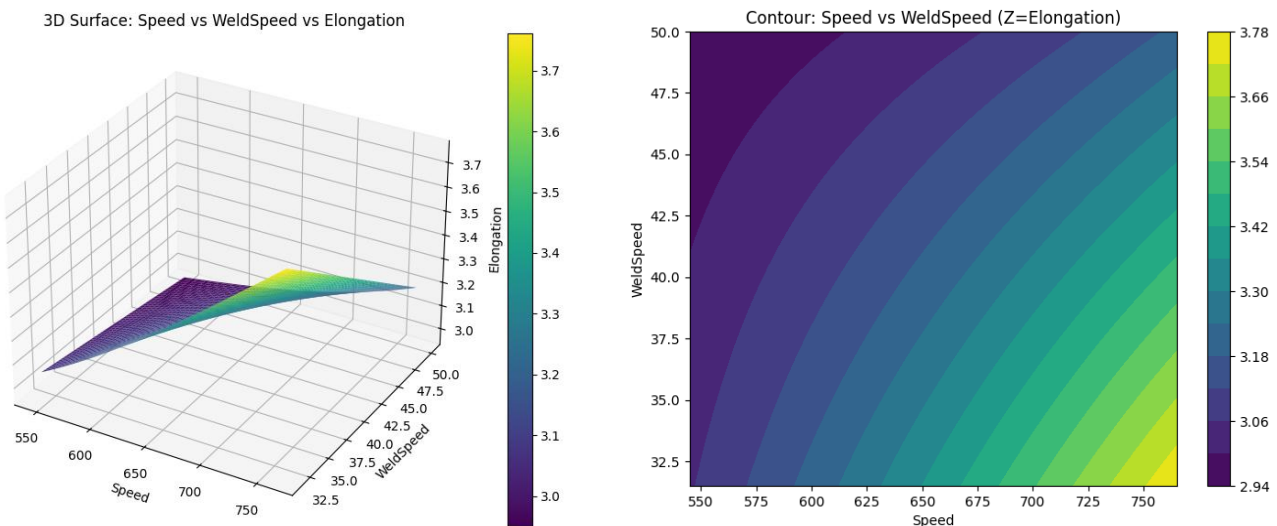


Fig. 12. (a) 3D response surface plot and (b) contour plot showing the combined effect of rotational speed and welding speed on percentage elongation.

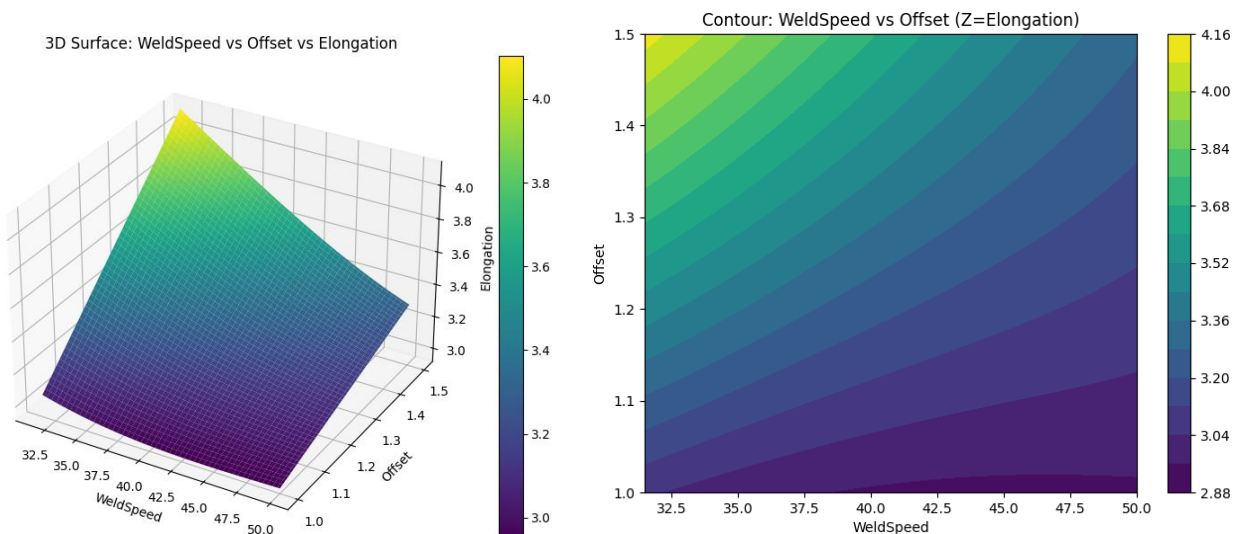


Fig. 13. (a) 3D response surface plot and (b) contour plot showing the combined effect of welding speed and tool offset on percentage elongation.

## CONCLUSION

Mathematical models were successfully developed to predict the ultimate tensile strength (UTS), yield strength (YS), microhardness (HV), and percentage elongation (%E) of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welded joints using a General Full Factorial Design approach. The developed second-order polynomial regression models exhibited good predictive capability with  $R^2$  values greater than 0.94 for all responses.

The analysis revealed that rotational speed and tool offset positively influenced the mechanical properties, whereas welding speed showed a comparatively negative effect. The optimum welding condition was obtained at a rotational speed of 765 rpm, welding speed of 31.5 mm/min, and tool offset of 1.5 mm, resulting in superior mechanical performance.

The close agreement between the predicted and experimental values confirmed the adequacy of the developed models. Therefore, the proposed mathematical models can be effectively used for predicting and optimizing the mechanical properties of dissimilar DP600 steel-AZ31B magnesium alloy friction stir welded joints.

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