ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20210605063515
Original scientific paper

# Multi-Response Optimization of FSW Parameters for Dissimilar Al-Mg Alloys

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**Abstract:** In this research, friction stir welding of dissimilar Aluminium alloy-AA6061 and magnesium alloy-AZ31B is performed by varying the process parameter such as Rotational speed, welding speed and tool tilt angle. The main objective of the research is to optimize the FSW process parameter for achieving high tensile strength and hardness of welded joints. The experiment is designed according to RSM-face centered central composite design techniques by varying process parameters. The regression equation is developed based on the result of the FSW experiment. ANOVA is used to validate the developed regression model and to identify the influences of process parameters on tensile strength and hardness of welded joints. The desirability approach is a statistical method for solving multiple response optimization. The optimum process parameters for high tensile strength and hardness are $S_R$ = 1000 rpm, $S_W$ = 20 mm/min, $T_A$ = 2 deg. The confirmatory test is performed for optimal setting and results are also acceptable with prediction.

**Keywords:** aluminium alloy-AA6061; dissimilar friction stir welding; magnesium alloy AZ31B; RSM; tensile strength; Vicker's hardness

## 1 INTRODUCTION

FSW is a solid-state welding process. It allows for the joining of similar and dissimilar nonferrous alloys. The welding institute developed the friction stir welding process in 1991 at UK [1]. In this process, a non-consumable rotating tool with a pin is allowed to rotate and plunge at the interface of workpieces. The tool is then allowed to move through the interface, causing the material to heat up and soften due to frictional heat. The softened material is then mechanically mixed by the rotating tool to form a solid-state bond. The advantages of FSW over traditional fusion welding processes has resulted in major benefits in aerospace, shipbuilding, automobile, rail, and other industries. Later many researchers conducted research on various factors such as tool geometry, welding equipment, and other process parameters to assess the welded joint's strength [2-4]. The primary focus of tool design is the tool shoulder and pin geometry, which affect the flow of materials.

The welding configuration, the material and thickness of the workpieces, and the type of welding are important factors in the selection of the tool material and dimension. Machine parameters and tool design are primarily responsible for the joint's ultimate strength. Furthermore, the manufacturing precision of the backing plate and clamping system has an impact on joint strength in FSW. Before initiating the welding process, the backing plate and fixtures should be designed properly [5-8].

Magnesium and aluminium alloys are becoming more common as lightweight structural materials for automotive applications. Both aluminium alloys and magnesium alloys allow for greater design flexibility and have better mechanical properties [9]. Welding dissimilar alloys is a difficult process, particularly when the mechanical, thermal, and chemical behavior of the alloys are completely different such as aluminium alloys and magnesium alloys [10]. Many researchers conducted research on dissimilar FSW welding by various tool pin profiles and dimensions, by changing machining process parameters and backing plates to determine the quality of the welded joint [11, 12]

The design of experiments and statistical techniques will significantly improve efficiency and reduce the number of these experiments. Response surface methodology is a statistical and mathematical tool used in the design of experiments. The goal is to optimize the output responses that are influenced by several factors. RSM is being used by most researchers to configure process parameters and to build a regression model to predict a response [13-15].

The main objective of the research is to optimize the FSW process parameter for achieving high tensile strength and hardness of welded joints. The response surface methodology (RSM) - Central composite design technique was used to analyse the impact of machine parameters (rotation speed, tool tilt angle and welding speeds) on tensile properties and hardness of dissimilar Al/Mg weld. ANOVA (Analysis of Variances) is used to validate the result and to calculate percentage contribution of each parameter. The desirability approaches are employed to optimize the multiple response.

## 2 EXPERIMENT DETAIL

Magnesium-AZ31B alloy and aluminium-AA6061 alloy plate were used for butt joints. The plate had a nominal thickness of 4 mm.

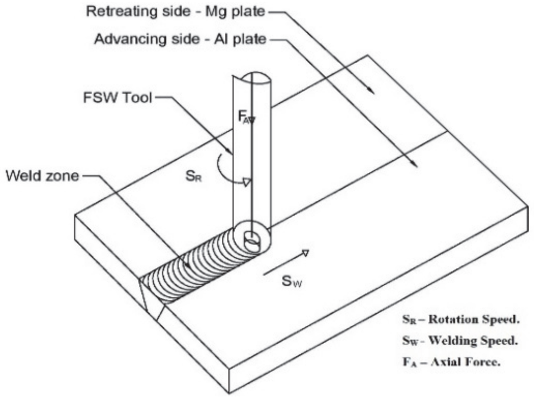

**Figure 1** Friction stir welding process, [12]

These materials were placed on a high-powered vertical milling machine unit, with Al plate on the advancing side and Mg plate on the retreating side. On the advancing side, the rotational tool was inserted at a 1 mm offset from the butt baseline, as shown in Fig. 2.

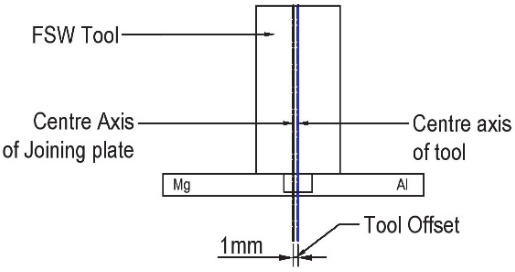

**Figure 2** Tool offset

WC Tool was used to make the FSW tool. The diameter of shoulder and the probe of tool are 18 mm and 6 mm respectively and the length of probe is 3.8 mm.

**Table 1** Chemical Composition of Material

| Workpieces | AA6061 | AZ31B |
|---|---|---|
| | wt. % | wt. % |
| Al | Balance | 3 |
| Mn | 0.01 | 0.2 |
| Zn | 0.06 | 1 |
| Fe | 0.4 | 0.005 |
| Cu | 0.24 | 0.05 |
| Cr | 0.18 | - |
| Si | 0.54 | 0.1 |
| Ni | - | 0.005 |
| Mg | 0.84 | Balance |

The RSM's CCD techniques were employed to design the experiment. The central composite design consists of 20 sets of experiments for three different input parameters with three levels [3, 16]. The experimental friction stir welding parameters are shown in Tab. 2.

**Table 2** Three level of process parameter

| S. No | Parameters | –1 | 0 | 1 |
|---|---|---|---|---|
| 1 | Rotation speed - $S_R$ / rpm | 600 | 800 | 1000 |
| 2 | Traverse speed - $S_W$ / mm/min | 20 | 40 | 60 |
| 3 | Tool tilt angle- $T_A$ / deg | 0 | 1 | 2 |

The tensile properties and hardness of FSW joints are influenced by welding speed, rotation speed and tilt angle and it can be expressed in Eq. (1).

$$Y = f(S_R, S_W, T_A) \tag{1}$$

It provides a mathematical model that shows the dependence of the tensile strength and hardness of the joint on the process parameter. This model can be used to calculate the hardness and tensile strength of joints within a selected range of the process parameter.

Tensile specimens were produced based on ASTM-E8M-04 standards to determine the tensile properties of the joints using the UTM machine. The hardness of welded joint is evaluated using Vicker's hardness tester.

## 3 RESULTS AND DISCUSSION

The experiments are carried out for 20sets of different parameter designed according to RSM-Central Composite Techniques. The tensile strength of dissimilar FSWed Al/Mg alloy is evaluated by using a universal testing machine. The hardness at the welded joint is observed by using Vicker's hardness test.

The result of tensile strength and hardness of the dissimilar FSWed Aluminium and magnesium alloys is shown in the table. The linear regression equation is developed based on the results of the FSW experiment of dissimilar Al/Mg alloys.

The Regression Equations of Ultimate Tensile Strength (*UTS*), Yield strength *YS*, percentage of elongation (%*E*) and Vicker's hardness (*HV*) of dissimilar FSW of aluminium and magnesium alloy are shown in Eqs. (2) to (5) where $S_R$ is rotational speed, $S_W$ is welding speed and $T_A$ is tool tilt angle.

$$UTS = 120.41 + 0.0312 \times S_R - 0.402 \times S_W + 5.2 \times T_A \tag{2}$$

$$YS = 105.88 + 0.03623 \times S_R - 0.2808 \times S_W + 4.005 \times T_A \tag{3}$$

$$\%E = 4.025 - 0.0015 \times S_R - 0.0375 \times S_W + 0.5 \times T_A \tag{4}$$

$$HV = 78.97 + 0.0284 \times S_R - 0.1975 \times S_W - 4.75 \times T_A \tag{5}$$

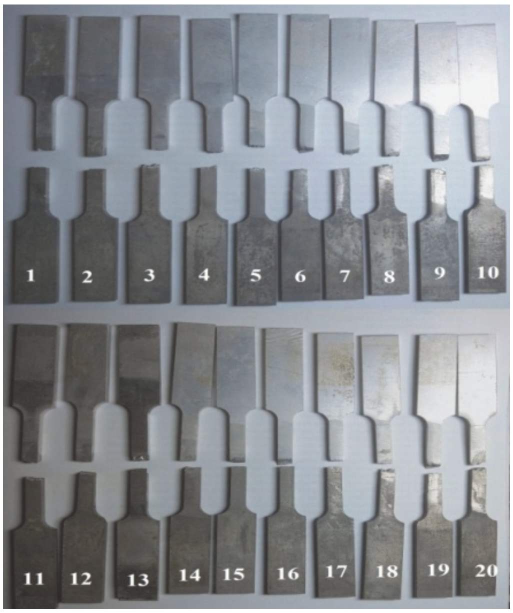

**Figure 3** Tensile test specimen

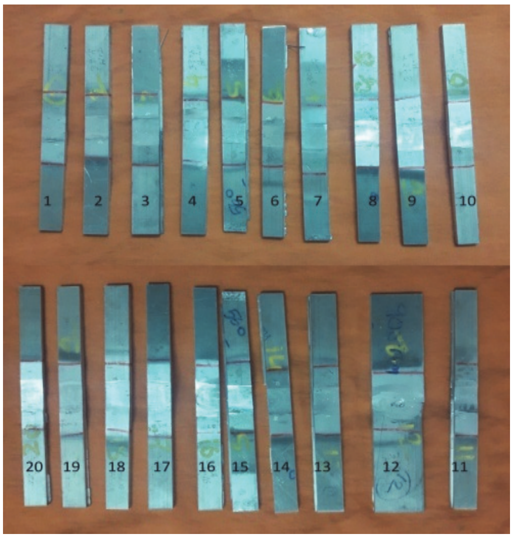

**Figure 4** Hardness tested specimens

**Table 3** Result of FSW experiment

| | Input parameters | | | Output responses | | | |
|---|---|---|---|---|---|---|---|
| Ex. no. | $S_R$ | $S_W$ | $T_A$ | Tensile strength | | | Vicker's hardness |
| # | rpm | mm/min | deg | *UTS* / MPa | *YS* / MPa | %*E* / % | *HV* |
| 1 | 600 | 20 | 0 | 129 | 118.65 | 1.75 | 95 |
| 2 | 600 | 20 | 2 | 142 | 131 | 2.5 | 81.5 |
| 3 | 800 | 20 | 1 | 137 | 122 | 2.5 | 95.2 |
| 4 | 1000 | 20 | 0 | 144.8 | 136.8 | 2.5 | 100.1 |
| 5 | 1000 | 20 | 2 | 159.6 | 145 | 3.5 | 96 |
| 6 | 600 | 40 | 1 | 133 | 123 | 1.5 | 80.5 |
| 7 | 800 | 40 | 0 | 133 | 130 | 1.5 | 95.2 |
| 8 | 800 | 40 | 2 | 137.2 | 128.2 | 2.5 | 82.1 |
| 9 | 800 | 40 | 1 | 136 | 128 | 2 | 90.6 |
| 10 | 800 | 40 | 1 | 137.5 | 130 | 1.5 | 86 |
| 11 | 800 | 40 | 1 | 134.5 | 128.5 | 2 | 91 |
| 12 | 800 | 40 | 1 | 134 | 125.5 | 2 | 86.9 |
| 13 | 800 | 40 | 1 | 129 | 123.6 | 2 | 90.5 |
| 14 | 800 | 40 | 1 | 131.2 | 127.2 | 1.5 | 85.3 |
| 15 | 1000 | 40 | 1 | 140 | 136 | 2.5 | 96.5 |
| 16 | 600 | 60 | 0 | 118 | 111 | 0.5 | 82.5 |
| 17 | 600 | 60 | 2 | 124 | 119 | 1.5 | 79 |
| 18 | 800 | 60 | 1 | 126 | 122 | 1 | 84.1 |
| 19 | 1000 | 60 | 0 | 125 | 124 | 0.5 | 98 |
| 20 | 1000 | 60 | 2 | 139 | 134.3 | 1.5 | 84.7 |

### 3.1 ANOVA Analysis

The ANOVA (Analysis of Variances) is used to test the effectiveness of the generated mathematical model [15]. ANOVA is also used to identify the effect of each factor (*RS*, *TS*, *TTA*) on the response (Hardness). The ANOVA table generated based on the results of the experiment is shown in Tabs. 4 to 7. The percentage of contributions of an individual factor was evaluated using Eq. (6).

$$\%C = \frac{SeqSS_{\text{factor}}}{SeqSS_{\text{total}}} \tag{6}$$

The percentages contributed by welding speed, rotation speed and tilt angle on *UTS*, *YS*, %*E* and *HV* are graphically represented in Fig. 5.

The Model *F*-value and *p*-value show that the model is adequate and satisfactory. Non-significant lack of fit results show that only a few chances of error occur due to noise.

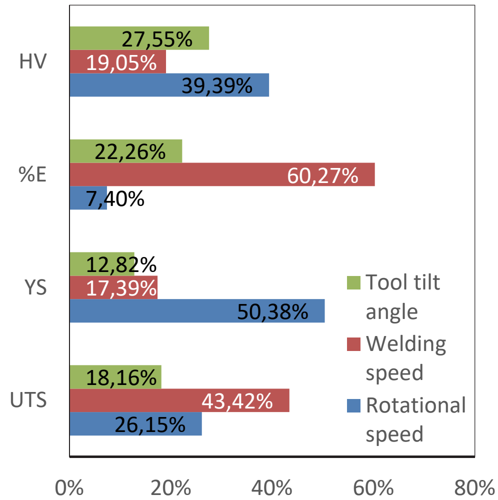

**Figure 5** Percentages contributed by rotational speed, welding speed and tool tilt angle on *UTS*, *YS*, %*E* and *HV*

**Table 4** ANOVA table for *UTS*

| Source | *DF* | Seq *SS* | Contribution | Adj *SS* | Adj *MS* | *F*-value | *p*-value |
|---|---|---|---|---|---|---|---|
| Model | 3 | 1306.19 | 87.74% | 1306.19 | 435.397 | 38.15 | <0.001 |
| $S_R$ | 1 | 389.38 | 26.15% | 389.38 | 389.376 | 34.12 | <0.001 |
| $S_W$ | 1 | 646.42 | 43.42% | 646.42 | 646.416 | 56.65 | <0.001 |
| $T_A$ | 1 | 270.4 | 18.16% | 270.4 | 270.4 | 23.7 | <0.001 |
| Error | 16 | 182.59 | 12.26% | 182.59 | 11.412 | | |
| LackofFit | 11 | 133.79 | 8.99% | 133.79 | 12.162 | 1.25 | 0.429 |
| Pure Error | 5 | 48.8 | 3.28% | 48.8 | 9.76 | | |
| Total | 19 | 1488.78 | 100.00% | | | | |

**DF* - degree of freedom, Seq *SS* - Sequential Sum of square, Adj *SS* - Adjusted Sum of square, Adj *MS* - Adjusted Mean sum of square, $S_R$ - Rotational speed, $S_W$ - Traverse speed, $T_A$ - Tilt angle

**Table 5** ANOVA table for *YS*

| Source | *DF* | Seq *SS* | Contribution | Adj *SS* | Adj *MS* | *F*-value | *p*-value |
|---|---|---|---|---|---|---|---|
| Model | 3 | 862.95 | 80.58% | 862.95 | 287.651 | 22.13 | <0.001 |
| $S_R$ | 1 | 539.49 | 50.38% | 539.49 | 539.49 | 41.51 | <0.001 |
| $S_W$ | 1 | 186.19 | 17.39% | 186.19 | 186.192 | 14.33 | 0.002 |
| $T_A$ | 1 | 137.27 | 12.82% | 137.27 | 137.27 | 10.56 | 0.005 |
| Error | 16 | 207.94 | 19.42% | 207.94 | 12.996 | | |
| Lack-of-Fit | 11 | 181.94 | 16.99% | 181.94 | 16.54 | 3.18 | 0.106 |
| Pure Error | 5 | 25.99 | 2.43% | 25.99 | 5.199 | | |
| Total | 19 | 1070.89 | 100.00% | | | | |

ANOVA result shows that the regression model is valid. The rotation speed and welding speed are the most important process parameters in determining ultimate tensile strength and yield strength are rotation speed and welding speed. Tilt angle and welding speed are an important parameter in determining the hardness of welded joint. It shows both hardness and tensile strength of the joint are highly dependent on rotation speed followed by welding speed and then tool tilt angle.

**Table 6** ANOVA table for %*E*

| Source | *DF* | Seq *SS* | Contribution | Adj *SS* | Adj *MS* | *F*-value | *p*-value |
|---|---|---|---|---|---|---|---|
| Model | 3 | 9.0202 | 89.93% | 9.0202 | 3.00673 | 47.61 | <0.001 |
| $S_R$ | 1 | 0.7426 | 7.40% | 0.7426 | 0.74256 | 11.76 | 0.003 |
| $S_W$ | 1 | 6.0451 | 60.27% | 6.0451 | 6.04506 | 95.72 | <0.001 |
| $T_A$ | 1 | 2.2326 | 22.26% | 2.2326 | 2.23256 | 35.35 | <0.001 |
| Error | 16 | 1.0104 | 10.07% | 1.0104 | 0.06315 | | |
| Lack-of-Fit | 11 | 0.6771 | 6.75% | 0.6771 | 0.06155 | 0.92 | 0.579 |
| Pure Error | 5 | 0.3333 | 3.32% | 0.3333 | 0.06667 | | |
| Total | 19 | 10.0306 | 100.00% | | | | |

**Table 7** ANOVA table for hardness

| Source | *DF* | Seq *SS* | Contribution | Adj *SS* | Adj *MS* | *F*-value | *p*-value |
|---|---|---|---|---|---|---|---|
| Model | 3 | 704.27 | 85.98% | 704.27 | 234.758 | 32.72 | <0.001 |
| $S_R$ | 1 | 322.62 | 39.39% | 322.62 | 322.624 | 44.96 | <0.001 |
| $S_W$ | 1 | 156.03 | 19.05% | 156.02 | 156.025 | 21.74 | <0.001 |
| $T_A$ | 1 | 225.63 | 27.55% | 225.63 | 225.625 | 31.44 | <0.001 |
| Error | 16 | 114.81 | 14.02% | 114.81 | 7.176 | | |
| Lack-of-Fit | 11 | 81.18 | 9.91% | 81.18 | 7.38 | 1.1 | 0.492 |
| Pure Error | 5 | 33.63 | 4.11% | 33.63 | 6.726 | | |
| Total | 19 | 819.09 | 100.00% | | | | |

## 4 EFFECTS OF PROCESS PARAMETER ON TENSILE STRENGTH AND HARDNESS

### 4.1 Ultimate Tensile Strength

The experiment results reveal that ultimate tensile strength is higher at low welding speed and high rotation speed. The mean effective plot of the UTS vs process parameter is shown in Fig. 5. The graph clearly shows that higher UTS is achievable at a rotation speed of 1000 rpm, tilt angle of 2 deg and welding speed of 20 mm/min.

The highest value of ultimate tensile strength is achieved by the experiment is 159 MPa. The UTS is highly influenced by rotation speed followed by welding speed and tool tilt angle.

### 4.2 Yield Strength

The yield strength is higher at low welding speed and high rotation speed and tilt angle. The mean effective plot of the YS vs process parameter is shown in Fig. 6. The graph clearly shows that higher YS is achievable at a rotation speed of 1000 rpm, tool tilt angle of 2 deg. and welding speed of 20 mm/min

The highest value of yield tensile strength achieved by the experiment is 145 MPa. The YS is highly influenced by rotation speed followed by tool tilt angle and welding speed.

### 4.3 Elongation

The percentage of elongation is higher at low welding speed and high tilt angle and rotation speed. The mean effective plot of the percentage of elongation vs process parameter is shown in Fig. 7. The graph clearly shows that a higher percentage of elongation is achievable at a rotation speed of 1000 rpm, tilt angle of 2 deg and welding speed of 20 mm/min.

The highest value of the percentage of elongation achieved in the experiment is 3.5%. The percentage of elongation is highly influenced by welding speed followed by rotation speed and tilt angle.

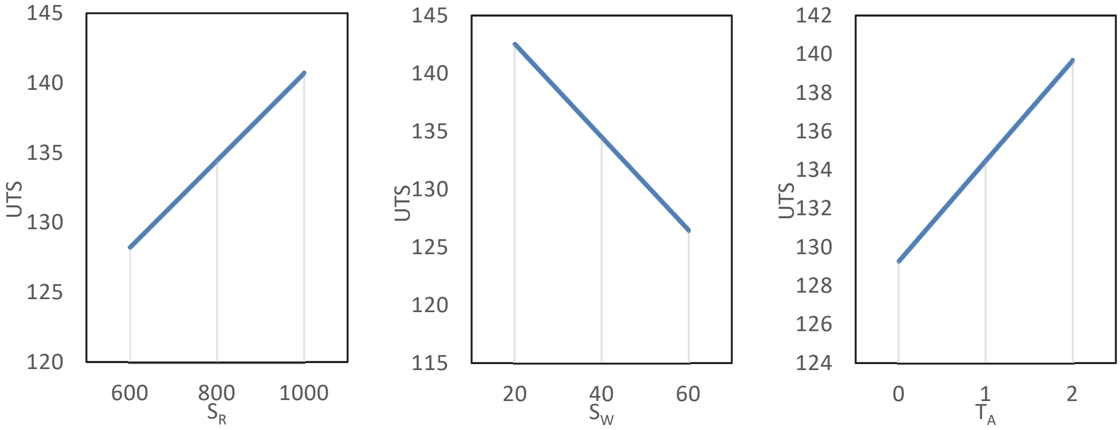

**Figure 6** Mean effective plot of *UTS* vs process parameter

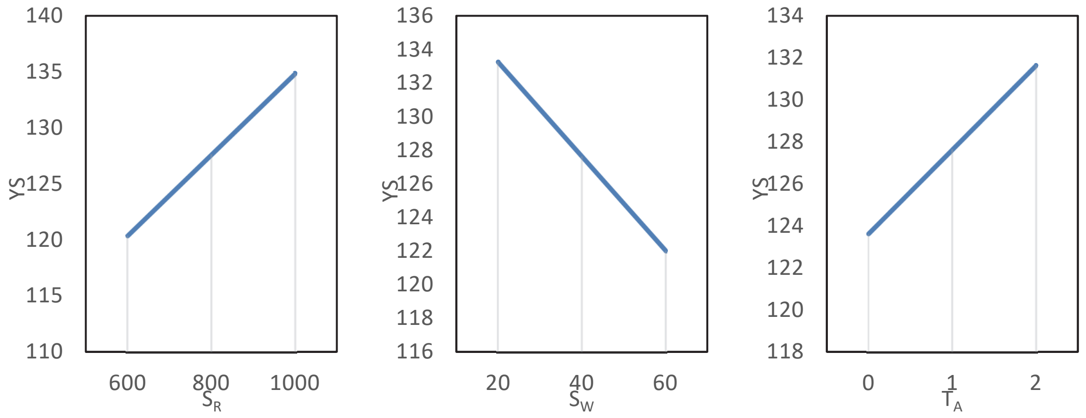

**Figure 7** Mean effective plot of *YS* vs process parameter

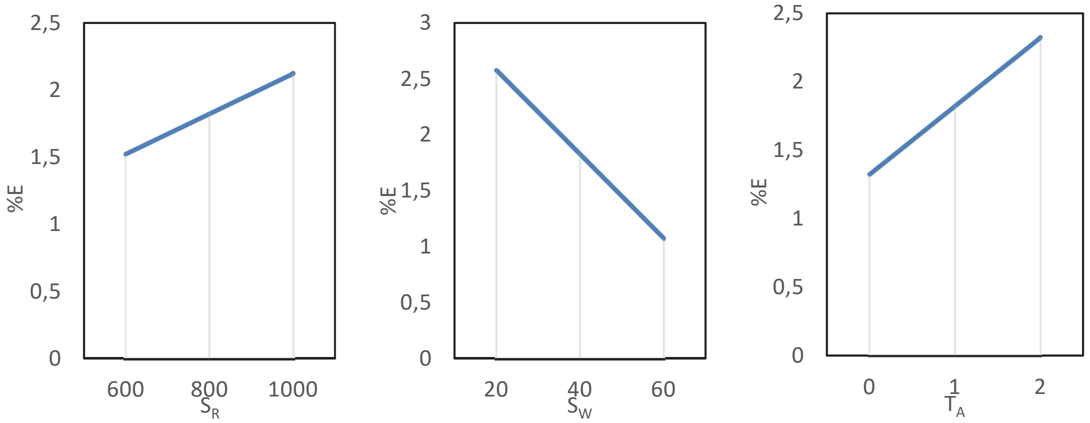

**Figure 8** Mean effective plot of %*E* vs process parameter

### 4.4 Hardness

The hardness of welded joint is higher at high rotation speed and low welding speed. The mean effective plot of hardness vs. process parameter is shown in Fig. 8. The graph clearly shows that higher hardness is achievable at a rotation speed of 1000 rpm, tilt angle of 0 deg and welding speed of 20 mm/min.

The highest value of hardness is achieved by the experiment is 101 HV. The HV is highly influenced by rotational speed followed by tool tilt angle and welding speed.

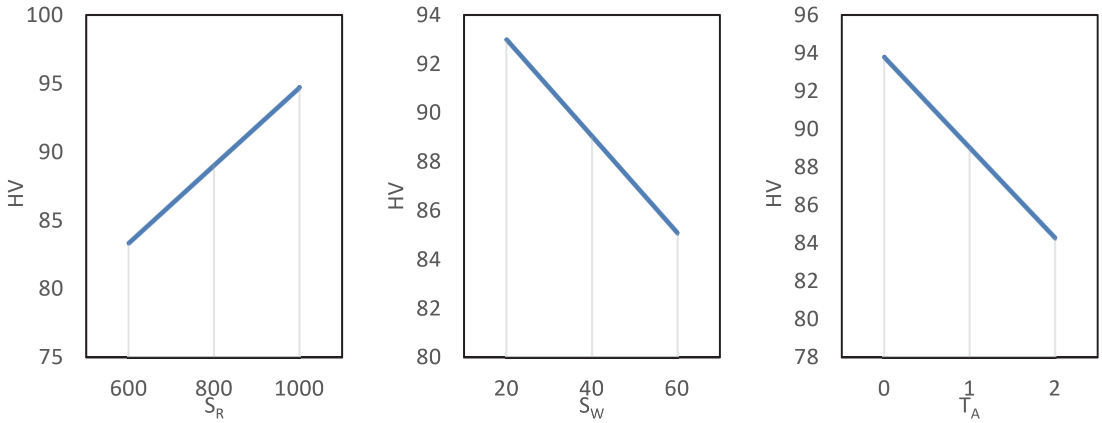

**Figure 9** Mean effective plot of *HV* vs process parameter

## 4 MULTIPLE RESPONSE OPTIMIZATION

The desirability approach is widely used in solving multiple response optimisation problems. The desirability function is a technique which converts the multiple outputs into a set of dimensionless quantity to measure the performance [7, 17]. In this paper, the desirability approach is used to optimise the FSW process parameter by using "Design Expert12" software. The FSW process parameter is set in the range of rotational speed from 600-1000 rpm, welding speed (20-40 mm/min) and tool tilt angle (0-2 deg) and maximize output is set for UTS, YS, %E and Hardness. The desirability approaches develop 61 sets of optimum parameter and the suggested best optimum parameter is $S_R = 600$, $S_W = 20$ and $T_A = 2$.

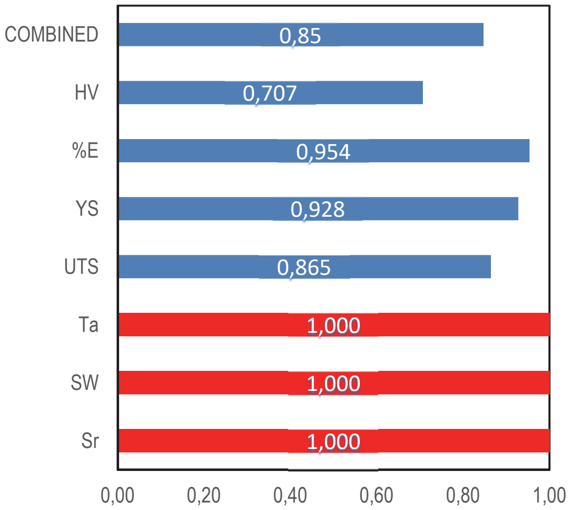

**Figure 10** Desirability Bar Chart

The desirability value for each response is shown in the bar diagram Fig. 10, which shows maximum *UTS* is 154 MPa, *YS* - 143, %*E* is 3.3 and hardness 94 HV with a high desirability value of 0.85.

## 5 VALIDATION OF RESULT

The FSW experiment of dissimilar aluminium and magnesium alloy is carried out for optimum process parameters suggested by the desirability approach. The tensile strength and hardness of welded joint are then evaluated by using a UTM testing machine and Vicker's hardness tester.

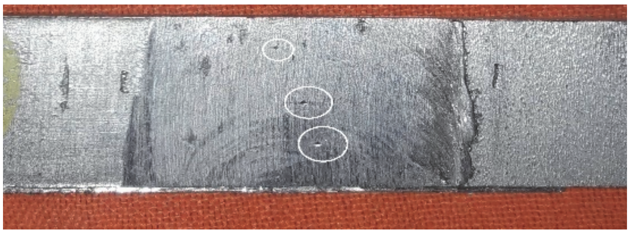

**Figure 11** Hardness specimen after testing

**Figure 12** Tensile specimen after testing

The specimen used for testing the hardness and tensile strength is shown in Fig. 11 and Fig. 12. The output response for optimum input parameter is *UTS* = 155 MPa, *YS* = 144 MPa, %*E* = 3.5% and *HV* = 92.

## 6 MICROSTRUCTURAL ANALYSIS

A total of two samples were taken for SEM analysis, one is upper part (a) shown in Fig. 13, and the other is the lower part (b) shown in Fig. 14, of friction stir welded samples at the optimal setting [18]. ($S_R$ =1000, $S_W$ = 20 and $T_A$ = 2)

Tool offset is employed here to improve bonding strength by reducing the thickness of intermetallic compound. Heavy plastic deformation of the AA6061 Al alloy and the AZ31 Mg alloy is observable in the upper part (a) of the joint, resulting in thorough mixing of the two alloys. On the other hand, the lower part (b) of the joint seems to have a much smoother interface with less compound intermixing.

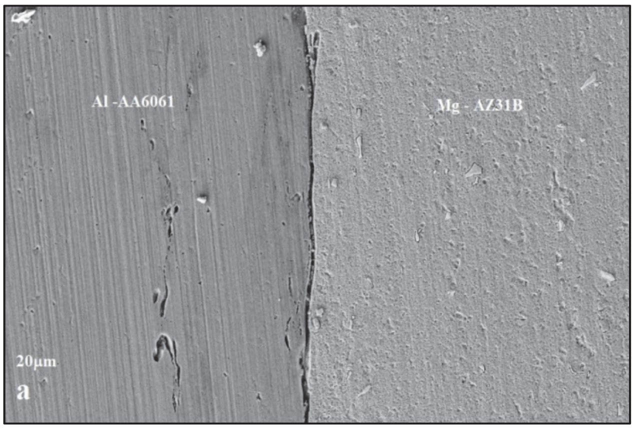

**Figure 13** Upper part of welded zone

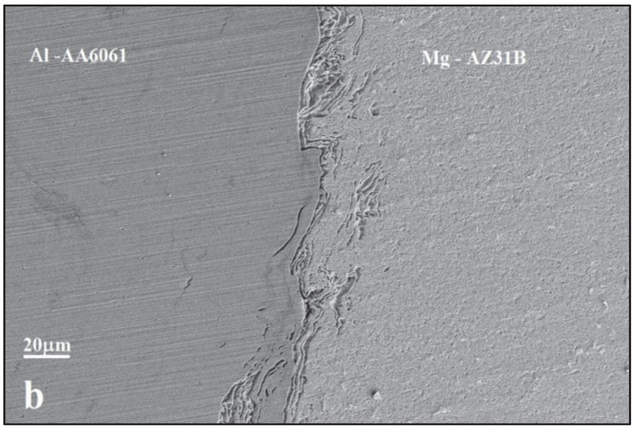

**Figure 14** Lower part of welded zone

## 7 CONCLUSION

In this research, the FSW experiment of dissimilar aluminium and magnesium alloy is successfully performed by changing process parameters according to the RSM-central composite design. The regression equation is generated based on the result of the tensile and hardness test. ANOVA is performed to validate the regression equation. ANOVA table shows that the model is significant and there are fewer chances of error. The welding speed and rotation speed are the most significant parameter in determining the tensile strength and hardness of welded joint. The tool tilt angle plays a vital role in increasing the percentage of elongation of the welded joint. From the desirability approach, the predicted optimum process parameters for high tensile strength and hardness are $S_R$ = 1000 rpm, $S_W$ = 20 mm/min, $T_A$= 2 deg. The confirmatory test is carried out for optimal setting and the results of the tensile and hardness test of a welded joint are acceptable with predicted values. The *UTS*, *YS*, %*E* and *HV* for optimum process parameters are 155 MPa, 144 MPa, 3.5 and 92 HV respectively. The confirmatory test is carried out for optimal setting and the results of the tensile and hardness test of a welded joint are acceptable with predicted values. SEM analysis is carried out for confirmatory specimen and that shows good intermetallic bonding at a cross-section of a welded joint.

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