Development of a Cutting Force Prediction Model for Silica/Phenolic Composite in Mill-grinding

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Abstract. A cutting force model was developed from silica/phenolic composites for mill-grinding process. The experimental was carried out on silica/phenolic material and found that the cutting force decreased significantly with the increase of cutting speed, whereas the same was found increased with the increase of feed rate and cutting depth. By comparison of the experimental and simulation data of the cutting force, it was found that the errors are below than 30 % in most of the sets of parameters. The variation found is due to the heterogeneity and other complex properties of silica/phenolic composites. The results were almost the same as previous experiments. So, the cutting force model developed in this paper is robust and it can be applied to predict the cutting force and optimization of the process.

1. Introduction
Silica/phenolic composite are attractive due their superior properties such as low density, low thermal conductivity, ultra high-adsorption ability, ablation resistant performance and thermal stability. Presently, Silica/phenolic composite are used in thermal protection systems[1]. Their applications are increasing in space, military, and aerospace industries day by day. In traditional machining processes, the cutting tools wear very quickly and the cutting tools like polycrystalline diamond (PCD) tools are very expensive. It is challenging to achieve desired accuracy, high efficiency, and cost-effective processing for such composites. Keeping in view of their special properties and critical engineering applications, there is a crucial need to research for machining of silica/phenolic composites in order to achieve economic and efficient processing with desired quality. Low efficiency, high processing costs, and quality issues are three main problems which hindered the applications of silica/phenolic materials. With mill-grinding, better results have been achieved as compared to conventional machining of composites materials. Jinguang Du developed a cutting force mathematical prediction model on the basis of the study on material removal mechanism of SiCp/Al. Based on the cutting force model, the distribution of chip deformation component force, friction component force and particle fracture with the change of machining parameters, such as cutting speed, feed rate and milling width, was calculated[2]. Li Wanqing studied the effects of cutting speed, feed rate, and cutting depth on mill-grinding force. The mill-grinding force has found increased with the increase of feed rate and cutting depth while it has decreased with the increase of cutting speed[3].

In this paper, the mechanistic model is developed to predict the cutting force for Silica/phenolic based on indentation fracture mechanics in mill-grinding. The mathematical relationship between cutting parameters (spindle speed, feed rate, and cutting depth) and cutting force is proposed. The parameter, k1, k2, k3, was obtained using response surface method. This paper is organized into five sections. After this introduction section, the predicted cutting force model is designed and developed
in Sect. 2. In Sect. 3, the experimental mill-grinding is carried out and the data acquired is reported. The results and discussion are mentioned in Sect. 4. Finally, the conclusions are presented in Sect. 5.

2. Modeling
The material removal mechanism in mill-grinding is based on indentation fracture theory. When the diamond abrasive grit penetrates into the surface of the workpiece material, there will be a plastic deformation. With the increase of penetration depth, the median crack will grow and also generate the lateral crack. The extended lateral cracks then induce and peeling off the workpiece material occurs as shown in ‘figure 1’[4]. The maximum penetration depth \((w)\) was used as an intermediate parameter to establish the relationships between the input parameters (spindle speed, feed rate, and cutting depth) and the output parameter, i.e., cutting force.

![Figure 1. Crack propagation](image)

Because of the randomness of distribution of wear debris, the abrasive angle is not a constant number. As shown in ‘figure 2’, while the value of penetration depth is \(w\), the maximum and the minimum of the sweep area are \(\Delta OBD\) and \(\Delta OEF\), the area can be expressed as[5]:

\[
S_{\text{max}} = \frac{1}{2} \cdot 2w \cdot w = w^2 
\]

\[
S_{\text{min}} = \frac{1}{2} \cdot \sqrt{2}w \cdot w = \frac{\sqrt{2}}{2} \cdot w^2
\]

![Figure 2. The sweep area of the diamond grits](image)

The mean area was used to simplify the calculation. The average area can be calculated as follows:
The microscopic contact length of abrasive and materials is shown in ‘figure 3’. The contact angle $\theta$ can be expressed as:

$$\theta = \arccos \left(1 - \frac{2w}{D}\right)$$

(4)

As $w<<D/2$, $\theta$ can be expressed as follows:

$$\theta = 2\sqrt{\frac{w}{D}}$$

(5)

The value of microscopic contact length can be expressed as:

$$l_c = \frac{D}{2} \cdot \theta = \sqrt{w \cdot D}$$

(6)

Figure 3. The microscopic contact length of abrasive and materials ($l_c$)

From a rather macroscopic perspective, the value of macroscopic contact length can be expressed as:

$$l_a = \frac{D}{2} \cdot \arccos \frac{D - 2a_e}{D}$$

(7)

Diamond abrasive concentration is the mass of abrasive per unit volume within working layer. Concentration is generally defined as follows: per cubic centimeter volume of abrasive grains containing 4.4 karats (1 karat diamond is equal to 0.2 g) is defined as 100. Each has an increase or decrease of 1.1 karats of abrasive, and then the concentration is increased or decreased by 25 %, respectively. According to this definition, the total number of active diamond abrasive grains involved in cutting, $N_\alpha$, can be expressed as

$$N_\alpha = \left\{ \frac{0.88 \times 10^{-3} \cdot C_a}{\sqrt{2 \times S_a^3}} \cdot \frac{100}{\rho} \right\} \cdot A_0 = 0.03 \cdot \frac{C_a^{2/3}}{S_a} \cdot l_a \cdot a_p$$

(8)

Material removal rate MRR is the summary of the material removed by all the effective abrasive particles during one period and can be expressed as follows:

$$MRR = N_\alpha \cdot V_c \cdot S$$

(9)

MRR can also be expressed as the volume swept by the cutting tool during one period:

$$MRR = a_e \cdot a_p \cdot f$$

(10)
By solving both Eqs. (9) and (10), the relationship between maximum penetration depth and cutting parameters can be obtained as follows:

\[
w = \left( \frac{4 \times a_w \cdot f_r \cdot S_a^2}{0.03 \times (2 + \sqrt{2}) \cdot C_{\alpha} \cdot D / 2 \cdot \arccos \left( \frac{D - 2a_w}{D} \right) \cdot \sqrt{D} \cdot S} \right)^{2/5} \tag{11}
\]

The cutting of mill-grinding can be expressed as three components: \( F_x, F_y\). \( F_x \) is caused by cutting materials of abrasive particles directly, can be expressed as follows:

\[
F_x = N_a \cdot F_a = k_1 \cdot N_a \cdot w^2 \cdot \sigma_b \tag{12}
\]

Where \( F_a \) is the cutting force caused by one diamond abrasive, \( \sigma_b \) is the yield strength of the silica/phenolic composite, \( k_1 \) is a constant number which demarcated by experiment.

\( F_y \) is proportional to the cutting area per unit time, which can be express as follows:

\[
F_y = k_2 \cdot 0.03 \times \frac{L^2 / 3}{S_a^2} \cdot a_w \cdot a_p \cdot w^2 \cdot \sigma_b \tag{13}
\]

Where \( k_2 \) is a constant number which demarcated by experiment.

### 3. Experimental setup

The schematic and the actual experimental setup is shown in ‘figure 4’, respectively. The setup is composed of three parts: three-axis milling machine (VMC0850B, Shenyang, China), diamond abrasive tool, and dynamometer (9257B, Kistler, Switzerland).

Silica/phenolic composite were used as the workpiece sample materials. The mechanical properties of Silica/phenolic composite are shown in Table 1. The parameters of diamond abrasive tool are shown in Table 2.

![Experimental setup](image)

**Figure 4.** Experimental setup

| Table 1. Mechanical properties of Silica/phenolic composite workpiece material |
|-------------------------------|---|
| Density (g/cm\(^3\))          | 1.6 |
| Tensile strength(MPa)         | 20  |
| Compression strength (MPa)    | 100 |
| Bending strength(MPa)         | 50  |
| Elongation at break(%)        | 0.35|

| Table 2. The properties of diamond abrasive tool |
|-----------------------------------------------|
| Abrasive          | Diamond |
| Bond type         | Electroplated |
Grain size  
Concentration $C_\alpha=100$
Radius $R=16\text{mm}$

The experimental design is shown in Table 3. Three groups of input parameters such as spindle speed, cutting depth, and feed rate were used in this research. These parameters were found significant on the basis of random experiments and the findings of previous research work. These cutting parameters were designed by response surface method with three factors.

Table 3. Experimental design

| Factor                  | Level 1 | Level 2 | Level 3 |
|-------------------------|---------|---------|---------|
| Spindle Speed (rev/min) | 1000    | 3500    | 6000    |
| Feedrate (mm/min)       | 150     | 325     | 500     |
| Cutting Depth (mm)      | 0.2     | 1.1     | 2       |

4. Experimental results and discussion

Table 4 shows the results of cutting force tests of cutting force. It was found that the simulation values are closest to measurement values, when $\Sigma (F - k^*F_S)^2$ got the minimum value. Here, $k_1$ has obtained as 1.44, $k_2$ has obtained as 5.38. The comparative analysis of measured values and simulated values of cutting force was carried out, and finally, the percentage error was found for each set of experiments. It was found that in most of the cases, the error is below 30 % expt 16 (77 %). Such variations are mainly due to the heterogeneity of silica/phenolic.

Table 4. Comparative analysis of measured values and simulated values of $F_x$

| Spindle Speed (rev/min) | Feedrate (mm/min) | Cutting Depth (mm) | $F_x$ N | Simulation $F_x$, N | Error $F_x$, % | $F_y$ N | Simulation $F_y$, N | Error $F_y$, % |
|-------------------------|-------------------|--------------------|---------|---------------------|----------------|---------|---------------------|----------------|
| 1                       | 3500              | 500                | 2       | 164                 | 173            | 5       | 250                 | 265            | 6 |
| 2                       | 3500              | 325                | 1.1     | 69                  | 68             | -2      | 97                  | 103            | 6 |
| 3                       | 3500              | 325                | 1.1     | 70                  | 68             | -3      | 100                 | 103            | 3 |
| 4                       | 1000              | 150                | 1.1     | 134                 | 99             | -26     | 215                 | 151            | -30 |
| 5                       | 6000              | 325                | 2       | 86                  | 79             | -8      | 122                 | 124            | 2 |
| 6                       | 3500              | 325                | 1.1     | 63                  | 68             | 7       | 92                  | 103            | 12 |
| 7                       | 6000              | 500                | 1.1     | 79                  | 62             | -22     | 111                 | 92             | -17 |
| 8                       | 3500              | 325                | 1.1     | 70                  | 68             | -3      | 106                 | 103            | -3 |
| 9                       | 1000              | 325                | 2       | 286                 | 333            | 16      | 479                 | 508            | 6 |
| 10                      | 1000              | 325                | 0.2     | 37                  | 33             | -10     | 38                  | 49             | 28 |
| 11                      | 3500              | 325                | 1.1     | 68                  | 68             | 0       | 98                  | 103            | 5 |
| 12                      | 1000              | 500                | 1.1     | 300                 | 259            | -14     | 412                 | 394            | -4 |
| 13                      | 3500              | 150                | 2       | 78                  | 66             | -15     | 109                 | 103            | -6 |
| 14                      | 6000              | 150                | 1.1     | 29                  | 23             | -21     | 50                  | 36             | -28 |
| 15                      | 3500              | 150                | 0.2     | 8                   | 7              | -10     | 9                   | 10             | 14 |
| 16                      | 6000              | 325                | 0.2     | 11                  | 9              | -21     | 7                   | 12             | 77 |
| 17                      | 3500              | 500                | 0.2     | 17                  | 17             | 2       | 22                  | 26             | 20 |

5. Summary

In this research, mill-grinding was carried out on silica/phenolic composite. The following conclusions...
can be drawn:

1. The cutting force model was developed and then validated by experimental machining of 
silica/phenolic using mill-grinding. It was found that percentage difference/error between the 
measured and simulated (from model) values of cutting force is less than 30 % in the most set of 
values. However, in few cases, this difference was recorded more than 30 %. The cause of this 
difference is due to the heterogeneity and some other factors related to silica/phenolic composites. So, 
this model is robust and can be applied for finding cutting forces.

2. The cutting force has found increased with the increase of feed rate and cutting depth while it 
has decreased with the increase of spindle speed.

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