PREDICTION OF CUTTING FORCE DURING GYPSUM FIBER COMPOSITE MILLING PROCESS USING RESPONSE SURFACE METHODOLOGY

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Abstract. Gypsum fiber composite (GFC) is a kind of building material widely used in interior decoration. Milling is the most commonly used machining process for GFC. Cutting force as an important cutting characteristic parameter has significant influence on the quality of machined surface, power consumption, and tools wear. The tangential force (F_x) and normal force (F_y) were measured and analyzed to find out the effects of milling parameters on these cutting forces. Milling parameters considered were spindle speed, feed rate, and depth of cut. The response surface methodology (RSM) was selected to develop mathematical models and optimize milling parameters. The results showed that with the increase of feed rate and depth of cut, the F_x and F_y increased. But the cutting forces decreased with the increase of spindle speed. The optimization results indicated that high spindle speed, low feed rate, and small depth of cut are preferable for milling of GFC to obtain the best result.

Keywords: Gypsum fiber composite, milling, Cutting force, RSM.

INTRODUCTION

Gypsum fiber composite (GFC) as a kind of building material is made of gypsum plaster and natural fiber (such as wood fiber and straw fiber, etc.). Because of its low production energy consumption, light heat-insulation, fire resistance, and ease of fabrication, it is widely used as internal wall covering, ceiling, and acoustic panel in interior decoration. In interior decoration process, GFC is machined to specified sizes and shapes before installation. Cutting process include milling, sawing, and drilling, etc. Cutting force is a critical physical quality in the machining process, it plays an important role in the practical cutting process and has direct influence on the power consumption, cutting tools wear, cutting heat, and quality of processed surface (Wyeth et al 2008; Marchal et al 2009; Guo et al 2014).

In view of achieving good machinability and improved product quality, the effect of cutting conditions on cutting process should be investigated. However, the cutting performance also varies with different types of cutting method. Milling as a basic method of material cutting process has been improved in the last decades because of the advent of new tooling systems, technologies, and control. Many aspects of milling process, such as cutting tools vibrations, dimensional errors, and milled surface quality is mainly affected by the cutting force (Grossi et al 2015). The understanding of milling process leads to models that reveal the relationship between milling behavior and machining parameters. In previous scientific studies, researchers presented many methods of achieving the optimum cutting parameters based on expensive experimental setups and long test durations. Because of these, different analyses, optimization. and modeling techniques have been proposed, including finite element analysis, multiple regression method, Taguchi method, fuzzy logic, genetic algorithms, response surface methodology (RSM), and artificial neural networks, etc. (Venkatesan et al 2009; Korkut et al 2011; Koklu 2013; Kara et al 2015; Shankar et al 2015; Mia and Dhar 2016; Rao et al 2016).

Summarizing the recent scientific studies, some researches based on RSM have been performed frequently because of the convenient calculation of this technique. Jeyakumar et al (2013) investigated the effects of machining parameters (such as spindle speed, feed rate depth of cut, and nose radius) on cutting force by RSM. As a result of the study, the prediction model was found to be in agreement with the experimental result. This result was helpful in the selection of cutting parameters to reduce the cutting force and tool wear. Aouici et al (2012) presented a modeling method to predict the cutting force during AISI H11 steel turning process. The parameters, such as the cutting speed, feed rate, hardness, and depth of cut were selected and the influence of cutting force investigated. The results showed that cutting force components were influenced principally by the depth of cut and work piece hardness. Sun et al (2015) studied the cutting force during cutting processing by RSM. The results showed that cutting force calculation models were suitable for the Fe-Al-based machining.

GFC is widely used for interior decoration. However, previous studies were mainly focused on manufacturing technique and performance modification; and there is in fact a paucity of literature on the cutting process for GFC. The

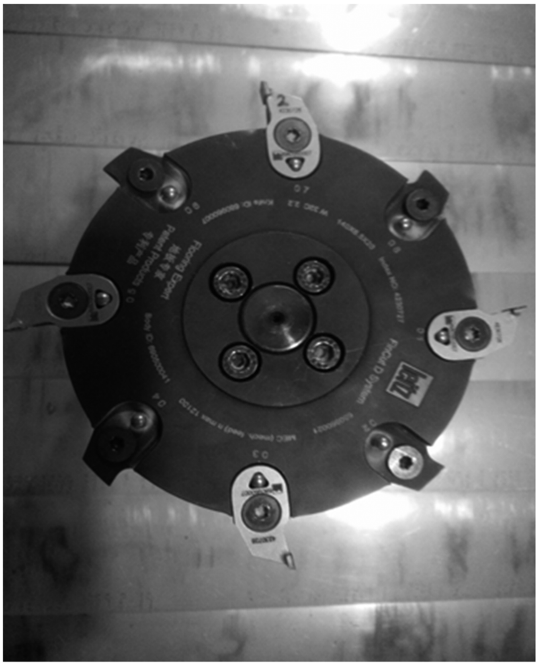

Figure 1. Cutting tools.

purpose of this work is to evaluate the effects of the various milling parameters on cutting forces during GFC milling using diamond cutting tools; a specific cutting force model for GFC milling process by RSM. The model considers the specific cutting force in terms of the milling parameters such as feed rate, spindle speed, and depth of cut. This model was found helpful in determining milling parameters, designing milling cutters, and choosing milling methods for GFCs.

MATERIALS AND METHOD

Materials and Equipment

The tested GFC was made of gypsum plaster, which was reinforced with natural wood fiber. The density and thickness were 860 kg/m^3 and 10 mm, respectively. The fracturing load in horizontal and longitudinal direction were 172 N and 470 N, respectively, the test was carried out according to the Chinese standard GB/T 9775-2008.

In the milling process, diamond cutting tools were selected to carry out the experiments. These cutting tools made by Leitz Co., Ltd. (located in Nanjing, China) had a rake angle of 12° and clearance angle of 16° as shown in Fig 1.

In this study, the cutting forces were tested by up-milling on the PAOLINO BACCI 5-axis horizontal CNC center (Italy). The cutting forces were recorded using a standard quartz dynamometer (Kistler 9257B) allowing measurements from -5 to 5 KN. The direction of F_x was paralleled to the feed rate, the direction of F_y was perpendicular to the feed rate. The experimental setup and flowchart of data collection are shown in Fig 2.

Plan of Experiment

The analyses and modeling techniques of RSM by Box-Behnken design (BBD) were applied. RSM is a collection of mathematical and statistical techniques that are useful for modeling and analyzing the effects of several variables on the

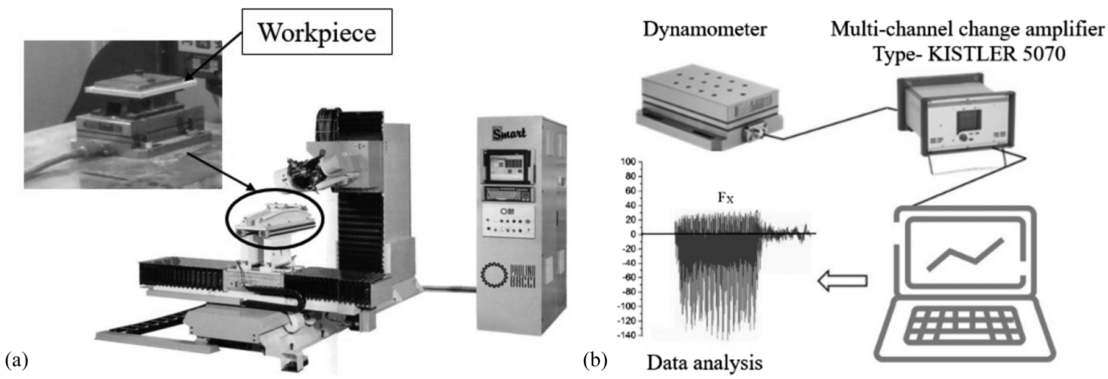

Figure 2. Experiment setup (a) and flow chat of experiment date collection (b).

Table 1. The milling parameters and levels.

Parameters	Code	Level −1	Level 0	Level 1
Spindle speed/n (r/min)	A	1000	2000	3000
Feed rate/U (m/min)	B	5	10	15
Depth of cut/d (mm)	C	0.5	1	1.5

response, to optimize this response. The Design-Expert Software was used in the organization of the experimental plan for RSM. It was also used to analyze the data obtained from the experiment (Rajamurugan et al 2012; Bhushan 2013).

In the analysis, procedure for the approximation of the response was achieved by developing BBD-based RSM model. Eq (1) presents a model of milling response.

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i,j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \quad (1)$$

where, b_0 is the free term of the regression equation. The coefficients, b_1, b_2, … b_k and b_{11}, b_{22}, … b_{kk} are the linear and quadratic terms, respectively. While b_{12}, b_{13}, … b_{k-1} are the interacting terms. $X_{n=1,2,3}$ is the coded variables. The experimental plan is developed to assess the influence of spindle speed, feed rate, and depth of milling on cutting force components (Aouici et al 2013).

In this study, spindle speed, feed rate, and depth of cut were considered as process parameters. The milling experiments are conducted at three levels. The parameters applied and their levels were presented in Table 1.

RESULTS AND DISCUSSION

The tangential force (F_x) and normal force (F_y) data were collected by a dynamometer. The results are shown in Table 2. The experiments were conducted in the order denoted [b] (random method), and the results were inputted into the RSM software in the order shown in the column denoted [a] (standard method).

Analysis of Mathematical Model

The analysis of variance (ANOVA) was carried out to ascertain the BBD model adequacy of this experimental design and to know the factors having significant influence on the milling process. Results of the ANOVA for F_x and F_y are shown in Table 3 and Table 4, respectively. The models for F_x and F_y were significant with

Table 2. Design matrix and experimentally recorded data.

		Factors			Responses	
Standard[a]	Run[b]	Spindle speed/n (r/min)	Feed rate/U (m/min)	Depth of cut/d (mm)	F_x	F_y
1	17	1000	5	1	22.65	12.87
2	7	3000	5	1	18.08	10.56
3	14	1000	15	1	30.61	22.87
4	6	3000	15	1	19.50	18.62
5	16	1000	10	0.5	25.33	15.39
6	11	3000	10	0.5	13.62	10.32
7	15	1000	10	1.5	30.13	21.22
8	5	3000	10	1.5	28.97	19.32
9	2	2000	5	0.5	15.87	9.02
10	10	2000	15	0.5	22.92	18.16
11	3	2000	5	1.5	25.88	16.87
12	9	2000	15	1.5	34.06	22.08
13	8	2000	10	1	24.65	15.45
14	12	2000	10	1	24.66	15.42
15	4	2000	10	1	24.53	15.56
16	1	2000	10	1	24.80	15.32
17	13	2000	10	1	24.60	15.41

[a] The experiment plan is run using standard method.
[b] The experiment plan is run using random method.

Table 3. Results of the analysis of variance for F_x.

Source	Sum of squares	df	Mean square	F value	p value Prob > F
Model	440.8319	9	48.9813	63.1516	<0.0001
A- Spindle speed	101.8878	1	101.888	131.364	<0.0001
B- Feed rate	75.70651	1	75.7065	97.6084	<0.0001
C- Depth of cut	213.2112	1	213.211	274.893	<0.0001
AB	10.69290	1	10.6929	13.7864	0.0075
AC	27.82563	1	27.8256	35.8756	0.0005
BC	0.319225	1	0.31922	0.41158	0.5416
A^2	4.677541	1	4.67754	6.03075	0.0437
B^2	3.290341	1	3.29034	4.24223	0.0784
C^2	3.552178	1	3.55218	4.57982	0.0696
Residual	5.429305	7	0.77562	—	—
Lack of Fit	5.389825	3	1.79661	182.027	<0.0001
Pure Error	0.039480	4	0.00987	—	—
Cor Total	446.2612	16	—	—	—

the probability of <0.0001. P value less than 0.05% indicate that the model terms were significant. In this case, model terms A, B, and C are significant for F_x and F_y, which have significant contribution to cutting forces during milling of GFC. These results will be important for selecting milling parameters during GFC milling processing.

Generation of Mathematical Models

Using the Design Expert software, the response surface equations of F_x and F_y were developed for milling of GFC. The summary statistics of suggested models are listed in Table 5. The values of R^2 are very close to 1, which means that the model achieved a high degree of fit and can provide a satisfying prediction for the experimental results in GFC milling processing. The quadratic model was selected to obtain the relationship between response parameters and milling variable because of the high value of R^2. The model equations are stated in Eq 2 and 3:

$$F_x = 24.65 - 3.57 \times A + 3.08 \times B + 5.16 \times C - 1.64 \times A \times B + 2.64 \times A \times C + 0.28 \times B \times C - 1.05 \times A^2 - 0.88 \times B^2 + 0.92 \times C^2 \quad (2)$$

Table 4. Results of the analysis of variance for F_y.

Source	Sum of squares	df	Mean square	F value	p value Prob > F
Model	253.8116	9	28.2013	67.1036	<0.0001
A- Spindle speed	22.882616	1	22.8826	54.4481	0.0002
B- Feed rate	131.30106	1	131.301	312.424	<0.0001
C- Depth of cut	88.44500	1	88.4450	210.451	<0.0001
AB	0.940900	1	0.94090	2.23883	0.1782
AC	2.512225	1	2.51223	5.97772	0.0444
BC	3.861225	1	3.86123	9.1876	0.0191
A^2	0.721668	1	0.72167	1.71717	0.2314
B^2	0.620867	1	0.62087	1.47732	0.2636
C^2	2.161567	1	2.16157	5.14334	0.0577
Residual	2.941855	7	0.42027	—	—
Lack of Fit	2.911975	3	0.97066	129.941	0.0002
Pure Error	0.029880	4	0.00747	—	—
Cor Total	256.7534	16	—	—	—

Table 5. Summary of results of the analysis of variance for different models.

Responses	Source	Standard deviation	R^2	Adjusted R^2	Predicted R^2	Press
F_x	Linear	1.042364	0.94499	0.93229	0.89449	27.089
	2FI	0.825254	0.97347	0.95756	0.90384	24.689
	Quadratic	0.648278	0.98854	0.97381	0.81835	46.638
F_y	Linear	2.065386	0.87573	0.84706	0.74245	114.93
	2FI	1.289105	0.96276	0.94042	0.81937	80.607
	Quadratic	0.880690	0.98783	0.97219	0.80662	86.299

$$F_y = 15.43 - 1.69 \times A + 4.05 \times B + 3.33 \times C - 0.49 \times A \times B + 0.79 \times A \times C - 0.98 \times B \times C + 0.41 \times A^2 + 0.38 \times B^2 + 0.72 \times C^2 \quad (3)$$

where, A is spindle speed in r/min, B is feed rate in m/min, and C is depth of cut in mm.

The results of predicted cutting forces and actual cutting forces for this experiment are shown in Fig 3. It can be seen that the predicted values from models are very close to the actual values of cutting force; in other words, these established models are effective to predict the cutting force in the milling of GFC.

Effects of Input Parameters on Cutting Force

The results obtained from this research revealed that the effects of spindle speed, feed rate, depth of cut, the surface quality, power consumption, and tools wear are directly influenced by the cutting force. From the foregoing, it can be asserted that research and modeling of cutting force during milling process are important; the models and effects can be carried out using RSM.

The effect graph for machining parameters (spindle speed, feed rate, and depth of cut) is shown in Fig 4, it is obvious that tangential force F_x and normal force F_y were significantly influenced by machining parameters. The F_x and F_y increased with the increasing feed rate and depth of cut, but decreased with increasing spindle speed. This result is in agreement with the result obtained by Raman et al (2012) using the Medium Density Fiberboard milling process. When the spindle speed increases, the cutting force decreases. This may be associated with the decrease of friction coefficient between tool and work piece (Guo et al 2016; Zhu et al 2017a). This is because the friction frequency between tool and work piece increases with the spindle speed, the higher friction frequency had positive influence on the cutting temperature in the contact zone, causing a decrease in the friction

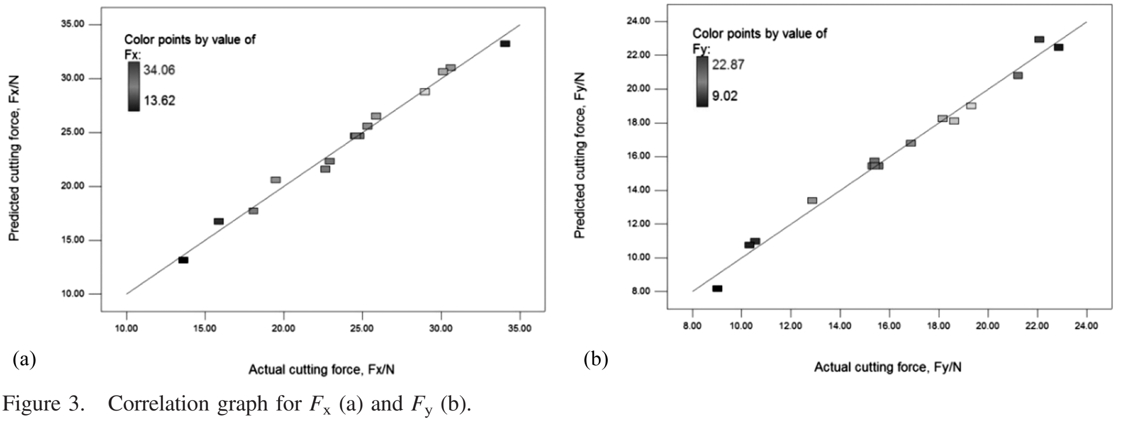

Figure 3. Correlation graph for F_x (a) and F_y (b).

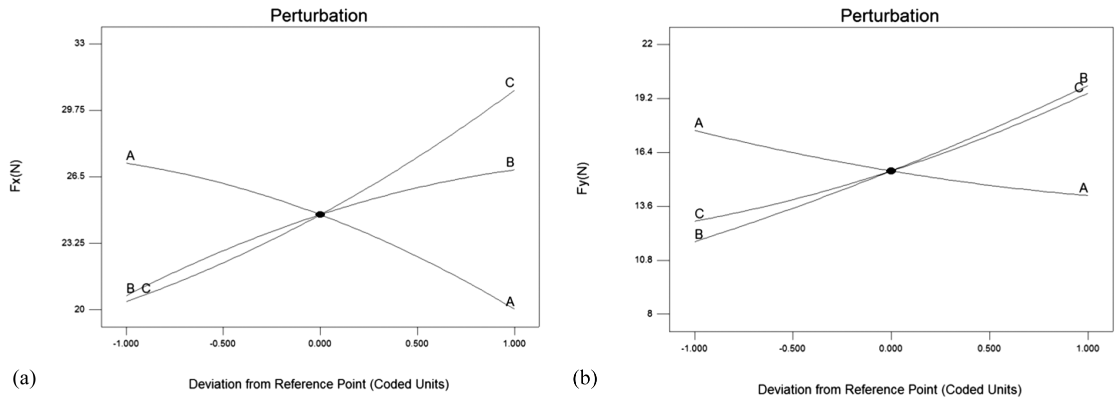

Figure 4. The effect of milling parameters on F_x (a) and F_y (b).

coefficient (Zhu et al 2017b). With increasing feed rate and depth of cut, each tooth cutting quantity increased. It induced the increasing of impact force between cutting tools and chip, which resulted in the increase of cutting force.

From the results of ANOVA, the interaction effect of spindle speed and depth of cut had a significant influence on F_x (as shown in Fig 5(a)). Also the interaction effect of the feed rate and depth of cut had significant influence on F_y (as shown in Fig 5 (b)). From Fig 5, it is easy to find the optimized milling parameters to achieve lowest cutting force. When the spindle speed is highest and the depth of cut is lowest, the lowest F_x was achieved. Also, the lowest F_y was obtained at the lowest level of depth of cut and feed rate. In this research, the optimization of milling parameters was conducted by RSM based on the goal of minimizing cutting forces and milling parameters in range, and the optimized combination of milling parameters realized were 2983 r/min, 5.47 m/min, and 0.57 mm for spindle speed, feed rate, and depth of cut, respectively. The optimization results indicated that high spindle speed, low feed rate, and small depth of cut are preferred for milling of GFC.

CONCLUSIONS

From the result of milling experiments carried out to investigate the cutting forces in cutting of GFC using Response-surface modeling, the following conclusions can be inferred:

1. The spindle speed, feed rate, and depth of cut have significant effect on cutting forces F_x and F_y, as the F_x and F_y increase with the increase of feed rate and depth of cut, but decreases with increasing spindle speed. Also, the interaction between spindle speed and depth of cut has more influence on F_x during the milling process. Whereas the interaction between feed

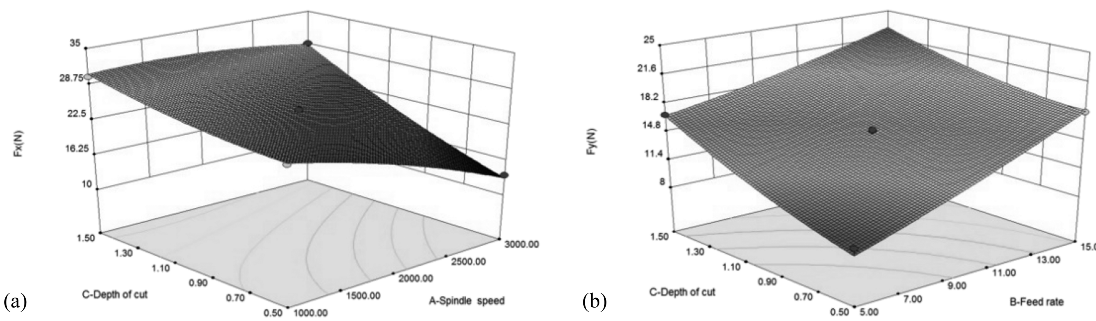

Figure 5. Estimated responses surface for F_x (a) and F_y (b).

rate and depth of cut affect the F_y more than other parameters.

2. The RSM modeling used for the milling parameters are effective in the prediction of the cutting forces for GFC.
3. The optimized combination of milling parameters are 2983 r/min, 5.47 m/min, and 0.57 mm for spindle speed, feed rate and depth of cut, respectively. In other word, high spindle speed, low feed rate, and small depth of cut provide optimum machine surface quality for the milling of the composite and should be adopted.

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