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# Optimization of Process parameters of friction stir welded joint of dissimilar Al-alloy AA2024 and AA5052 using response surface methodology

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## Abstract

Identification of process parameters and their effects to the outcomes of the system using experimental method could be time consuming, daunting and costly course. Using proper statical methods, i.e. response surface methodology (RSM) could significantly reduce the number of required experiments and statistical significant of the process parameters can be identified. Friction stir welding (FSW) is one of those welding techniques with various parameters which have different effects on the quality of the welds. In FSW the tool rotational speed (TRS) and traverse speed (TS) influence the mechanical properties of the fusion zone.
In this work, the effect of tool rotational speed, traverse speed and tilt angle on mechanical properties of friction stir welded joint of AA2024 and AA5052 have been investigated. There are 20 experiments were performed as per center composite design (CCD) approach of RSM. The tensile test were carried out to observe tensile strength and percentage elongation of FSWed joints. The quadratic regression mathematical model was developed to establish a relation between inputs and outputs. ANOVA was used to ensure the significance of the process parameters and their interactions. Optimized combination of process parameters was determined using grey relation coupled with principal component analysis, a hybrid approach.


*Keywords:* Friction stir welding, Tensile strength, Micro-hardness, Optimization.

## 1. Introduction

Friction stir welding (FSW) is an automatic, innovative and solid state welding process as shown in fig.1. FSW is popular for the welding of various aluminum alloy [1]. This technique has solved the problem of porosity, shrinkage and unusual grain growth which is found to occur in conventional welding of aforesaid alloys [2-3]. The previous research comprises several mathematical regression analysis and optimization techniques such as Taguchi, RSM, etc., for modelling the FSW process. Central composite design (CCD) in RSM has proved to be one of most significant technique for designing experiments, prediction of responses, and for determining the optimized process parameters. Maximum research is focused on mechanical and metallurgical properties of the FSW joint. FSW for joining AA7075 plates. The experiments are conducted at three different rotational and welding speeds. It is concluded that joints strength are lower than parent metal. Minimum residual stresses are observed in joint fabricated at higher rotational speed [4]. The effect of tool material on FSW joint of AA7075 plates. The maximum joint strength is obtained by uncoated tool material at a rotational speed of 900 rpm. In addition, it is also concluded that TiN-coated X210Cr12 alloy steel stirring tools decreased the tensile properties of the joint [5]. The optimization of FSW process parameters for AA5083 aluminum alloy with multiple responses based on orthogonal array with gray relational analysis. He found the optimum levels of the process parameters to attain maximum tensile strength and minimum power consumption [6]. The effect of FSW parameters such as spindle rotational speed, traverse speed, and stirrer geometry on ultimate tensile strength (UTS) and hardness of welded joint [7]. The tensile strength of the welded joint is higher than the parent material and it is directly proportional to the welding speed, welding parameter such as tool rotation, transverse speed and axial force is also effect the welded joint in friction stir welding [8-13]. The investigated of mechanical properties and the microstructure of the welded zone using different tool pin profiles and diameters have been done. The welded sample is made from AA2218-T72 aluminum alloy

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sheet of 3.8 mm thickness. It was deducted that the sample used in the experiment can be successfully welded using a threaded, cylindrical 5-mm diameter pin, at 900 rpm and a welding speed of 0.03 m/min [14].

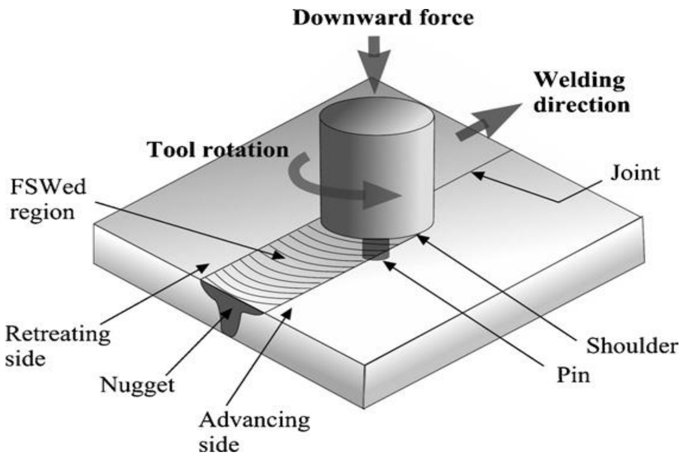



*Figure 1: The friction stir welding proces*

The hardness and strength of the FSW joint were investigated under different rotational and transverse tool speeds. In the experiment, the FSW was applied to join two pieces made of different aluminum alloys (i.e., AA 5383 and AA7075). The study showed that using 700 rpm as the rotational speed and 40 mm/min as the transverse speed produced the best hardness and strength of materials of the welded region [15]. The effect of FSW welding parameters on the tensile strength of butt joints made of AA7039 aluminum alloys using Taguchi parametric design approach have been studied [16]. The hardness and ultimate tensile strength of bimetallic weld joint was increases by increasing the pre-stresses, and by increasing the thermal loading ductility was decreases. To avoid the brittle failure, the value of thermal stress and pre stress should take low as possible. At plastic range, the shape of stress strain curve of stainless steel is higher than the carbon steel [17-19]. The influence of friction stir welding parameters such as tool rotational speed, welding speed and tool pin diameter on tensile strength of friction stir welded dissimilar AA2024 and AA6061 joint have been investigated. Experiments are designed with three factors and three levels Box–Behnken matrix by using RSM. FSW parameters such as traverse speed 28 mm/min, tool rotational speed of 710 rpm and tool pin diameter of 5 mm yield the maximum tensile strength of 163.76 MPa [20].

In this work, the effect of tool rotational speed, traverse speed and tilt angle on mechanical properties of friction stir welded joint of AA2024 and AA5052 have been investigated. There are 20 experiments were performed as per center composite design (CCD) approach of RSM. The experiments were carried out to observe tensile strength, percentage elongation and micro-hardness of FSWed joints. The quadratic regression mathematical model was developed to establish a relation between inputs and outputs responses.

## 2. Materials and Methods

### 2.1 Chemical composition and mechanical properties of the base materials

In this present study, experimental work was conducted on dissimilar aluminum alloy AA5052 and AA2024 plates of 6 mm thickness. These aluminum alloys were fabricated by friction stir welding. The chemical composition and mechanical properties of parent material of the dissimilar aluminum alloys as shown in table 1 and 2.

***Table 1.*** *Chemical composition of AA5052 and AA2024 Al-alloy*

| Material | Si | Cu | Fe | Zn | Mg | Mn | Cr | Al |
|---|---|---|---|---|---|---|---|---|
| AA5052 | 0.13 | 0.01 | 0.3 | 0.03 | 2.5 | 0.05 | 0.2 | Bal. |
| AA2024 | 0.5 | 4.4 | 0.5 | 0.25 | 1.5 | 0.6 | 0.1 | Bal. |

***Table 1.*** *Mechanical properties of AA5052 and AA2024 Al-alloy*

| Material | UTS (MPa) | Yield Strength (MPa) | Elongation (%) | Hardness (HV) |
|---|---|---|---|---|
| AA5052 | 232 | 190 | 14 | 94 |
| AA2024 | 364 | 247 | 19 | 135 |

### 2.2 Experimental set up

The experimental set up consists of a Friction Stir Welding machine. The FSW machine has a rigid base, tool head, table, rotating spindle, horizontal and automated process control which favors the FSW process.

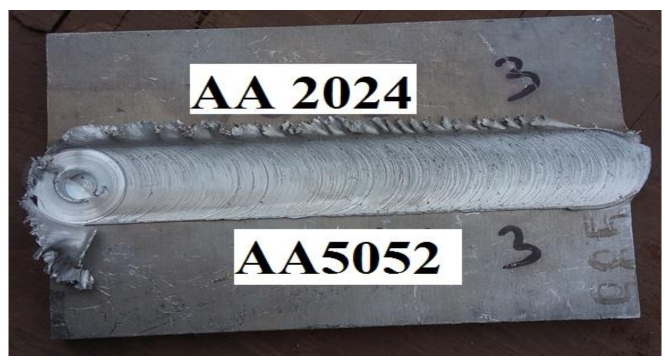



*Figure 2: Friction stir welded joint of AA5052 and AA2024*

*Figure 3: Friction stir welding tool of H13 tool steel*

Single pass butt welding procedure was used to fabricate the dissimilar AA5052 and AA2024 FSW joints in the plate's size of 120×80×6 mm as shown in fig. 2. Specially designed fixture was used to firmly hold the work piece against the axial force of rotating FSW tool. The input parameters range which are in FSw welded joint have been taken as rotational speed (1100 rpm to 1400 rpm), feed rate (40-70 mm/min) and tilt angles ($0^0$-$2^0$).

*2.3 Fabrication of FSW tools*

Variety of tool materials like high carbon high chromium steel, carbide and high speed steel were considered for fabricating the tool. After vast research, The non-consumable H13 steel tool with pin diameter, shoulder diameter and pin length of 7 mm, 19.5 mm, and 5.5 mm respectively was used is shown in fig. 3.

*2.4 Design of experiments*

Response surface methodology (RSM) is an interaction of mathematical and statistical techniques for modelling and optimizing the response variable models which several independent variables influence a dependent variable or response and the goal is to optimize the response. Experiments have been carried out according to the experimental plan based on central composite rotatable second-order design (CCD)matrix with the star points being at the center of each face of factorial space was used,. The upper limit of a factor was coded as +1, and the lower limit was coded as –1. The face-centered CCD involves 20 experimental observations at three independent input variables. The experimental Friction stir welding parameters and their levels in this study in the actual form is given in Table 3.

***Table 3:*** *Processing parameter of friction stir processing and its level*

| Parameters | Notation | Range | Levels | | |
|---|---|---|---|---|---|
| | | | -1. | 0. | 1. |
| Tool rotational Speed (rpm) | A | 1100-1400 | 1100 | 1250 | 1400 |
| Traverse Speed (mm/min) | B | 40-70 | 40 | 55 | 70 |
| Tilt angle (degree) | C | 0-2 | 0 | 1 | 2 |

*Table 4: Friction stir welding parameters and their output responses*

| S.No | A:Tool Rotational Speed (rpm) | B:Travere Speed (mm/min) | C:Tilt Angle(degree) | Tensile Strength (MPa) | Elongation (%) | Micro-hardness (HV) |
|---|---|---|---|---|---|---|
| 1 | 1250 | 55 | 1 | 173 | 8.16 | 62 |
| 2 | 1400 | 55 | 1 | 180 | 8.5 | 68 |
| 3 | 1250 | 55 | 1 | 179 | 8.4 | 65 |
| 4 | 1250 | 55 | 1 | 194 | 9.1 | 70 |
| 5 | 1250 | 40 | 1 | 172 | 8.1 | 60 |
| 6 | 1400 | 70 | 0 | 187 | 8.8 | 65 |
| 7 | 1400 | 40 | 0 | 244 | 9.4 | 73 |
| 8 | 1400 | 40 | 2 | 248 | 11 | 88 |
| 9 | 1100 | 70 | 0 | 252 | 14.5 | 112 |
| 10 | 1100 | 55 | 1 | 244 | 11.5 | 105 |
| 11 | 1250 | 55 | 0 | 201 | 9.5 | 73 |
| 12 | 1100 | 40 | 0 | 244 | 14.5 | 89 |
| 13 | 1100 | 70 | 2 | 295 | 15.8 | 98 |
| 14 | 1400 | 70 | 2 | 298 | 17.6 | 105 |
| 15 | 1250 | 55 | 1 | 230 | 10.8 | 85 |
| 16 | 1250 | 70 | 1 | 205 | 9.76 | 76 |
| 17 | 1250 | 55 | 1 | 231 | 10.9 | 86 |
| 18 | 1250 | 55 | 1 | 242 | 11.4 | 92 |
| 19 | 1250 | 55 | 2 | 225 | 10.6 | 82 |
| 20 | 1100 | 40 | 2 | 195 | 7.5 | 56 |

## 3. Results and discussion

*3.1 Developing the mathematical model*

The adequacy of the developed empirical relationship for the response variables tensile strength, elongation and micro-hardness were tested using the analysis of variance (ANOVA) technique [21]. The experimental FSW parameters and their levels in this study in the actual form is given in Table 3. The fit summary reveals that the fitted quadratic model is statistically significant to analyze the response variables. It is found that the calculated F ratios are larger than the tabulated values at a 95% confidence level. The value which are less than 0.05 are considered significant and the values greater than 0.05 are not significant and the model is adequate to represent the relationship between machining response and the machining parameters. The mathematical regression model equations are developed using RSM approach for process responses. Regression equations in coded values of process parameters are written in equations 1, 2, and 3 for UTS, % elongation and micro-hardness respectively.

$$\text{Tensile strength} = 1454.8 - 2.17A + 8.26B - 248.67C - 0.006\,AB + 0.10BC + 1.66AC + 0.0009\,A^2 - 0.009\,B^2 + 22.4\,C^2 \quad (1)$$

$$\text{Elongation} = 119.43 - 0.155A + 0.026B - 25.98C - 0.0001\,AB + 0.0134BC + 0.129AC + 0.00006\,A^2 - 0.001\,B^2 + 1.345\,C^2 \quad (2)$$

$$\text{Micro-hardness} = 787.56 - 1.33A + 7.1B - 131.53C - 0.003\,AB + 0.085BC + 0.367AC + 0.0055\,A^2 - 0.027\,B^2 + 3.4\,C^2 \quad (3)$$

Tool rotational speed is most significant term followed by B, C, AB, AC, $A^2$, $B^2$, and $C^2$. In FSW process, the work-piece is subjected to different thermal cycles and cooling rate in addition to plastic deformation, which resulted in variation of joint properties. The variation in thermal cycle also causes the dissolution, formation, and coarsening of strengthening precipitates in the nugget zone.

*Table 5: ANOVA test results for tensile strength*

| Source | Sum of Squares | df | Mean Square | F-value | p-value | |
|---|---|---|---|---|---|---|
| Model | 19642.39 | 9 | 2182.49 | 3.11 | 0.0046 | significant |
| A-Tool Rotational Speed | 532.9 | 1 | 532.9 | 0.7584 | 0.4042 | |
| B-Traverse Speed | 1795.6 | 1 | 1795.6 | 2.56 | 0.141 | |
| C-Tilt Angle | 1768.9 | 1 | 1768.9 | 2.52 | 0.1437 | |
| AB | 1653.13 | 1 | 1653.13 | 2.35 | 0.1561 | |
| AC | 1830.13 | 1 | 1830.13 | 2.6 | 0.1376 | |
| BC | 4950.13 | 1 | 4950.13 | 7.04 | 0.0241 | |
| $A^2$ | 1255.11 | 1 | 1255.11 | 1.79 | 0.211 | |
| $B^2$ | 12.55 | 1 | 12.55 | 0.0179 | 0.8963 | |
| $C^2$ | 1375.36 | 1 | 1375.36 | 1.96 | 0.192 | |
| Residual | 7026.56 | 10 | 702.66 | | | |
| Lack of Fit | 2595.73 | 5 | 519.15 | 0.5858 | 0.7142 | not significant |
| Pure Error | 4430.83 | 5 | 886.17 | | | |
| Cor Total | 26668.95 | 19 | | | | |

*Table 6: ANOVA test results for % elongation*

| Source | Sum of Squares | df | Mean Square | F-value | p-value | |
|---|---|---|---|---|---|---|
| Model | 130.88 | 9 | 14.54 | 8.81 | 0.0011 | significant |
| A-Tool Rotational Speed | 7.22 | 1 | 7.22 | 4.38 | 0.0628 | |
| B-Travere Speed | 25.47 | 1 | 25.47 | 15.44 | 0.0028 | |
| C-Tilt Angle | 3.36 | 1 | 3.36 | 2.04 | 0.1838 | |
| AB | 0.6612 | 1 | 0.6612 | 0.4008 | 0.5409 | |
| AC | 32.4 | 1 | 32.4 | 19.64 | 0.0013 | |
| BC | 30.03 | 1 | 30.03 | 18.2 | 0.0016 | |
| $A^2$ | 4.62 | 1 | 4.62 | 2.8 | 0.1254 | |
| $B^2$ | 0.1398 | 1 | 0.1398 | 0.0847 | 0.7769 | |
| $C^2$ | 4.98 | 1 | 4.98 | 3.02 | 0.113 | |
| Residual | 16.5 | 10 | 1.65 | | | |
| Lack of Fit | 6.59 | 5 | 1.32 | 0.6649 | 0.6674 | not significant |
| Pure Error | 9.91 | 5 | 1.98 | | | |
| Cor Total | 147.38 | 19 | | | | |

*Table 7: ANOVA test results for Micro-hardness*

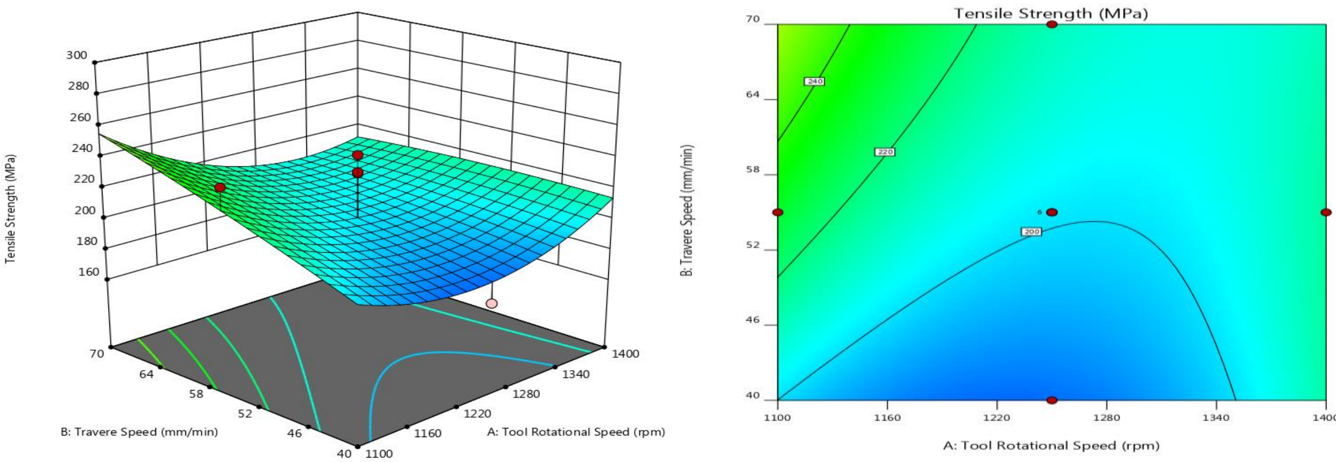
| Source | Sum of Squares | df | Mean Square | F-value | p-value | |
|---|---|---|---|---|---|---|
| Model | 3834.77 | 9 | 426.09 | 3.49 | 0.00322 | significant |
| A-Tool Rotational Speed | 372.1 | 1 | 372.1 | 3.05 | 0.1114 | |
| B-Travere Speed | 810 | 1 | 810 | 6.64 | 0.0276 | |
| C-Tilt Angle | 28.9 | 1 | 28.9 | 0.2368 | 0.637 | |
| AB | 392 | 1 | 392 | 3.21 | 0.1033 | |
| AC | 1300.5 | 1 | 1300.5 | 10.66 | 0.0085 | |
| BC | 242 | 1 | 242 | 1.98 | 0.1894 | |
| $A^2$ | 423.46 | 1 | 423.46 | 3.47 | 0.0921 | |
| $B^2$ | 102.02 | 1 | 102.02 | 0.8361 | 0.382 | |
| $C^2$ | 31.96 | 1 | 31.96 | 0.2619 | 0.6199 | |
| Residual | 1220.23 | 10 | 122.02 | | | |
| Lack of Fit | 432.89 | 5 | 86.58 | 0.5498 | 0.7363 | not significant |
| Pure Error | 787.33 | 5 | 157.47 | | | |
| Cor Total | 5055 | 19 | | | | |

The purpose of ANOVA is to evaluate the significance of process parameters for variation of responses. The ANOVA results for tensile strength, % elongation and micro-hardness are shown in table 5, 6 and 7, respectively. The F-value of model is calculated by dividing the mean square value of model to the mean square values of residuals. The F-values test was accomplished by investigating a correlation of the model variance with the residual variance. When the values of variances are almost identical, fraction will be near unity and it is not estimated that the model has significant effect on the outcomes. The developed models have F-values of 3.11, 8.81 and 3.49 for tensile strength, % elongation and micro-hardness respectively and a P-value of less than 0.01. Table 5-7 reveals that the models are significant with including significant term that affects the outcomes. In the current study, the adequacy of the model is check with 95% confidence level. A, B, C, AB, BC, AC, $A^2$ , $B^2$ , and $C^2$ are the most significant terms available in the model for the tensile strength, % elongation and micro-hardness. The p-value higher than 0.05 reveals the insignificance of model term. The lack of fit F-value is 0.58, 0.66 and 0.549 for tensile strength, % elongation and micro-hardness respectively as shown in table 5-7, which is insignificant correlation with pure error. The lack of fit occurring possibilities is 0.7142, 0.6649, and 0.5498 for tensile strength, % elongation and micro-hardness respectively which is due to noise.

This insignificant lack of fit makes the developed models orthodox. The determination coefficient ($R^2$) for tensile strength, % elongation and micro-hardness are 73.65%, 88.8% and 75.86% respectively as shown in Table 8. Higher value of $R^2$ simplifies the exactness between the response model and experimental outcomes. The values of $R^2$ moving towards 1 show less variation between experimental and estimated values. However, the values of R should not be sufficient for the adequacy of the developed model. Thus, remaining properties such as adjusted $R^2$, predicted $R^2$ and adequate precision are also considered for the adequacy of the model.

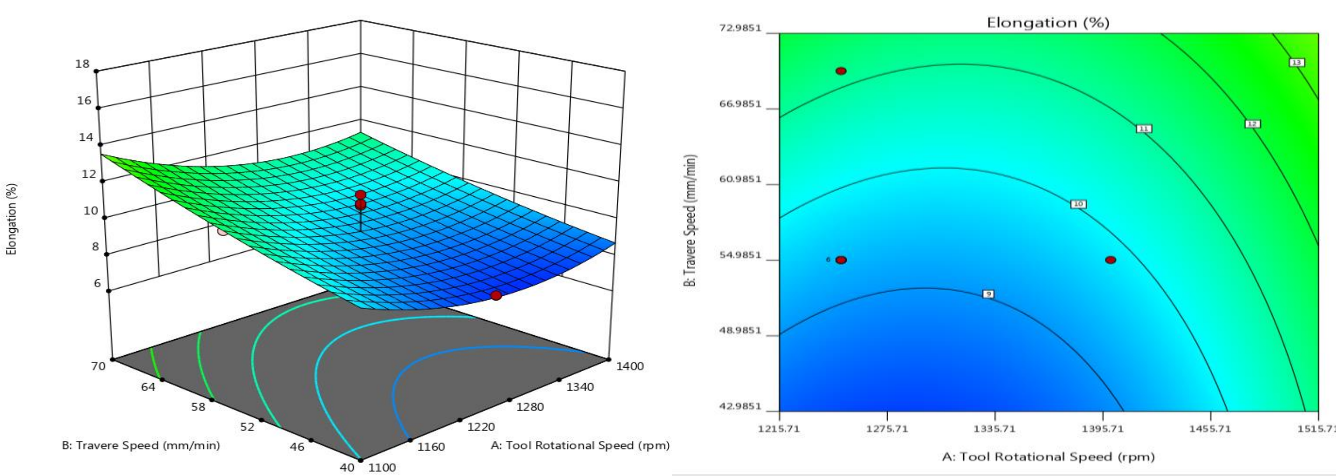
*Table 8: $R^2$ value for tensile strength, % elongation and micro-hardness*

| Value of $R^2$ | Std Dev | Mean | C.V (%) | $R^2$ | Adj $R^2$ | Predicted $R^2$ | Adeq Precision |
|---|---|---|---|---|---|---|---|
| Tensile Strength | 26.51 | 221.95 | 11.94 | 0.7365 | 0.4994 | 0.1508 | 6.3861 |
| % Elongation | 1.28 | 10.79 | 11.90 | 0.888 | 0.7873 | 0.6457 | 10.34 |
| Micro-hardness | 11.05 | 80.50 | 13.72 | 0.7586 | 0.5414 | 0.1366 | 6.9262% |



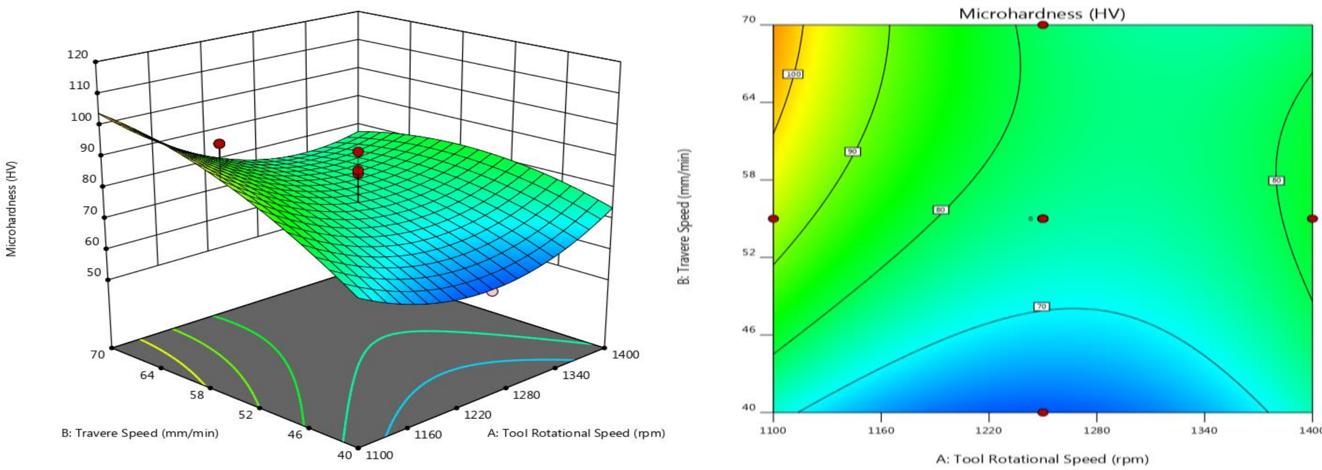

(a) (b)

*Figure 4: Effect of tool rotational speed and traverse speed on tensile strength of friction stir welded joint*




(a) (b)

*Figure 5: Effect of tool rotational speed and traverse speed on % elongation of friction stir welded joint*




(a) (b)

*Figure 6: Effect of tool rotational speed and traverse speed on micro-hardness of friction stir welded joint*

The 3D surface and contour for tensile strength, % elongation and micro-hardness of friction stir welded joint of AA2024 and AA5052 as shown in fig. (4-6), these figures provides the response surface and shows the change of output responses while each FSW parameters moves from the reference value. Fig. (4-6) illustrates the counter plots representing the interaction effect of any two input parameters on the tensile strength, % elongation and micro-hardness where the other parameters are on their center level. The increase in tool rotational speed and traverse speed results in the increase the tensile strength, whereas when decrease in traverse speed results in the increase the tensile strength. He maximum tensile strength (298 MPa) was found at tool rotation 1400 rpm, 70 mm/min and $2^0$ tilt angle.

The optimized input parameters were found as tool rotational speed 1111 rpm, traverse speed 61.74 and tilt angle $1.234^0$ and optimized output response were found as tensile strength of 241.31 MPa, % elongation of 12.10, and micro-hardness of 95.94 HV as shown in fig. 7

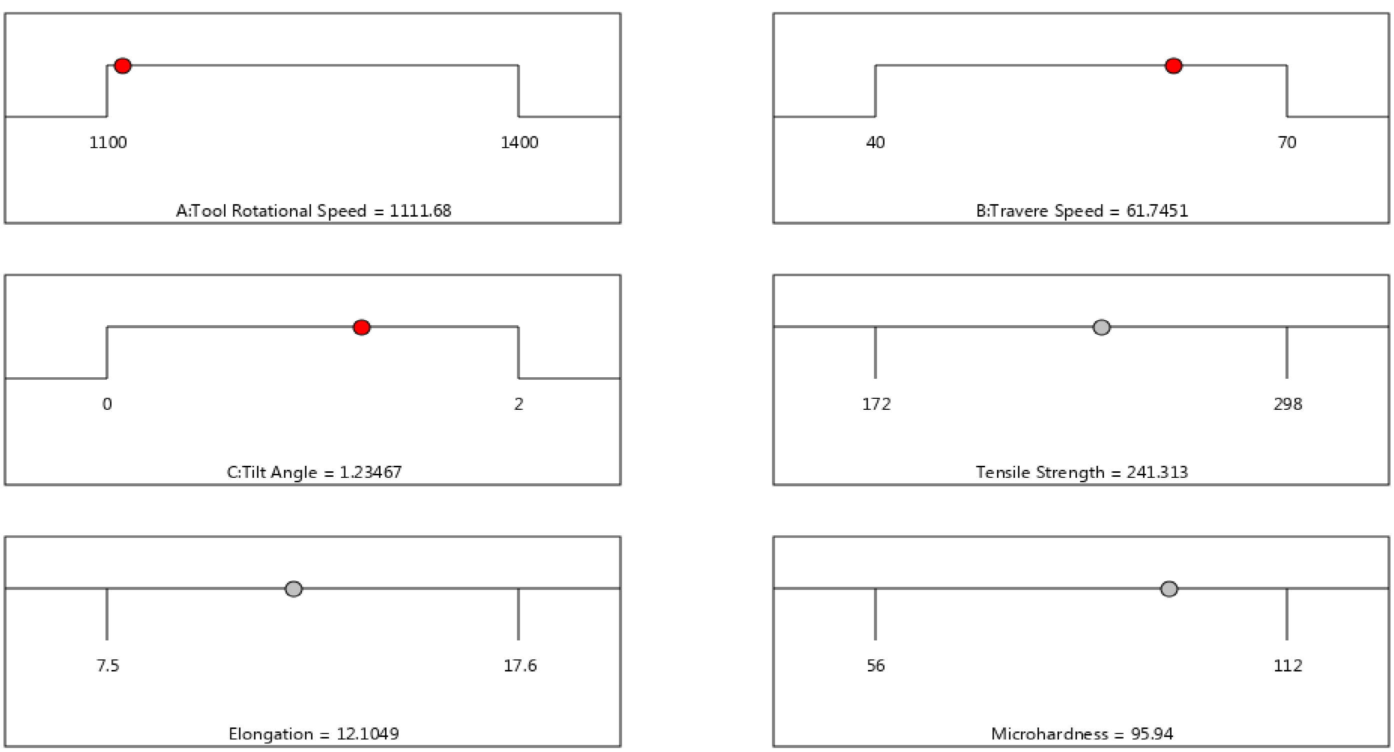



*Figure 7: Ramp functiion graph for input parameter and Multi response optimization*

## 4. Conclusions

The following conclusion are made from the above investigation.

- Mathematical empirical relationship were developed to estimate the Ultimate tensile strength, % elongation and micro-hardness of friction stir welded joint of AA5052 and AA2024.
- The ANOVA analysis showed that the developed model can be effectively used to predict the tensile strength, % elongation and micro-hardness of welded joint at 95% confidence level.
- The mechanical properties of welded joints increased with increase of tool rotational speed, welding speed and tilt angle.
- The maximum tensile strength of 298 MPa, % elongation of 17.6 were found at 1400 rpm, 70 mm/min and $2^0$ tilt angle, whereas maximum micro-hardness of 112 HV was found at 1100 rpm, 70 mm/min and $0^0$.
- The optimized input parameters were found as tool rotational speed 1111 rpm, traverse speed 61.74 and tilt angle $1.234^0$ and optimized output response were found as tensile strength of 241.31 MPa, % elongation of 12.10, and micro-hardness of 95.94 HV

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