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FRICTION STIR DRILLING OF AA7075 ALUMINUM ALLOYS

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ABSTRACT In the present investigation, holes were produced in AA7075 aluminum alloy sheets using friction stir drilling. The friction stir drilling process was performed using computer numerical control (CNC) vertical machining center. The influence of the spindle rotational speed and the tool's conical angle on the hole characteristics, typically, hole diameter, bushing height and thickness, were investigated. The analysis of variance (ANOVA) calculations were performed to estimate the significance of the studied process parameters. Regression analysis was carried out to find correlations between the investigated friction stir drilling process parameters and the fabricated hole characteristics. The results revealed that the conical angle is the most influential factor that affect the hole characteristics. Increasing the tool rotational speed reduces the hole diameter and the bushing thickness. However, increasing the conical angle increases the bushing height. The developed regression equations showed high accuracy. The equations for the hole diameter, bushing height and bushing thickness have mean absolute error (MAE) values of 0.6%, 3.04% and 6.10%, respectively.

KEYWORDS: Friction stir drilling, Aluminum Alloys, Design of Experiments.

1 INTRODUCTION

The friction stir drilling is a hole forming process, usually used, in the sheet metals. The friction stir drilling uses the heat generated by means of friction between the workpiece and the rotating tool to form the holes [1-3].

The friction stir drilling process consists of five steps. The five steps of the friction stir drilling is illustrated in Figure 1 [4]. A conical tool with a tip approaches and contacts the workpiece (see Figure 1a). The tool tip marks into the workpiece and supports the drill in both the radial and axial directions. The friction between the conical tool and the workpiece contact surfaces produces heat and softens the work-material. The tool is then penetrating the workpiece (see Figure 1b) pushes the softened work-material sideward, and pierces through the workpiece (see Figure 1c). Once the tool tip penetrates the workpiece (see Figure 1d) the tool moves further forward to push aside more work-material and form the bushing using the cylindrical part of the tool. The shoulder of the tool may contact the workpiece to trim or collar the extruded burr on the bushing. Finally, the tool retracts and leaves a hole with a bushing on the workpiece (see Figure 1e) .

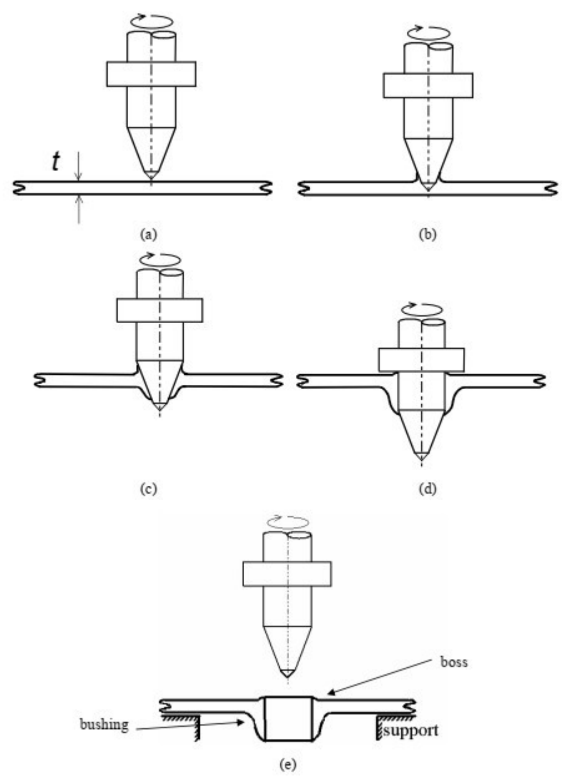


Figure 1. The steps of the friction stir drilling process [4].

Friction stir drilling are generally used to create a bushing on sheet metal, tubing, or thin walled profiles for joining components in a simple and efficient way. The bushing produced in the friction stir drilling is usually two to three times as thick as the original workpiece [5]. This added thickness can be threaded, providing a more solid connection for attachment than try to thread the original sheet. Figure 1.2 shows a cross-section of the bushing produced for a tapped and untapped hole [6]. All work-material from the hole contributes to form the bushing. In addition, no cutting fluid or lubricant is necessary, which makes friction drilling a totally clean, environmentally friendly process.

In the present investigation, the effect of the spindle rotational speed and the tool's conical angle on the manufactured hole characteristics, including the hole diameter, bushing height and thickness were investigated. The ANOVA statistical technique was used to estimate the significance of the friction stir drilling process parameters under investigation. Moreover, regression models were developed to corelate the relationship between the friction stir drilling process parameters and the hole characteristics. These models can be used to reduce the tedious and expensive experiments.

2 EXPERIMENTAL PROCEDURES

2.1. Materials

Sheets of AA7075 Al alloy having the chemical composition listed in Table 1 were friction stir drilled. The sheets have thickness of 3.4 mm. The friction stir drill tools are made of AISI H13 (Cr-Mo-V) hot worked tool steel manufactured by *Bohler-Uddeholm* UDDEHOLM ORVAR (Germany) [7]. Table 2 shows the chemical composition of the AISI H13 tool steel.

Table 1. Chemical composition of AA7075 aluminum alloy (wt.-%).

Elements	Zn	Mg	Cu	Fe	Mn	Si	Cr	Ti	Pb	Al
Weight %	5.94	2.29	1.33	0.258	0.052	0.112	0.166	0.023	0.005	Bal.

Table 2. Chemical composition of H13 tool steel (wt.-%).

Elements	Cr	Si	C	Mn	Mo	V	Fe
Weight %	5.21	1.1	0.39	0.40	1.37	0.90	Bal.

2.2. The Dimensions of the Drill

The key dimensions of the friction stir drill tool is illustrated in Figure 2. The tools have shank diameter (D_{shank}) of 30 mm. The diameter (d) and height (h_l) of the cylindrical region are equal to 15 mm and 30 mm, respectively. The center region angle (α) and height (h_c) are equal to 70° and 4.97 mm, respectively. The conical region has a height (h_n) of 15 mm and the conical angle (β) varies from 38° to 58°, typically, 38°, 42° and 58°. Figure 2 shows photographs of the friction stir drilling tools used in this study.

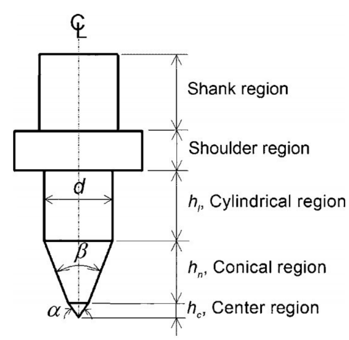


Figure 2. A schematic illustration of the friction stir drilling tool key dimensions.

2.3. Friction Stir Drilling Process

The holes were drilled using Sino computer numerical controlled (CNC) vertical manufacturing center. The friction stir drilling process was carried out using constant feed rate of 30 mm/min and several spindle speeds of 3300, 3600 and 3900 rpm. Table 3 shows the friction stir drilling process parameters under investigation and their levels. Before friction stir drilling the sheet was put on a die with a hole (30 mm diameter) and clamped rigidly.

Table 3. Friction stir drilling process parameters and their levels.

Parameter	Symbol	Unit	Level		
			Min.	Avg.	Max.
Conical angle	β	Degree	38	42	58
Spindle speed	S	rpm	3300	3600	3900

2.4. Hole and Bushing Dimensions Measurements

After friction stir drilling the workpieces were cut, from the center of the hole, using wire cut machine and the hole and bushing characteristics were measured. The resulted hole diameter (d) was measured. The measured bushing dimensions are the average bushing thickness (t) and the bushing height (h). Figure 3 shows a schematic illustration of the measured hole and bushing characteristics. The dimensions were measured using image analyzing techniques using JMicrovision image analysis software.

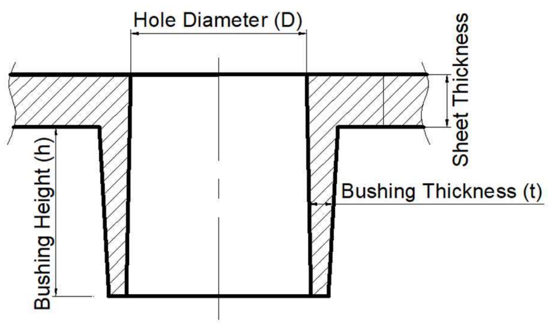


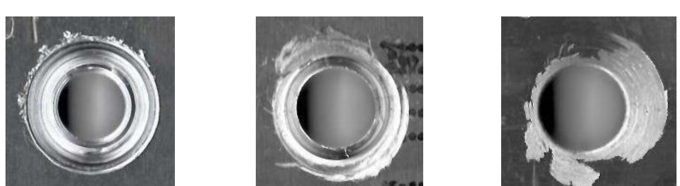
Figure 3. Bushing height, thickness and hole measurements.

The friction stir drilling experiments were designed using full factorial design of experiments (DOE) technique. The hole and bushing measurements were carried out for each sample and the average values was calculated. The analysis of variance (ANOVA) statistical approach was used to get the influence of the friction stir drilling parameters on the performance characteristics (i.e. hole and bushing characteristics). Regression analysis was used to correlate the independent parameters (spindle rotational speed and conical angle) with the dependent parameters (hole diameter, bushing height and bushing thickness). The ANOVA and regression calculations were carried using MiniTab V16 statistical commercial software. The mean absolute error (MAE) was calculated to find the accuracy of the equations obtained from regression analysis.

3 RESULTS AND DISCUSSION

3.1. The Hole & Bushing Shapes

Figure 4 shows photographs of typical friction stir drilled holes in the AA7075 Al sheets using different conical angles and constant rotational speed of 3300 rpm. Figure 5 show photographs of typical bushes formed in friction stir drilling of AA7075 Al sheets using different conical angles and constant rotational speed of 3300 rpm. The photographs showing the views of bushing from bottom of the sheets. Figure 6 shows photographs of the cross-sections of typical bushes formed in friction stir drilling of the AA7075 Al sheets using different conical angles and constant rotational speed of 3300 rpm.

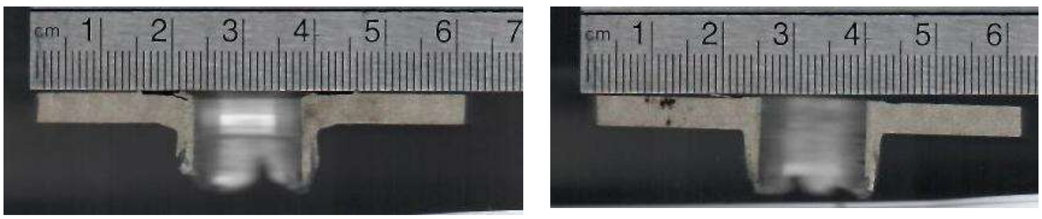


(a) (b) (c)

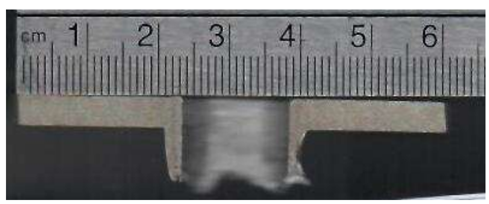
Figure 4. Photographs of friction stir drilled holes. The holes were drilled using constant rotational speed of 3300 rpm and different angles of (a) 38°, (b) 42° and (c) 58°.

(a) (b) (c)

Figure 5. Bushes formed in AA7075 aluminum alloy sheets after fiction stir drilling at constant spindle speed of 3300 rpm and several conical angles of (a) 38°, (b) 42° and (c) 58°.



(a) (b)



(c)

Figure 6. Bushes cross-sections formed at constant spindle rotational speed of 3300 rpm and several conical angles of (a) 38°, (b) 42° and (c) 58°.

3.2. The Hole Diameter Measurement Results

Figure 7 shows main effects plot for means for the diameter of friction stir drilled holes in AA7075 Al sheets. The results revealed that increasing the tool rotational speed reduces the hole diameter. Increasing the conical angle from 38° to 42° reduces the hole diameter, however, further increase in the conical angle from 42° to 58° increases again the hole diameter. Table 4 shows the response table for means for hole diameter. The results showed that conical angle has higher significance effect when compared with the spindle speed. The conical angle is ranked #1, while the spindle speed is ranked #2.

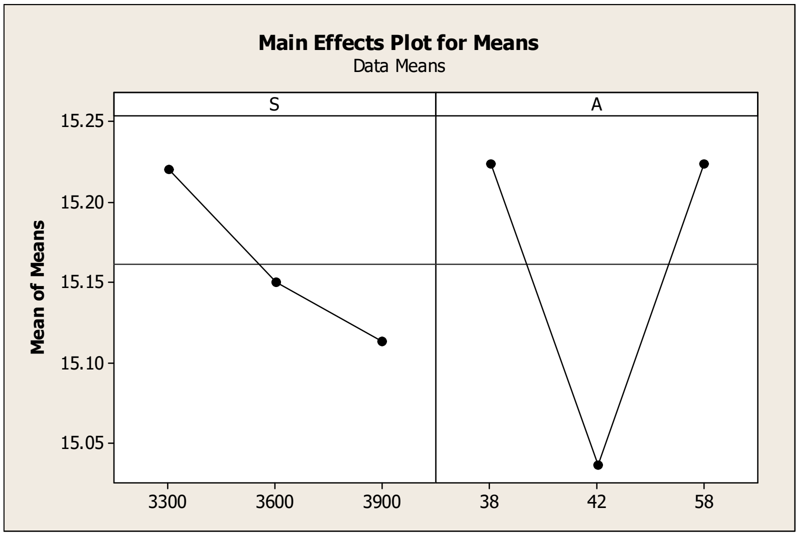


Figure 7. Main effects plot for means for the diameter of friction stir drilled holes in AA7075 Al sheets.

Table 4. Response table for means for hole diameter.

Response Table for Means

Level	S	A
1	15.22	15.22
2	15.15	15.04
3	15.11	15.22
Delta	0.11	0.19
Rank	2	1

The relationship between the spindle rotational speed, conical angle and the average hole diameter can be written as follows:

$$D = 15.6 - 0.000178\ S + 0.00333\ A \quad \ldots(1)$$

Where: D is the average hole diameter in mm, S is the spindle speed in rpm and A is the conical angle in degree. Equation 1 exhibited MAE of ≈ 0.6 %, which is very low.

3.3. The Busing height and Thickness Measurement Results

Figures 8 and 9 show the main effect plots for means of the bushing heights and thicknesses, respectively. Increasing the conical angle increases the bushing height, while increasing the spindle speed from 3300 rpm to 3600 rpm increases slightly the bushing height. Further increase in the spindle speed (i.e. from 3600 rpm to 3900 rpm) reduced the bushing height even smaller than those obtained at 3300 rpm. The bushing thickness reduced with increasing the spindle speed. Increasing the conical angle from 38^o to 42^o tends to reduce the bushing thickness. While increasing the conical angle from 42^o to 58^o increases bushing thicknesses.

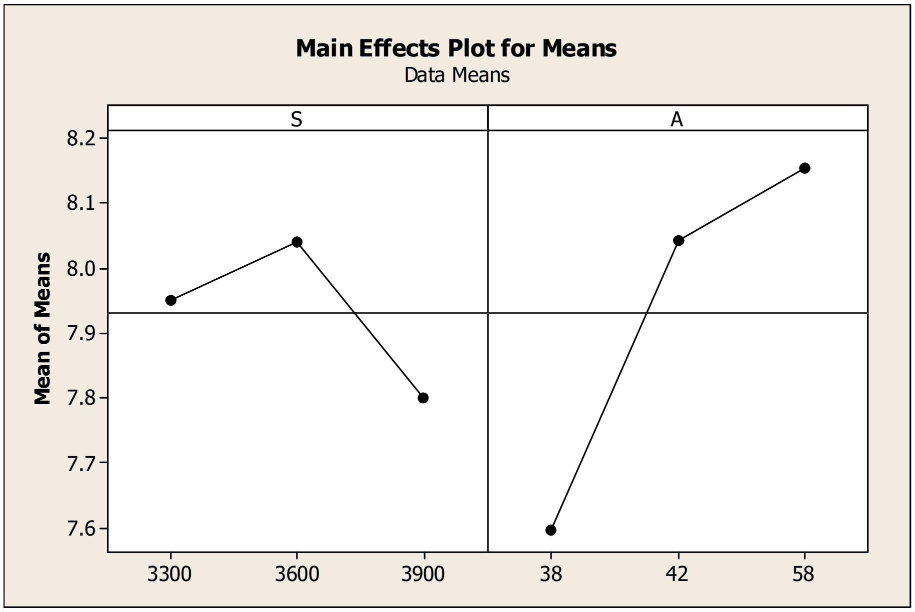


Figure 8. Main effects plot for means for the bushing heights.

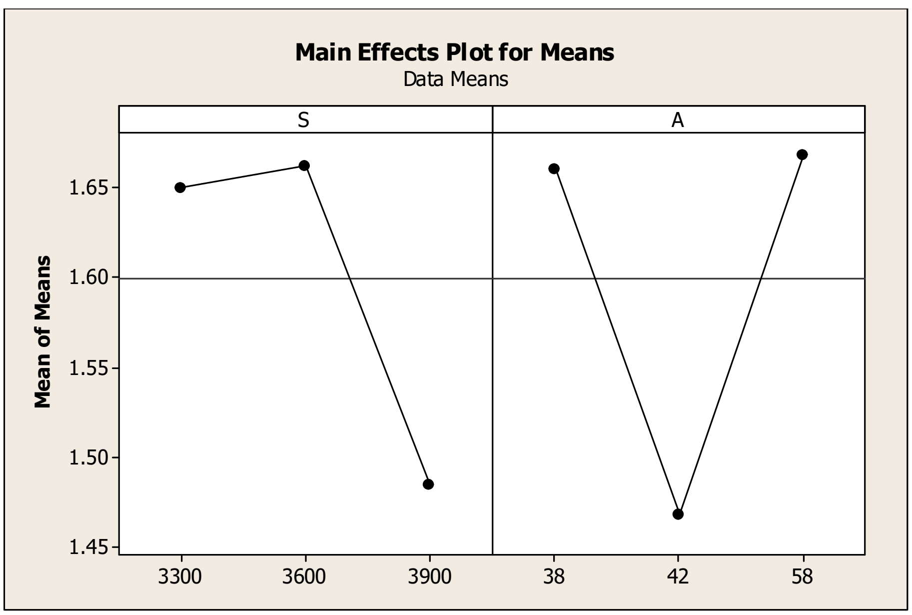


Figure 9. Main effects plot for means for bushing thicknesses.

Tables 5 and 6 show the response tables for means for the bushing heights and thicknesses, respectively. The results showed that, in both cases, the conical angle exhibited higher significance effect when compared with the spindle speed. In case of bushing height and bushing thickness, the conical angle is ranked #1, while the spindle speed is ranked #2.

Table 5. Response table for means for bushing height.

Response Table for Means

Level	S	A
1	7.952	7.597
2	8.042	8.043

3	7.802	8.155
Delta	0.240	0.558
Rank	2	1

Table 6. Response table for means for bushing thickness.

Response Table for Means

Level	S	A
1	1.650	1.660
2	1.662	1.468
3	1.485	1.668
Delta	0.177	0.200
Rank	2	1

Equations 2 and 3 show correlations between the spindle speed and the conical angle with the bushing height and bushing thickness, respectively. Equation 4.2 and 4.3 exhibited MAE 3.04% and 6.10% values of and , respectively. The values of the MRE are within the acceptable level.

$$H = 7.82 - 0.000250\ S + 0.0219\ A \qquad \ldots(2)$$
$$T = 2.41 - 0.000275\ S + 0.00387\ A \qquad \ldots(3)$$

Where: H is the bushing height in mm, T is the bushing thickness in mm, S is the spindle speed in rpm and A is the conical angle in degree.

4 CONCLUSIONS

The conclusions of significance are drawn as follows :-

4. The conical angle is the most influential factor that affect the hole characteristics. The conical angle exhibited higher statistical and physical significance than the spindle rotational speed.
5. Increasing the tool rotational speed reduces the hole diameter and the bushing thickness. However, increasing the conical angle increases the bushing height.
6. The developed mathematical models exhibited relatively high accuracy. The regression models for the hole diameter, bushing height and bushing thickness exhibited mean absolute error values of 0.6%, 3.04% and 6.10%, respectively.

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