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# The Effect of Rotation and Welding Speeds on Surface Texture of FSW AL Plates

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**Abstract.**Friction stir welding (FSW) is a solid-state welding process that is used for fabricating high-quality aluminum weldments. In this study, FSW is used to weld aluminum alloy AA6063 plates. Different combinations of FSW conditions were used, and the generated welds were tested for surface quality. Factorial design of experiment approach was used to investigate the significance of the FSW factors on the surface roughness of the joints. Moreover, response surface methodology (RSM) was used to optimize the surface roughness response and the optimal FSW conditions were determined. The results revealed that both tool rotational and traverse speeds have a great influence on the surface quality. The interaction of tool rotational and traverse speeds exhibited the most significant influence on the surface roughness of the FSW specimens. However, the rotational speed exhibited a higher significant effect on the surface roughness than the traverse speed.

**Keywords**:Friction Stir Spot Welding, Aluminum Alloys, Surface Roughness, Response Surface Methodology.

## 1. INTRODUCTION

Friction stir welding (FSW) is a relatively new welding technique that is based on the principle of joining materials in the solid-state. The FSW process depends on the heat generation in the gap between the two joined parts that is produced due to stirring movement of a rotating tool. FSW is superior compared to other fusion-based techniques as it avoids problems such as weld porosity defects, which are common in welding aluminum alloys using these techniques. FSW is mainly used for joining light metals such as aluminum, magnesium and titanium alloys [1-3]. The tool rotational and welding speeds are the most influential FSW process parameters that affect the mechanical performance of the welded joints [4].

It has been observed that most of the available investigations on FSW are focusing on the microstructural and mechanical characteristics of the produced joints [2,3-5]. Few investigations were reported on the influence of the FSW process parameters on the surface roughness of the joints [6-11]. However, in the manufacturing industry, the surface must be within certain limits of roughness to improve fatigue and corrosion resistances of the joints as well as to reduce the finishing costs [12]. Sicilan and Kumar [6] studied the effect of FSW process parameters on the surface quality of AA6063 aluminum joints using image processing technique. The surface roughness of the specimens was also measured using roughness tester. The results reveal a significant relationship between the roughness and peak values from the image histograms and contour plots. Shigematsu et al. [8] reported that the rotation speed tool and traverse speed tool are very important parameters in controlling the surface morphology of the joint. Also, Nejah [9] suggested that surface roughness is a result of the geometry of the tool and feed rate. The results indicated that an increase in the ratio (transverse speed/rotational speed) improves the surface state.

Dwight et al. [11] investigated the welds produced by FSW using tools with various shoulders. They showed that the surface roughness and metal deformation in the uppermost layers of welds are greatly influenced by shoulder design.

The aim of the present investigation is to study the effect of FSW process parameters, typically, the tool rotational and traverse speeds on the surface quality of AA6063 butt joints. Full factorial design of experiments approach has been employed to examine the effects of the aforementioned FSW process parameters on the surface roughness. Moreover, optimization of such FSW parameters to minimize the surface roughness was carried out using response surface methodology (RSM).

## 2. EXPERIMENTAL WORK

### 2.1. Materials

Plates of the AA6063 wrought aluminum alloys were joined using FSW. The plates have dimensions of 12 mm (thickness) × 300 mm (length) × 50 mm (width). The chemical compositions of alloys are listed in Table 1.

Table 1. Chemical composition of the AA6063 aluminum alloy (wt.-%)

| Alloy | Elements (wt.-%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cu | Fe | Mn | Mg | Si | Zn | Cr | Al |
| AA6063 | 0.01 | 0.36 | 0.01 | 0.36 | 0.35 | 0.06 | 0.01 | Bal. |

### 2.2. FSW Process

The two plates of AA6063 aluminum alloys are joined in a butt configuration. The FSW was conducted using a tool has a tapered cylindrical pin profile and a plate shoulder. The tool is made from W304 tool steel. The shoulder diameter was 40 mm while the smaller and larger diameters of the tapered pin were 8 mm and 13.5 mm, respectively. The tilt angle and plunging depth were kept constant at 3o and 0.1 mm, respectively. FSW was conducted using different four rotational speeds and three traverse (welding) speeds. The experiment design resulted had 12 runs (4×3) and the FSW process parameter values were set as shown in Table 2.

**Table 2. The FSW parameters and their levels**

| FSW Parameter | Level | | | |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | Level 4 |
| Rotational speed (rpm) | 470 | 590 | 740 | 900 |
| Traverse speed (mm/min.) | 16 | 31.5 | 50 | - |

### 2.3 Surface Roughness Measurements

Surface roughness of welded joint is defined as the inherent irregularities of the work piece form semicircular streaks affected by interaction tool/work piece. Fig. 1 shows a typical surface texture of a friction stir welded specimen at 470 rpm and 16 mm/min. In the present investigation, the surface quality of the FSW specimen was evaluated by the arithmetic average roughness value (*Ra*) using Mitutoyo SURFTEST SJ-310 contact-stylus roughness tester. It is quantified by the vertical deviations of a real surface from its ideal form. A typical roughness plot for FSW specimen welded at 470 rpm and 16 mm/min is shown in Fig. 2. From each welded sample, three roughness measurements were carried out at the start, middle and end of the welded specimen and the average Ra value is determined.

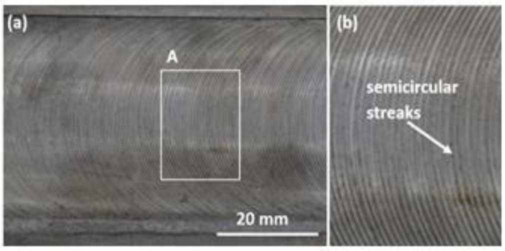


Fig. 1. Surface texture of a friction stir welded specimen (a) general view and (b) higher magnification of the area A

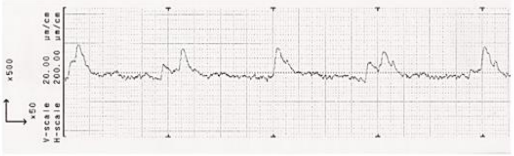


Fig. 2. Typical roughness plot of FSW specimen welded at 470 rpm and 16 mm/min.

### 2.4 Analysis of Variance (ANOVA) and Response Surface Methodology (RSM)

In the present investigation, full factorial design of experiments was employed. The total number of welding conditions were 12. The Analysis of Variance (ANOVA) statistical method was employed to determine the most significant FSW process parameter (i.e. the tool rotational speed and the traverse speed) on output response characteristics (i.e. the surface roughness). The ANOVA calculations was carried out using P-value test with a significance level of P-value < 0.05 using the Minitab statistical software.

The response surface methodology (RSM) was adopted to obtain an optimal response using second degree polynomial model. Central Complex Design (CCD) is used to create the response surface. The significant factors are included to find values that optimize response, while the CCD requires 2 levels (i.e. upper and lower limits) for each factor. Response optimizer setup in Minitab software was used to identify the optimum FSW process parameters values for the surface roughness which help to find the combination of input FSW parameters settings that minimize the surface roughness.

## 3. RESULTS AND DISCUSSION

### 3.1. General Appearance of the Surface Texture

Figure 1a shows general appearance of a surface of AA6063 welded specimen at 470 rpm and 16 mm/min. It is known that, the better the quality of surface the lower the cost of machinability required to finish the surface of the plates after FSW. It is clear from Fig. 1 that the surfaces of friction stir welded specimens are characterized by presence of semi-circular streaks at the contact surface between the shoulder and the plate. It has been observed that, the contour lines of the semi-circular streaks are continuous and uniform throughout the surface of the welded specimens. The developed surface textures are attributed to the friction at the contact surface between the shoulder of the tool and the workpiece surface. During FSW, a metal transfer is taken place by the rotating tool which causes the variations in surface texture, there by affecting the surface quality .

### 3.2. Effect of Tool Rotational and Traverse Speeds

Fig. 3 shows the effects of the tool rotational speed and transverse speed FSW process parameters on the surface roughness parameter (*Ra*). According to main factor plots, an increase in the transverse speed from 16 mm/min to 50 mm/min decreases the surface roughness while increasing the tool rotational speed from 470 rpm to 590 rpm reduces the surface roughness. Any further increase in the tool rotational speed above 590 rpm tends to increase the surface roughness.

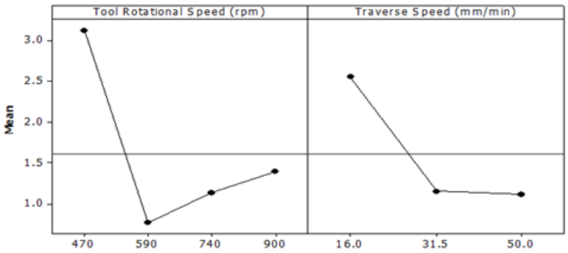
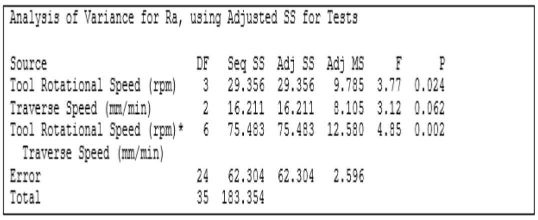


**Fig. 3. Effect of process parameters on surface roughness response mean**

### 3.3. ANOVA Results

Table 3 shows the results obtained from ANOVA calculations. The ANOVA results reveal that the corresponding p-values of the interaction between the tool rotational speed and traverse speed is significantly smaller than the individual FSW process parameters, which indicates that the change of the levels of combination of the two factors has the most significant influences on the surface roughness. The P-values of the tool rotational speed and/or the traverse speed are higher, which implicates less significant factors. Furthermore, the rotational speed has a higher significant effect on the surface roughness than the welding speed.

**Table 3. ANOVA Results for *Ra* of FSW surfaces**



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Analysis of Variance for Ra, using Adjusted SS for Tests


Source                        DF   Seq SS  Adj SS  Adj MS     F      P
Tool Rotational Speed (rpm)    3   29.356  29.356   9.785  3.77  0.024
Traverse Speed (mm/min)        2   16.211  16.211   8.105  3.12  0.062
Tool Rotational Speed (rpm)*   6   75.483  75.483  12.580  4.85  0.002
  Traverse Speed (mm/min)
Error                         24   62.304  62.304   2.596
Total                         35  183.354
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### 3.4. RSM Results

Fig. 4 shows the 3D plot of surface response as well as contour plots of the *Ra* with tool rotational and traverse speeds. For minimizing surface roughness, Fig. 4b shows that for *Ra* values are minimum when the combination between the tool rotational speed and the traverse speed is located at the light grey region. The surface quality of welded work piece depends on controlling the rotation speed with the traverse speed. Fig. 4b shows that at tool rotational speed of 800 rpm, the traverse speed has no effect on the surface roughness of the work piece.

### 3.5. Desirability Approach

In the present investigation the desirability method was used for finding the optimum values of the FSW process parameters that produces minimum *Ra* value. The method was used due to its simplicity, flexibility and ease of availability in software. This method converts the multiple response values into a dimensionless measure of performance called the overall desirability function whose range are between 0 to 1. The optimization plot for the input tool rotational and traverse speeds variables obtained for the *Ra* values is shown in Fig. 4. The results revealed that the predicted optimal result of *Ra* from the above technique value of 0.0714 µm at 691.51 rpm and 40.0404 mm/min. The combined desirability value is 0.92859.

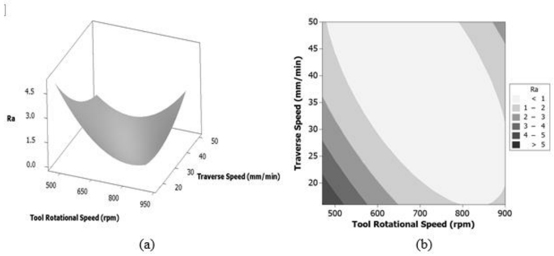

Fig. 4. The variation of the *Ra* with the tool rotational and traverse speeds; (a) 3D surface plots and (b) contour plots.

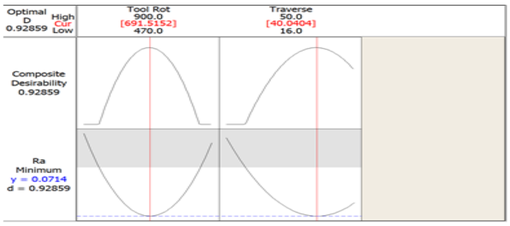

Fig. 5. Optimization plot using response optimizer for the *Ra*

## 4. CONCLUSIONS

Based on the results obtained from the present investigation, the following conclusions can be derived:

1. The surface quality of AA6063 welded plates depends significantly on controlling the rotation speed with the traverse speed .
2. The interaction of tool rotational and traverse speeds showed the most statistical and physical significant influence on the surface roughness of the AA6063 friction stir welded plates. The rotational speed showed higher significant influence on the surface roughness when compared with the traverse speed.
3. The optimization process showed that the predicted optimal result of *Ra* is 0.0714 µm at tool rotational and traverse speeds of 691.51 rpm and 40.0404 mm/min, respectively .

   Low surface roughness with good surface quality is produced at higher rotational speeds and medium traverse speeds. At tool rotational speed of 800 rpm, the traverse speed has no influence on the surface roughness of the welded AA6063 aluminum plates.

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