Original Article

Study of parametric optimization of burr formation in step drilling of eutectic Al–Si alloy–Gr composites

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A B S T R A C T

In this study, the effect of the step drill’s geometries such as step angle, step size and cutting parameters such as feed and spindle speed on the exit burr height was investigated for burr minimization in drilling of Al–Gr composites which are fabricated through squeeze casting method. The experimental study was conducted as per the L27 orthogonal array of Taguchi method to find the optimum drilling parameters, and analysis of variance (ANOVA) was performed to investigate the influence of parameters on the burr height of composites during drilling. Confirmation tests were conducted to validate the test results. Results revealed that feed, step angle, step size and spindle speed were the significant parameters in the formation of exit burr.

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1. Introduction

Metal Matrix Composites (MMCs) have emerged as a potential material particularly for automotive and aerospace industries. Since the demands on performance and functionality of components are increasing rapidly, the machining parameters have to be optimized in order to attain the good surface quality. Burr is an unwanted projection of material as a result of plastic deformation during drilling operation. Burrs could create many problems during assembling and inspection of precision components. Moreover it degrades the performance of precision parts. Burrs would lead to blockage of critical passages in pneumatic, hydraulic and electronic circuits, which would cause serious problems during service. Entrance and exit burrs are produced during the drilling of every hole. The entrance burr which is generally smaller than the exit burr can be removed easily by chamfering the hole. On the other hand the exit burr is of prime importance due to the difficulty in removing it. If the burr is formed inside a hole, special tools could be employed for deburring. The deburring process is usually done manually because of the difficulties in automation.

Moreover, deburring operation increases the total manufacturing cost by 20% and requires a significant amount of time [1]. Hence burr minimization requires major attention. Various researchers [2,3] have analyzed the drilling parameters such as drill’s geometry, feed rate and cutting speed in...
the formation of exit burrs and have proposed burr formation mechanisms. Pande and Relekar [4] analyzed burr formation in terms of burr height and thickness by varying the cutting speed and feed rate. Ko and Lee [5] analyzed the effect of cutting conditions such as cutting velocity, feed rate and the drill’s geometries on accuracy of hole and burr formation. Dornfeld and Guo [6] developed a three-dimensional finite element model to predict and analyze the different stages in the formation of burr in drilling of 304 stainless steel. Min et al. [7] reported that the work piece material, drill bit material and its geometry, and feed rate are the major parameters that influences the burr size. Davim [8] studied the drilling of metal matrix composites to find the effect of drilling parameters on tool wear, torque and surface finish using Taguchi technique. Gaitonde et al. [9] studied the Taguchi methodology for minimization of burr height and burr thickness influenced by drill’s geometries and cutting parameters. Nihat Tosun [10] optimized the drilling parameters for the surface roughness and burr height using grey relational analysis. Several investigations have been carried out in order to simulate the drilling burrs. Gillespie and Blotter [11] developed an analytical model which demonstrates the burr formation mechanisms, and the model was compared to experimental observations. Stein and Dornfeld [12] reported that burr height and un-deformed chip thickness could be a fundamental property of work material for particular tool geometry in drilling operation.

Akhlaghi and Zare-Bidaki [13] have reported that during dry sliding, Al alloy – graphite composite forms a layer of graphite with solid lubricant between the contacting surfaces and this improves the machinability. Songmene and Balazinski [14] analyzed machinability on drilling and milling of Al–SiCp, Al–SiC–Gr and Al–Al₂O₃–Gr composites and concluded that the addition of graphite particles enhances the machinability of the composite. Limited attempts have been made in the investigation of the formation of burr height of Al–Si alloy–graphite composite in step drilling.

Literature study [15,16] revealed that the burr formation can be minimized by choosing optimal drill’s geometries and cutting parameters according to the work piece material. In this study, a step drill was chosen to minimize the burr height. In case of step drill, two cutting stages have to be completed to drill a hole. At first, front cutting edge drills the work piece and then the second cutting process starts at the step edge which is used to enlarge the pilot hole to final size. Hence burr formation in the second cutting stage is determined by the step angle and step size of the drill. Therefore, designing a step drill requires an optimal step angle and step size to minimize the burr. Therefore, the present work aimed to investigate the effect of parameters such as feed, spindle speed and step drill’s geometries (step angle, step size) on the exit burr formation in drilling of Al–Gr composites using Taguchi and ANOVA techniques. To study the influence of thrust forces on burr height, force signals from dynamometer were also investigated through the data acquisition system.

2. Materials and fabrication of composites

Eutectic Al–Si alloy (Si–12.6, Fe–0.02, Al–rest by weight) was used as the matrix material and graphite particles (50–125 µm) were used as the solid lubricant. Squeeze casting method was employed to fabricate the Al–Gr composites [17]. Al–Gr composite melt was prepared by employing stir casting method and poured into the preheated (350 °C) mould cavity. Squeeze pressure of 50 MPa was applied on the melt for 50 s through the preheated punch till solidification was completed. The punch was withdrawn and the specimen was removed from the mould assembly.

2.1. Microstructure analysis

The micrograph of Al–7.5 wt.% Gr composite in Fig. 1 showed a distribution of graphite particles. The dark phases observed in the micrograph are the graphite particles which are being distributed more uniformly throughout the specimen.

The EDS of the surface of the composite specimen, which is shown in Fig. 2, indicates the presence of Al, Si and Fe from the Al–Si alloy matrix, whereas the existence of C peak confirms the presence of the graphite in the composite.

3. Drilling process

The drilling test was carried out on a vertical machining centre (Fig. 3) without using any lubricants. Al–Gr

![Graphite](Image)

**Fig. 1 – SEM micrograph of the Al–7.5 wt.% Gr composite.**

![Spectrum](Image)

**Fig. 2 – EDS spectrum of the Al–7.5 wt.% Gr composite.**
composites were selected as work piece material having a size of 50 mm × 40 mm × 25 mm. A 6 mm diameter carbide step (Fig. 4) drill was employed. Summary of experimental conditions is presented in Table 1. The experiments were carried out as per L27 Taguchi orthogonal array. Parameters and levels are presented in Table 2. The exit burr height of each drilled hole was measured by using a digital indicator (resolution of 0.001 mm) as shown in Fig. 5. The stylus was swept slowly towards the periphery of the drilled hole by moving the base of the dial indicator gauge on the surface plate. Burr height readings were taken at four positions spaced at 90° intervals around the circumference of the hole, and mean value was considered. Thrust forces were measured with a multi-component dynamometer and force signals were processed through computerized data acquisition system.

4. Taguchi method

Taguchi’s parameter design provides a systematic and efficient methodology for determining optimum design parameters which have an effect on the process and performance. The Taguchi method utilizes orthogonal arrays to study a large number of variables with a minimum number of configurations. By studying the effect of individual parameters on the results, the combination of optimum parameters can be determined. In the Taguchi method, the term ‘signal’ expresses

<table>
<thead>
<tr>
<th>Table 1 – Summary of experimental conditions.</th>
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</thead>
<tbody>
<tr>
<td><strong>Drill</strong></td>
</tr>
<tr>
<td>Work piece materials</td>
</tr>
<tr>
<td>Step drill’s geometry parameters</td>
</tr>
<tr>
<td>Cutting parameters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 – Parameters and levels.</th>
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<tbody>
<tr>
<td><strong>Code</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
</tbody>
</table>
the desirable value (mean) and the term ‘noise’ expresses the undesirable value (standard deviation) for the output quality characteristics. The mean S/N ratio for each level is the measure of quality characteristics deviating from the desired value and provides a measure of the impact of noise parameters on performance. Several types of S/N ratios are available based on the characteristics. In this study, “smaller is better” S/N ratio is used to predict the optimum parameters because a smaller burr height was desirable. Mathematical equation of the S/N ratio for “smaller is better” is represented in the following equation.

\[
\frac{S}{N} = -10 \log \left( \frac{1}{N} \sum y^2 \right)
\]  

(1)

where \( y \) is the observed data and \( N \) is the number of observations.

In addition, analysis of variance (ANOVA) was used to study the influence of the parameters on burr height.

5. Results

The measured burr height values are presented in Table 3. The ranking of parameters is presented in Table 4. The statistical analysis was performed by ANOVA (Analysis of variance) for a level of significance of 5% (i.e., the level of confidence 95%) to study the contribution of the parameters on the burr height. In the ANOVA analysis (Table 5), there is a P-value for each independent parameter, which is used to test the significance of each parameter and interaction among the parameters. A lower P-value indicates a higher level of significance. When the P-value is less than 0.05, the parameter can be considered as statistically higher level of significance.

5.1 Multiple linear regression model

A multiple linear regression equation was developed to establish the correlation among the parameters on the response.
Table 5 – ANOVA analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dof</th>
<th>SS</th>
<th>F-Value</th>
<th>P-value</th>
<th>Pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – feed (mm/rev)</td>
<td>2</td>
<td>0.660541</td>
<td>187.34</td>
<td>0.000</td>
<td>34.32</td>
</tr>
<tr>
<td>B – spindle speed (rpm)</td>
<td>2</td>
<td>0.306163</td>
<td>86.83</td>
<td>0.000</td>
<td>15.91</td>
</tr>
<tr>
<td>C – step angle</td>
<td>2</td>
<td>0.482007</td>
<td>136.70</td>
<td>0.000</td>
<td>25.05</td>
</tr>
<tr>
<td>D – step size (mm)</td>
<td>2</td>
<td>0.366582</td>
<td>104.04</td>
<td>0.000</td>
<td>19.06</td>
</tr>
<tr>
<td>A × B</td>
<td>4</td>
<td>0.017081</td>
<td>2.42</td>
<td>0.160</td>
<td>0.89</td>
</tr>
<tr>
<td>A × C</td>
<td>4</td>
<td>0.046504</td>
<td>6.59</td>
<td>0.022</td>
<td>2.42</td>
</tr>
<tr>
<td>A × D</td>
<td>4</td>
<td>0.034659</td>
<td>4.91</td>
<td>0.042</td>
<td>1.80</td>
</tr>
<tr>
<td>Error</td>
<td>6</td>
<td>0.010578</td>
<td></td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>1.924385</td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Dof: degrees of freedom; Seq. SS: sequential sums of squares; Adj. MS: adjusted sums of squares; Pc: percentage of contribution.

The value of regression coefficient $R^2$ (0.9945) is in good agreement with the adjusted $R^2$ (0.9762). The measured data were not scattered since the value of regression coefficient for the model is 0.9945. Since both the coefficients are reasonably close to unity, models provide a reasonably good explanation of the relationship among the parameters and the response (burr height).

The regression equation,

$$H = -0.390 + 9.25(A) + 0.000503(B) + 0.00357(C) + 0.0056(D)$$  \hspace{1cm} (2)


It can be observed from Eq. (2) that the coefficients associated with feed ($A$), spindle speed ($B$), step angle ($C$) and step size ($D$) are positive. It indicates that the burr height increases with increasing feed, step angle, spindle speed and step size ($D$). Feed has a larger effect compared with other parameters according to its coefficient value.

5.2. Confirmation experiments

The confirmation experiments were conducted as per the parameters which are given in Table 6. Results of the confirmation tests are presented in Table 7. Best results (minimum burr height) were found and comparison was made with computed values developed from the regression model. It can be observed that the experimental values and calculated values for burr height from the regression equation are nearly same with least error ($\pm 2\%$).

The resulting equations seem to be capable of predicting the burr height to the acceptable level of accuracy. However if the number of observations of performance characteristics are further increased, these errors can be reduced.

6. Discussion

Ranking of parameters is presented in Table 4 which revealed that the feed is a dominant parameter in the burr height followed by step angle, step size and finally spindle speed. The S/N ratio response graph for exit burr height is shown in Fig. 6. It was observed that the optimum parameters for exit burr height were feed (0.1 mm/rev), speed (600 rpm), step angle (40°) and step size (1 mm). The last column of Table 5 shows the percentage contribution (Pc%) of each variable in the total variation indicating their degree of influence on the burr height of the composites. It shows that the feed was the highest contribution, about 34%, followed by step angle (25%), step size (19%) and finally spindle speed (16%). It was observed that feed, step angle, step size and spindle speed have P-value less than 0.05, which means that they are highly significant at 95% confidence level. Moreover the interaction effects of the feed with step angle ($A \times C$) and feed with step size ($A \times D$) are significant model terms that influence the burr height because they have P-value < 0.05.

It can be observed that the feed is the significant parameter influencing the burr height in drilling. Higher feed increases...
the thrust force which enhances the plastic deformation, resulting in a larger burr formation.

A measurement of thrust–time characteristics was taken by employing a computerized multi-component dynamometer. In order to analyze the influence of feed on thrust force and burr formation, an additional drilling test was conducted on the composite specimens by increasing the feed from 0.06 mm/rev to 0.1 mm/rev without changing the other optimum parameters (600 rpm, step angle 40°, step size 1 mm). Thrust–time characteristics are presented as shown in Fig. 7(a) and (b).

It can be seen from Fig. 7(a) and (b) that thrust force signals, which were obtained during the drilling operation by front and step cutting edges, are almost steady before the front edge of the drill passes the exit surface of the work piece. But when the front cutting edge surpasses the exit surface, thrust force begins to drop. Again, thrust force slightly increased when the step cutting edge passed the exit surface of the work piece. It was observed that uncut portion which is left at the exit of the work piece during the front edge operation is to be cut by the step edge which reduces the burr height.

It can be observed that the mean thrust increased from 130.77 N to 163.97 N when the feed was increased from 0.06 mm/rev to 0.1 mm/rev in drilling of Al–Gr composites.

Fig. 8 shows that burr height increased from 0.48 mm to 0.80 mm when feed was increased from 0.06 mm/rev to 0.1 mm/rev. It can be concluded that at lower feed, the thrust experienced by the material is less and leads to reduced plastic deformation which minimizes the burr height.

Burr height values were plotted with three different spindle speeds (Fig. 9), keeping the other parameters, feed (0.06 mm/rev), step angle (40°) and step size (1 mm), as constants at their optimum values to find the influence of spindle speed on burr height.

ANOVA results (Table 5) revealed that the influence of spindle speed does have physical and statistical significance. Spindle speed was found to be significant (15.91%) in burr formation. Generally when spindle speed increases, heat generation increases at the interface between the tool and work piece. It increases the plasticity of the Al alloy which increases the burr height.

The effect of spindle speed on the burr height was examined by increasing speed from 600 rpm to 1100 rpm, while keeping other parameters at their optimum levels. It can be seen from Fig. 9 that the burr height increases with increasing spindle speed. The burr height increased by 42% when the spindle speed was increased from 600 rpm to 1100 rpm.

The smaller step angle (40°) was found to be the optimum parameter in minimizing the burr height. This can be attributed to the fact that when the step edge passes the exit side of the work piece, the work material at the bottom side of the step edge remained rigid and the cutting operation continues since it withstands the thrust force until the step edge exited. Hence only a thin section of material which is left during the operation is subjected to plastic deformation which in turn minimizes the burr height.

Fig. 10 illustrates that the burr height is apparently to have an increasing trend with increase in step angle. The results revealed that the burr height increased by 25% when the step angle was increased from 40° to 130° when drilled at the optimum cutting parameters.

It was found from main effects plot for S/N ratios (Fig. 6) that optimal step size (1 mm) ensures the minimum burr height. In order to analyze the effect of step size on the burr height, burr height values were plotted with three different step sizes (Fig. 11). Burr height increased by 17% when the step size was increased from 0.5 mm to 1.5 mm. It can be demonstrated that a large step size shows a larger depth of cut, whereas a smaller step size would make the rubbing action instead of cutting operation against the uncut portion of the work piece and leads to early initiation of the bending action

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Fig. 6 - Main effects plot for S/N ratios (burr height).

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Fig. 7 – (a) Thrust-time characteristics at 0.06 mm/rev, 600 rpm, step angle 40°, step size 1 mm. (b) Thrust-time characteristics at 0.1 mm/rev, 600 rpm, step angle 40°, step size 1 mm.

Fig. 8 – Effect of feed on burr height.

Fig. 9 – Effect of spindle speed on burr height.
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Feed was found to have a significant influence on thrust force. The results uniquely revealed that an increase in feed increases the thrust force and Burr height. The best combination values of optimum parameters were confirmed with the verification experiments. The closeness of the results of predictions based on calculated S/N ratios and experimental values shows that the Taguchi experimental design technique can be used successfully for both optimization and prediction.

7. Conclusions

This paper has presented an application of L27 orthogonal array of Taguchi method and analysis of variance for investigating the effects of step drill’s geometries and cutting parameters on the exit Burr height in drilling of Al–Gr composite. Based on this study, the following conclusions have been summarized. The results of ANOVA revealed that feed, step angle and step size were the most significant parameters followed by spindle speed in the exit Burr height. It was found that the optimum parameters for minimum exit Burr height were feed (0.06 mm/rev), spindle speed (600 rpm), step angle (40°) and step size (1 mm).

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Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES