Testing and Modeling of Thrust Force and Torque in Drilling Recombinant Bamboo

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Recombinant bamboo with a thickness of 15 mm was drilled on a CNC machine. The process parameters considered were spindle speed, feed rate, and diameter of the drill, and the response parameters were thrust force and torque. Mathematical models were developed to establish the relationship between the process parameters and the response parameters. The results showed that the main influence on thrust force came from spindle speed and feed rate. High spindle speed with low feed rate was a combination that minimized the thrust force. The process parameters that have a major effect on torque are the diameter of the drill and the spindle speed.

Keywords: Drilling; Recombinant bamboo; RSM; Thrust force; Torque

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INTRODUCTION

Recombinant bamboo is a new type of engineered wood that is characterized by great structural integrity, high dimensional stability, good mechanical properties, and a density similar to that of hardwood (Wang and Hua 1991). It is a material made from bamboo *via* defibering, drying, gluing, laying-up, and hot-pressing (Zhao and Yu 2002). It is suitable for many interior construction and industrial applications, such as fabrication of wooden structures and furniture. This kind of material has favorable characteristics to include high density and hardness, but this can also reduce the machinability of the material. Drilling is a commonly used machining operation in manufacturing of products made out of recombinant bamboo. The assembly of such products requires drilling processes in order to connect the component parts. To date, there are few published works that present results from drilling tests of recombinant bamboo.

Singh and Kumar (2006) and Asiltürk and Neseli (2012) meant that process parameters affecting quality features of drilled holes fall into different categories, as indicated in Fig. 1. Valarmathi *et al.* (2012) showed that surface characteristics and some processing defects were significantly affected by the cutting force during the drilling process. The thrust force and torque induced by drilling can cause damage, such as rough surfaces and delamination of the material. The cutting force and torque in drilling wood composite products have been considered by many researchers. Gaitonde *et al.* (2008) revealed that delamination increased with increasing feed rate because of the increased thrust force; it decreased at higher cutting speeds in drilling of wood panels. Valarmathi *et al.* (2012) modeled the thrust force in drilling of plain medium density fiberboard composite panels using response surface methodology. The results showed that high spindle speed with low feed rate reduced the thrust force. The influence of process parameters on drilling forces using medium density fiberboard (MDF) panels was studied by Dippon *et al*. (2000) and Engin *et al*. (2000). They found that the cutting forces were affected by tool geometry parameters and "uncut chip area" and subsequently developed a model to predict the cutting forces for tools having complex geometry. Valarmathi and Palanikumar (2011) conducted drilling experiments and found that the thrust force in drilling of MDF decreased with low feed rate and high spindle speed. Zhao and Ehmann (2002) developed a mechanistic model for force and torque prediction throughout all phases of spade drill penetration. Valarmathi *et al.* (2013) measured and analyzed the thrust force in drilling particle board panels. The results showed that the thrust force was minimized by the combination of high spindle speed and low feed rate. Palanikumar *et al.* (2009) investigated the delamination when drilling medium density fiber boards and found that high spindle speed, low feed rate, and low drill diameter improved the drilling quality. Silva *et al.* (2014) evaluated the drilling-induced damage in composites. A systematic analysis of the image processing methodologies was carried out.

In this study, cemented carbide drills were used in recombinant bamboo drilling experiments. Spindle speed, feed rate, and diameter of the drill were chosen as process parameters. The thrust force (F_z) and torque (M_z) were chosen as response parameters because they are major parameters when modeling hole quality and induced damage.

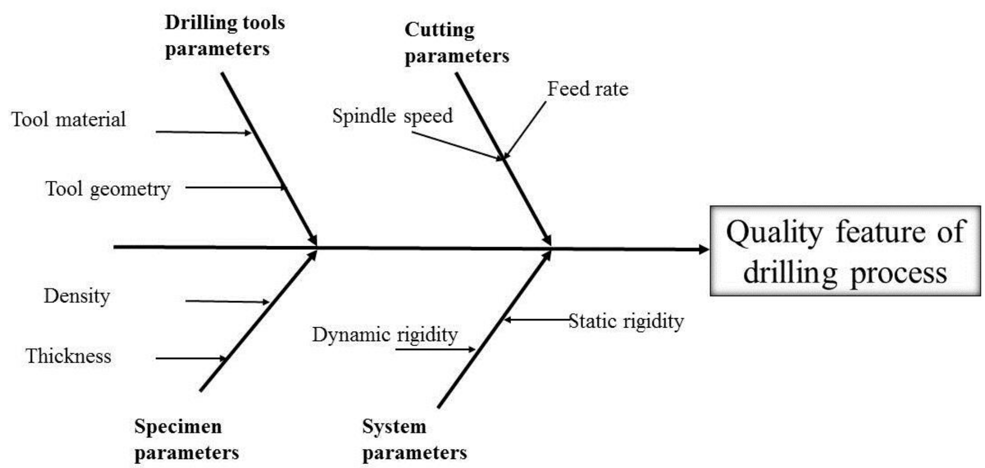


Fig. 1. The cause-effect diagram of the drilling process. Modified from Singh and Kumar (2006) and Asiltürk and Neseli (2012)

EXPERIMENTAL

Materials

Recombinant bamboo samples with a thickness of 15 mm were chosen as work pieces. The size of the samples was 170 mm (longitudinal, fiber direction) × 100 mm (width) × 15 mm (thickness). The samples were cut out from a larger strip of size 2000 mm x 100 mm x 15 mm. The recombinant bamboo was supplied by the Hunan Taohuajiang Industries Co., Ltd. (China). Cemented carbide drills with diameters of 6, 8, and 10 mm, 20° helix angle, and 60° point angle were used in the experiments. All drilling tools used in this experiment are new and sharp.

Methods

All experiments were performed on a CNC machine (Excitech E1, China) with a table size of 1900 mm × 1800 mm, a maximum spindle speed of 20000 rpm, and a maximum feed rate of 3000 mm/min. The thrust force (F_z) and torque (M_z) were recorded using a standard quartz dynamometer (Kistler 9257B, Switzerland) allowing measurements from -5 to 5 kN. The setup of the equipment with the recombinant bamboo, drilling tool, and dynamometer is shown in Fig. 2.

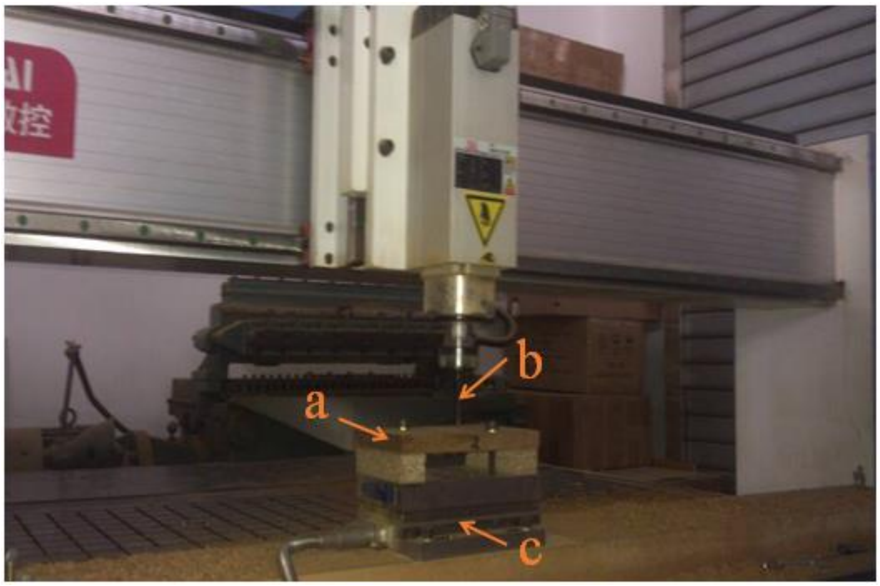


Fig. 2. The equipment setup with the recombinant bamboo. (a) Recombinant bamboo, (b) drilling tool, and (c) dynamometer

Plan of experiment

Response surface methodology (RSM) using a Box-Behnken design (Box and Behnken 1960) was used in this work. RSM is a collection of mathematical and statistical techniques that are used here for modeling and analyzing the effects of several process parameters on the response parameters. Version 8.0.6 of the Design-Expert Software (Stat-Ease Inc., USA) was used to set up the experimental plan and to analyze the experimental data.

Corresponding to the present work, the RSM-based second order mathematical model is given by Eq. 1:

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

In Eq. (1), b_0 is the free term of the regression equation and coefficients b_1, b_2, … b_k and b_{11}, b_{22}, . . . b_{kk} are the linear and the quadratic terms, respectively, while b_{12}, b_{13}, . . . b_{k-1} are the interaction terms.

The three process parameters were in the experiments according to the values shown Table 1. The values were chosen out of experience of reasonable parameters and the limits for the CNC machine. Coded levels -1, 0 and 1 were chosen to represent a low, medium and high process parameter value, respectively.

Table 1. Process Parameters and Corresponding Codes and Levels

Process parameters	Code	Dimensions	Level		
			-1	0	1
Spindle speed	A	rpm	6000	10000	14000
Feed rate	B	mm/min	100	200	300
Drill diameter	C	mm	6	8	10

RESULTS AND DISCUSSION

Table 2 shows the results from all 17 tests. Index a shows the numbering of experiments using the standard RSM method, and index b shows the order in which the experiments were carried out in reality, *i.e.* in a random way.

Table 2. Experimentally Recorded Data

Standard order[a]	Real order[b]	process parameters			Response parameters	
		A (rpm)	B (mm/min)	C (mm)	Thrust Force (N)	Torque (Nm)
1	3	6000	100	8	51.8	1.56
2	12	14000	100	8	43.3	1.01
3	10	6000	300	8	77.2	1.79
4	11	14000	300	8	56.4	1.43
5	16	6000	200	6	57.2	0.89
6	2	14000	200	6	34.5	0.75
7	8	6000	200	10	63.1	2.56
8	14	14000	200	10	50.1	1.88
9	9	10000	100	6	41.1	0.90
10	13	10000	300	6	56.5	1.01
11	4	10000	100	10	47.9	1.96
12	6	10000	300	10	67.8	2.87
13	7	10000	200	8	52.7	1.63
14	1	10000	200	8	52.2	1.62
15	15	10000	200	8	53.0	1.61
16	17	10000	200	8	52.7	1.62
17	5	10000	200	8	53.0	1.61

[a] The experiment order in standard way
[b] The experiment order in random way

Analysis of Variance

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences between group means and their associated procedures (Mohammed Ali *et al.* 2014). The ANOVA of the response parameters, with the objective of achieving the influence of process parameters on the total variance of the results, was carried out with 9 degrees of freedom. The ANOVA results for R^2, adjusted R^2, and predicted R^2 with this approach are listed in Table 3. These values are very close to 1 because of the high number of degrees of freedom in relation to the number of experiments.

Table 3. Summary of ANOVA

Response	Degrees of Freedom	Probability (F model)	R^2	Adjusted R^2	Predicted R^2
Thrust Force	9	<0.0001*	0.998	0.996	0.973
Torque	9	<0.0001*	0.996	0.990	0.934
*Denotes statistical significance at a confidence interval greater than 99%					

Regression Equations

The final mathematical models are provided by Eqs. 2 and 3, where A represents the spindle speed, B the feed rate, and C the diameter of the drill in terms of the coded levels.

$$F_z = 52.72 - 8.91A + 8.44B + 4.95C - 1.50AB + 2.43AC + 1.13BC + 1.96A^2 + 4.06B^2 - 3.46C^2 \quad (2)$$

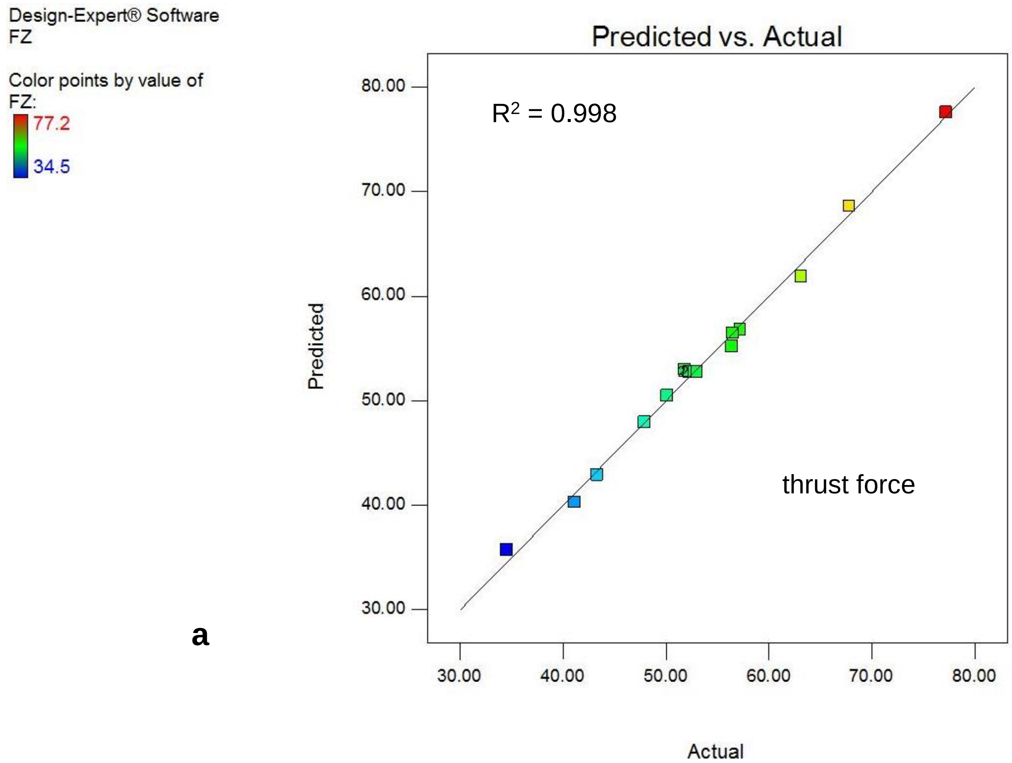
$$M_Z = 1.62 - 0.22A + 0.21B + 0.71C + 0.049AB - 0.14AC + 0.20BC - 0.17A^2 - 0.002B^2 + 0.07C^2 \quad (3)$$

Adequacy of the Developed Models

The adequacy of the developed models was tested by carrying out two confirmation experiments with different and unique process parameter combinations. Predicted values for the thrust force and torque were calculated using the mathematical models developed above. Table 4 presents the actual experimental values, the predicted values, and the errors. It is obvious that the predicted values are very close to the actual values and hence the model is effective in predicting the thrust force and torque in drilling recombinant bamboo.

Table 4. Confirmation Experiments

Process parameters			Values	Response parameters	
A (rpm)	B (mm/min)	C (mm)		Thrust Force (N)	Torque (Nm)
11000	220	10	Actual	55.4	2.40
			Predicted	54.7	2.39
			Error (%)	1.3	0.58
9000	150	6	Actual	43.1	0.99
			Predicted	44.4	0.99
			Error (%)	-2.9	0.61



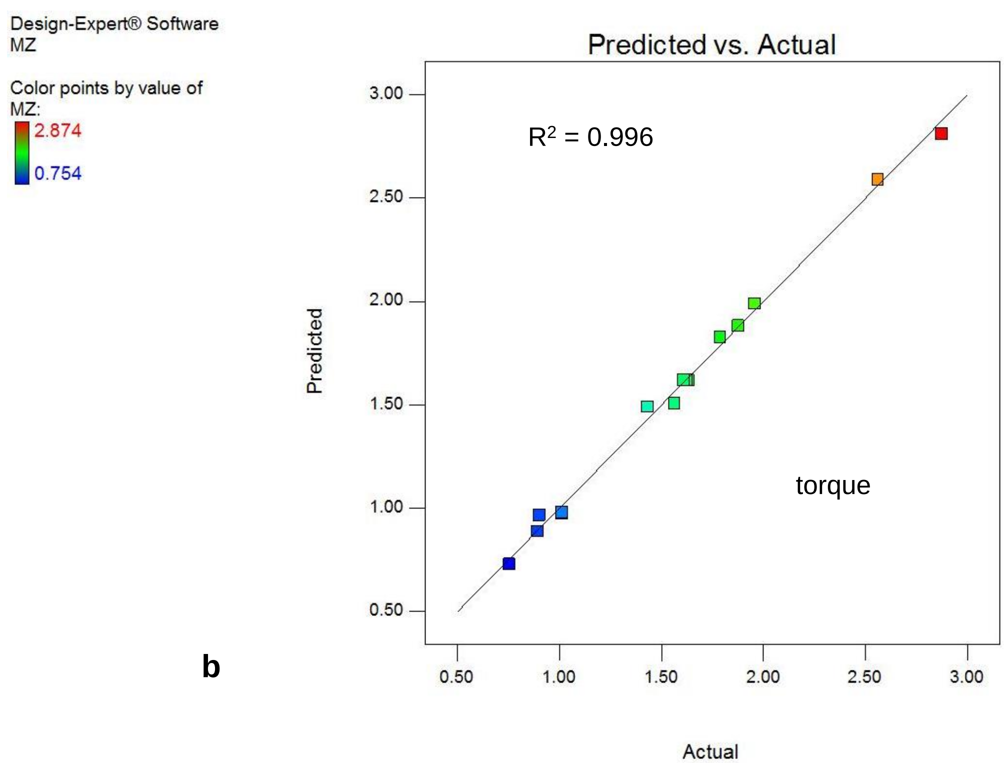
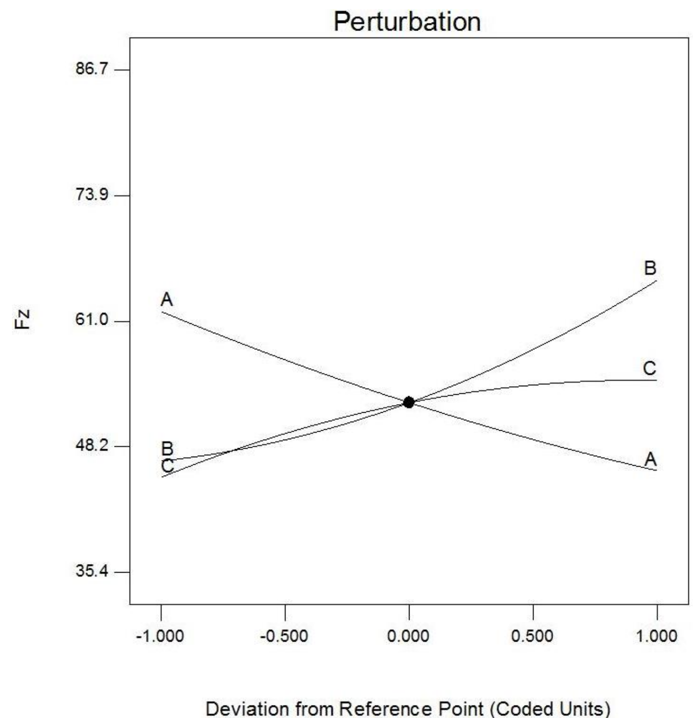


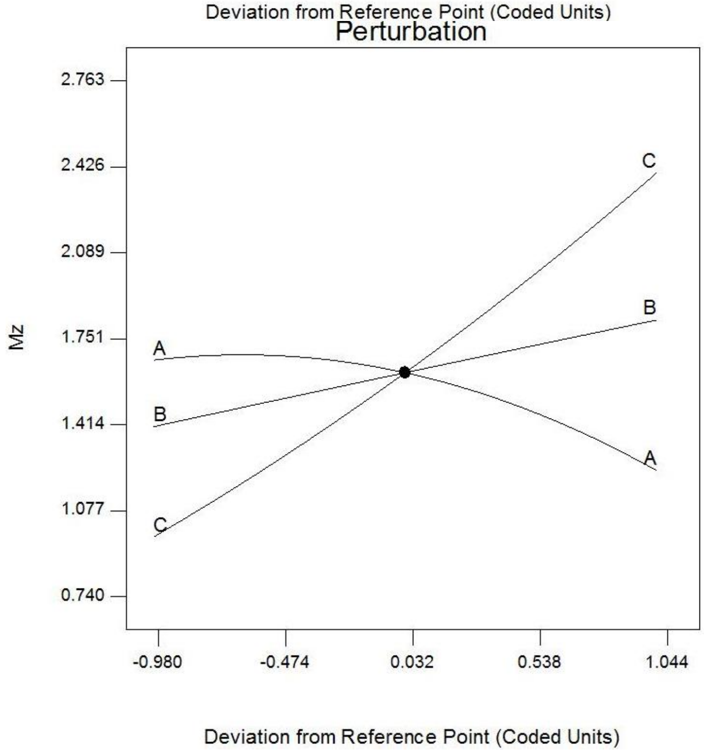
Fig. 3. Correlation graph for (a) thrust force (N) and (b) torque (Nm)

DISCUSSION

Figure 4 shows the effects of process parameters on the thrust force and torque. In Fig. 4a, it can be seen that the process parameters that have a major effect on thrust force are A (spindle speed) and B (feed rate).



a



b

Fig. 4. Perturbation plots showing the effect of each process parameter on the (a) thrust force (N) and (b) torque (Nm)

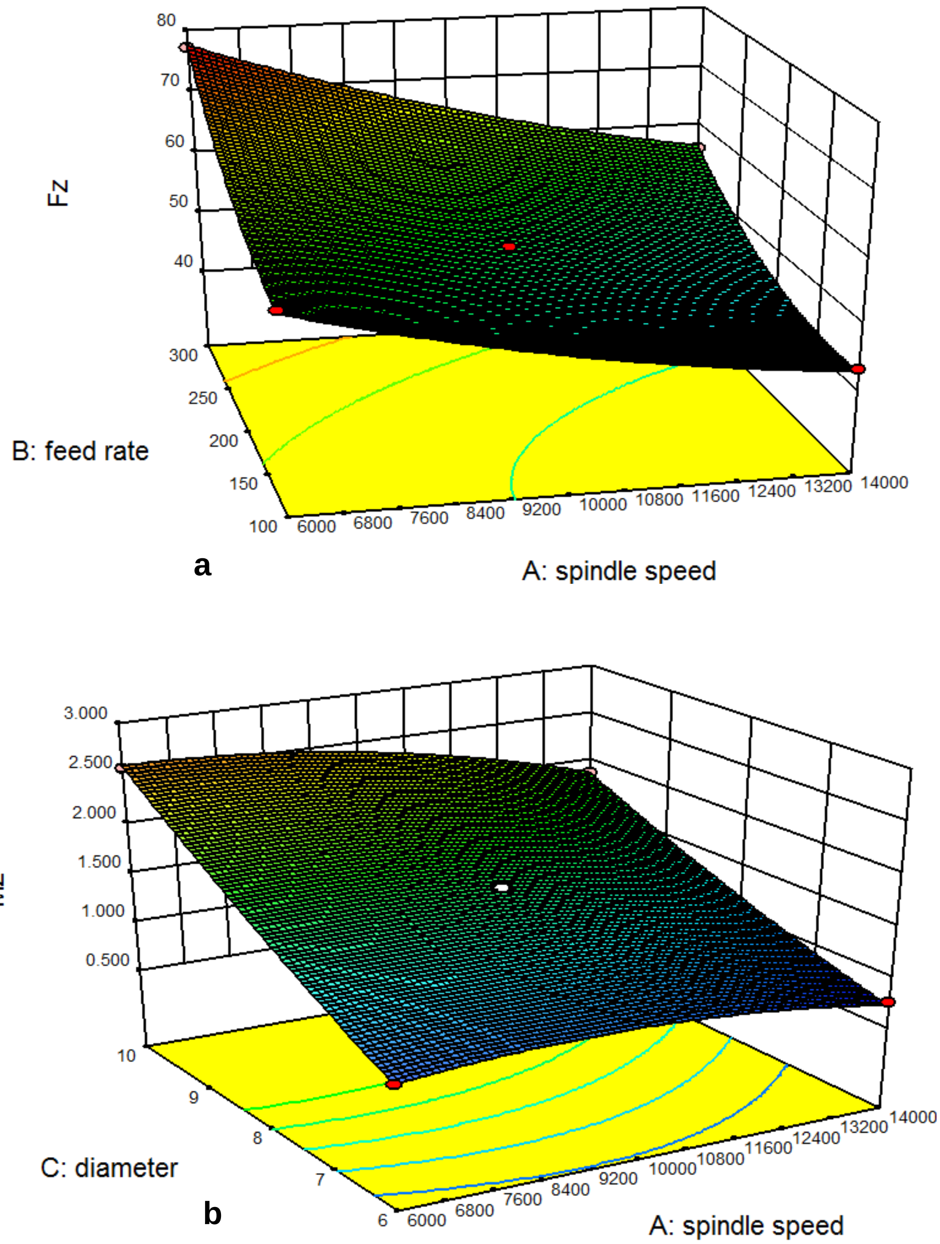


Fig. 5. Responses for (a) thrust force (N) and (b) torque (Nm) as function of major process parameters

The thrust force decreased as the spindle speed increased and increased as the feed rate increased. This is probably partly because the cutting temperature increases with the increase of spindle speed and the matrix of recombinant bamboo is softened by the cutting heat. With the increase of feed rate, more chip material needs to be moved away, which can partly explain the increasing of thrust force. The minimum thrust force was achieved by the combination of high spindle speed with low feed rate. These results are in good agreement with the results obtained in a previous work (Valarmathi *et al*. 2012, 2013). Figure 4b shows that A (spindle speed) and C (diameter of the drill) had more influence than B (feed rate) on the torque. The torque increased as the diameter of drill increased, and also increased as the spindle speed decreased. Reasons for the increase with diameter of drill are obvious, but reasons for decrease with spindle speed are not. The results are in good agreement with the results in previous work (Satoshi 2012). The thrust force and torque from the mathematical models as functions of the major process parameters are given in Fig. 5a and Fig. 5b. From Fig. 5a, it is noted that the thrust force developed is at a minimum when the spindle speed is at a high level and the feed rate is at a low level. From Fig. 5b, it is observed that the torque developed is at a minimum when the spindle speed is at a low level and the diameter of drill is at a low level.

CONCLUSIONS

1. The response parameters thrust force and torque were affected by all the process parameters considered in the experiments. Spindle speed and feed rate had the greatest effect on thrust force, while the major effects on torque were diameter of the drill and spindle speed.
2. The thrust force decreased as the spindle speed increased and increased as the feed rate increased.
3. The torque increased as the diameter of drill increased and increased as the spindle speed decreased.
4. The values from the mathematical models are in good agreement with the actual values; hence, the models are effective in predicting the thrust force and torque in drilling recombinant bamboo within the parameters and levels considered.
5. The adequacy of the developed mathematical models for torque and thrust force is shown with two confirmation tests which gave a maximum of 3% error for thrust force and less than 1% for torque.

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