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Optimization of Drilling Parameters of Carbon Fiber Composites Using RSM based Desirability Function

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Abstract. This paper deals with the drilling of Carbon Fiber Reinforced Polymer (CFRP) composite filled with Carbon Nano Tube (CNT) using Response Surface Method (RSM) based desirability function. In drilling of hybrid metal matrix CFRP composites, excess thrust force and burr height degrades the performance of composite. Therefore, thrust force and burr height of the composite to be minimized in order to improve the performance of the hybrid metal matrix composite. Hence, thrust force and burr height are factors being considered in the present investigation are the major responses to be minimized using RSM based Desirability function. Four important input factors are considered such as drilling speed, feed rate, percentage of CNT and cone angle of drill bit to analyze the performance of drilling process. The results showed that, feed rate is highly influential parameter which influences thrust force and burr height in hybrid metal matrix composites. During drilling operation, due to mutual rubbing of CNT abrasive particles causes extensive surface damages like voids, cracks and fiber pullouts. ANOVA result indicates experimental data are well correlated at 95% confidence interval and this technique can be very much useful and reliable for predicting the drilling parameters of hybrid CFRP metal matrix composite.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been extensively used in various engineering applications due to their outstanding mechanical properties (1, 2). Therefore, it enables light weight products manufacturing and extend their service-life structures. In the past decades metallic materials have been widely replaced by CFRP. In view of growing engineering applications with composites requires a systematic study for their machining characteristics was envisaged. The efficient and economical machining parameters required for obtaining desired profile and dimensions of the composite. However, it is well known that the many factors affecting the mechanical properties of the CFRP during loading. Especially during manufacturing processes, the factors such as temperature, pressure and processing time may lead cracking, fiber delamination’s and breakages in the composites that affects the mechanical properties of fabricated composite (3). Hence composites can be considerably modified by resins, adding nano filler and method of fiber layups, etc. Therefore, numerous surface treatments have been developed to improve interfacial adhesion characteristics of the polymer composites namely electrochemical method, plasma treatment and high energy irradiation and oxidation method (4). Although homogeneous scattered nano particles are of great importance to enhance the surface strength and hardness of the composite. Thus, increase of addition amount of nano particles may lead poor surface finish, and increase thrust force which cause excess tool wear, exhibit numerous pits and burrs (5). Therefore, by selecting appropriate machining parameters can minimize thrust force and reduces burr and pits during composite machining. Therefore, in view of above a
detailed systematic study was conducted using RSM based Desirability function. The mathematical model was developed using RSM for modeling and analysis performance in the drilling of hybrid metal matrix composites.

2. Experimental setup

2.1. Materials and methods
Carbon fibers of single ply lamina having a diameter of 5-10µm was fabricated with a thickness of 5 mm sheet for conducting a drilling process. 60% resin and 40% hardener are mixed together in a required proportion, and the gel time is measured. In addition to that 5% of carbon nano tubes having the sizes of 50 – 80nm were added in a liquid epoxy resin based on weight fraction. The mixture stirred at room temperature for 48 hours under a seal condition to make homogeneous CNT filled epoxy solution. Carbon fiber reinforced polymers (CFRP) composites is made into laminas by 300 mm x 300 mm with 0, 90, 45 degrees of angle. Weights are added on the setup to remove the excess amount of resin and hardener mixture. The fabricated CNT filled CFRP composite plate as presented in Figure 1.

![Fabricated CNT filled CFRP composite](image)

Figure 1. Fabricated CNT filled CFRP composite

2.2. Experimental design
The experiment was conducted with 29 runs as per the RSM design matrix. The design matrix was selected as per the number of input factors planned for the drilling experiments. The input parameters and their corresponding range chosen in the experiment are presented in Table 1.

| PARAMETERS               | RANGE         |
|--------------------------|---------------|
| Drilling speed (N)       | 500-1100 (rpm)|
| Feed rate (f)            | 0.4-0.8 (mm/min)|
| % of CNT                 | 3-5           |
| Point angle (θ)          | 110-120       |

3. Experimental procedure
Drilling experiment was conducted using a vertical CNC machining center. Each CFRP sample to be drilled was cut into the sizes of 100mm x 100mm. The solid carbide drill was used to conduct each run involved in the design matrix. The Point angle of the carbide drill tool 110°, 115° and 120° respectively was maintained according to the sequence of the experimental run in the design matrix. Two responses namely thrust force on z – axis and burr height were considered as a response in the present investigation. The schematic representation of drilling process is presented in Figure 2 and the design matrix and their corresponding response obtained is presented in Table 2.
Figure 2. Schematic representation of drilling process

Table 2. Design matrix and their corresponding responses

| Std | Run | Rotational speed (N) | Feed rate (mm/min) | Percentage of CNT % | Point angle (θ) | Thrust force (N) | Burr height (mm) |
|-----|-----|----------------------|--------------------|---------------------|----------------|-----------------|-----------------|
| 1   | 10  | 500                  | 4                  | 4                   | 115            | 15.75           | 0.02            |
| 2   | 9   | 1100                 | 4                  | 4                   | 115            | 58.5            | 0.36            |
| 3   | 25  | 500                  | 8                  | 4                   | 115            | 15.2            | 0.09            |
| 4   | 24  | 1100                 | 8                  | 4                   | 115            | 104.33          | 0.3             |
| 5   | 11  | 800                  | 6                  | 3                   | 110            | 33.17           | 0.12            |
| 6   | 18  | 800                  | 6                  | 5                   | 110            | 22.14           | 0.06            |
| 7   | 8   | 800                  | 6                  | 3                   | 120            | 18.16           | 0.26            |
| 8   | 4   | 800                  | 6                  | 5                   | 120            | 45.85           | 0.2             |
| 9   | 17  | 500                  | 6                  | 4                   | 110            | 12.36           | 0.02            |
| 10  | 19  | 1100                 | 6                  | 4                   | 110            | 80.14           | 0.29            |
| 11  | 7   | 500                  | 6                  | 4                   | 120            | 16.86           | 0.14            |
| 12  | 5   | 1100                 | 6                  | 4                   | 120            | 95.5            | 0.41            |
| 13  | 21  | 800                  | 4                  | 3                   | 115            | 15.4            | 0.12            |
| 14  | 14  | 800                  | 8                  | 3                   | 115            | 35.68           | 0.21            |
| 15  | 2   | 800                  | 4                  | 5                   | 115            | 23.18           | 0.16            |
| 16  | 26  | 800                  | 8                  | 5                   | 115            | 44.68           | 0.05            |
| 17  | 12  | 500                  | 6                  | 3                   | 115            | 14.33           | 0.08            |
| 18  | 20  | 1100                 | 6                  | 3                   | 115            | 65.67           | 0.38            |
| 19  | 3   | 500                  | 6                  | 5                   | 115            | 12.17           | 0.06            |
| 20  | 22  | 1100                 | 6                  | 5                   | 115            | 90.3            | 0.29            |
| 21  | 29  | 800                  | 4                  | 4                   | 110            | 21.17           | 0.09            |
| 22  | 27  | 800                  | 8                  | 4                   | 110            | 42.94           | 0.09            |
| 23  | 6   | 800                  | 4                  | 4                   | 120            | 22.63           | 0.22            |
| 24  | 1   | 800                  | 8                  | 4                   | 120            | 46.75           | 0.21            |
| 25  | 15  | 800                  | 6                  | 4                   | 115            | 42.48           | 0.26            |
| 26  | 16  | 800                  | 6                  | 4                   | 115            | 42.18           | 0.27            |
| 27  | 13  | 800                  | 6                  | 4                   | 115            | 41.63           | 0.29            |
| 28  | 23  | 800                  | 6                  | 4                   | 115            | 41.84           | 0.28            |
| 29  | 28  | 800                  | 6                  | 4                   | 115            | 44.94           | 0.28            |
4. Modeling the process parameters using RSM

Response Surface Methodology (RSM) is a statistical technique used for modeling, optimization, and to analyze the problems (6-10). It is also used to establish the relationship between the input drilling process parameters and the required responses. Usually, the goal is to estimate the values of input process parameters in the drilling process at which the responses are optimized. The optimum may be either minimum or maximum depends upon the user interest in the experiment. Hence RSM is widely used in many application areas in order to get an optimum values on their corresponding processes (11-13). The thrust force and burr height of the CRFP composites are related to rotational speed (N), feed rate (f), percentage of CNT (% CNT), and Point angle (G). The surface is represented by the following,

\[ \text{Thrust force (T)} = f(N, f, \%\text{CNT}) \]
\[ \text{Burr height (BH)} = f(N, f, \%\text{CNT}) \]

The second order polynomial response surface model used to evaluate the parametric effects of the drilling process parameters are as follows,

\[ Y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \]

Where \( \beta_o \) is the average response, \( \beta_i \), \( \beta_{ii} \) and \( \beta_{ij} \) are the coefficients that depend on the major and interaction effects of the parameters and \( \varepsilon \) is the statistical error (14). A second order response surface for thrust force and burr height can be represented as below,

**Thrust force (T)**
\[ +42.61 +33.98 A +11.08 B +4.66 C +2.82 D +11.60 A \times B +6.70 A \times C +2.72 A \times D +11.60 B \times C +6.70 B \times D +2.72 C \times D +11.63 A^2 -5.23 B^2 -8.42 C^2 -3.80 D^2 \]

**Burr Height (BH)**
\[ +0.28 +0.13 A -1.667E-003 B -0.029 C +0.064 D -0.033 A \times B -0.018 A \times C -0.050 B \times C -2.500E-003 B \times D +9.250E-003 A^2 -0.074 B^2 -0.066 C^2 -0.051 D^2 \]

ANOVA is applied for estimating the significance of the model at 95% significance level. The main objective of conducting ANOVA is to estimate the interaction and significant effects on thrust force and burr height of drilling process. In ANOVA, adequacy of the developed model was conformed with R-Sq values. In the present investigation the R-Sq was obtained 0.9974 and 0.9953 for thrust force and Burr height.

![Normal Plot of Residuals for Thrust Force](image1)

![Normal Plot of Residuals for Burr Height](image2)

**Figure 3. Experimental vs. predicted values of thrust force**

**Figure 4. Experimental vs. predicted values of Burr height**
burr height respectively. The larger R-Sq values is desirable. Therefore, the present R-Sq value is indicates high correlation between experimental and predicted values. Also, the aforementioned experimental and predicted values are plotted in Figure 3 and Figure 4. Hence the predicted mathematical model is very useful and effectively predict the thrust force and burr height of CFRP composite filled with CNT nano particles in drilling process within the limits of factors studied.

5. Optimization using RSM based desirability function

Derringer and Suich (1980) proposed a multi-response optimization technique namely desirability function. The overall desirability function of the multi-response system can be estimated by combining the individual desirability function. The desirability function can be represented as \( D = d_1^{w_1} d_2^{w_2} \ldots d_n^{w_n} \) where \( w_j (0<w_j<1) \) is the weight value given for the importance of \( j^{th} \) response variable and \( \sum_{j=1}^{n} w_j = 1 \). The parameter settings with maximum overall desirability is considered for optimum parameter combination. In the present investigation the goal is to minimize the thrust force and burr height of the drilling process of CFRP composite. The optimization analysis was performed using Design Expert software. The goal sets and targets of input parameters namely \( N, f, \% \) of CNT and \( \Theta \) and the response are presented in Table 3.

| Drilling parameters | Goal       | Lower limit | Upper limit | Lower weight | Upper weight | Importance |
|---------------------|------------|-------------|-------------|--------------|--------------|------------|
| Drilling Speed (N)  | is in range| 500         | 1100        | 1            | 1            | 3          |
| Feed rate (f)       | is in range| 4           | 8           | 1            | 1            | 3          |
| % of CNT            | is in range| 3           | 5           | 1            | 1            | 3          |
| Point angle (\( \Theta \)) | is in range | 110 | 120 | 1 | 1 | 3 |
| Thrust force (T)    | minimize   | 12.17       | 104.33      | 1            | 1            | 3          |
| Burr height (h)     | minimize   | 0.02        | 0.41        | 1            | 1            | 3          |

The solution with high desirability is preferred. Therefore, the best three combination of obtained desirability values and their corresponding suggested input process parameters are presented in Table 4.

| Number | Drilling Speed (N) | Feed rate (f) | % of CNT | Point angle (\( \Theta \)) | Thrust force (T) | Burr height (h) | Desirability |
|--------|--------------------|---------------|----------|---------------------------|------------------|-----------------|--------------|
| 1      | 511.56             | 4.11          | 4.74     | 113.48                    | 7.55313          | 0.00867         | Selected     |
| 2      | 538.44             | 4.57          | 4.99     | 111.1                     | 7.0906           | 0.0308          | 1            |
| 3      | 551.72             | 8             | 4.55     | 112.58                    | 11.7932          | 0.01169         | 1            |
| 4      | 502.25             | 4             | 4.98     | 116.68                    | 7.85585          | 0.01972         | 1            |

6. Results and discussion

The contour plots for drilling speed, feed rate, % of CNT and Point angle on thrust force and burr height are presented in Figure 5. Increasing feed rate increasing thrust force of drilling process and vice versa. Therefore, the increase in thrust force bends the materials larger to the extent interfacial bond cracking progresses, resulting larger burr formation. The increase in weight percentage of CNT increases thrust force. The presence of addition of CNT in the metal matrix composited increases tensile strength, hardness and heat resistance of the composite (15, 16). This can be attributed increasing brittleness of the composite that reduce built-up edge in the drilling of hybrid composites. Increasing point angle of drill increases thrust force of drilling process whereas the burr height of the composite is
decreases. As the drill advances it forms a pivot point thereby it decrease the burr height of the metal matrix composite. This results are in good agreement with Basavarajappa et al (17).

Figure 5. Contour plots for Thrust force
Low feed rate encourages less thrust force therefore exist poor plastic deformation on the metal matrix composite. Due to low interfacial strength CNT particles smears before bending the material during the plastic deformation in the drilling process. Increasing feed rate increase temperature at the tool-work surface therefore softening plastic deformation. Hence, burr height predominantly increases with increase in spindle speed. SEM was used to analyze the machined surface. During drilling operation, due to mutual rubbing of CNT abrasive particles causes extensive surface damages like voids, cracks and fiber pullouts.

7. Conclusions

The mathematical models were developed for estimating the thrust force and burr height in drilling of hybrid carbon fiber composites. Response surface modeling-based desirability-based optimization was carried out to minimize the thrust force and burr height in drilling process. Based on the experimentation the following conclusions can be drawn,

1. Response surface method-based desirability is very useful in predicting the thrust force and burr height of the hybrid metal matrix composites.
2. The result indicates feed rate is highly influential parameter which influences thrust force and burr height in hybrid metal matrix composites.
3. SEM analysis of the drilled hole surface indicates higher feed rate and spindle speed increase voids, cracks and fiber pullouts.
4. The ANOVA result indicates that the experimental data are well correlated with the predicted data at 95% confidence interval; hence, this technique can be very much useful for a reliable prediction of different performances.

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