Effect of Pressure, Feed Rate, and Abrasive Mass Flow Rate on Water Jet Cutting Efficiency When Cutting Recombinant Bamboo

Rongrong Li,[a] Mats Ekevad,[b] Xiaolei Guo,[a] Jianwen Ding,[a] and Pingxiang Cao [a,]*

The impact of varying pressure, feed rate, and abrasive mass flow rate on the efficiency of an abrasive water jet cutting process was studied in this work. Recombinant bamboo samples with thicknesses of 5, 10, and 15 mm were cut by the abrasive water jet. The upper kerf width, lower kerf width, and the ratio of the upper kerf width to lower kerf width were chosen as the efficiency parameters. Mathematical models were developed to describe the relationship between the input process parameters and the efficiency parameters. The arrangement of experiments and analysis of results were performed based on response surface methodology. The evaluated model yielded predictions in agreement with experimental results.

Keywords: Recombinant bamboo; Response surface methodology; Abrasive water jet; Kerf width

*Contact information: a: Faculty of Material Science and Engineering, Nanjing Forestry University, Nanjing 210037, China; b: Division of Wood Science and Engineering, Luleå University of Technology, Skellefteå 93187, Sweden; *Corresponding author: caopx@njfu.com.cn*

INTRODUCTION

Recombinant bamboo is a wood-like material made from bamboo *via* the following processes: defibering, drying, gluing, laying-up, and hot-pressing (Zhao and Yu 2002). This material has great structural integrity, high dimensional stability, and good mechanical properties, and is widely used both indoors and outdoors. Unfortunately, the machinability of the material is poor because of its high density and hardness (Li *et al.* 2014). To some extent, nontraditional machining processes can be effective solutions for some machining problems.

Abrasive water jet (AWJ) technology is one such machining process now used in many manufacturing industries. The positive features of this technology include precise shape cutting, good surface quality, small kerf widths, long tool life, complex free-form curve cuts, easy-to-adopt process automation, no dust problems, and improved working environment conditions (Karakurt *et al.* 2014).

In previous works, researchers have attempted to determine the effects of AWJ input parameters on the cutting performance of wood and wood-like materials. Surface quality was investigated during wood-based panel cutting. The impacts of feed rate, abrasive mass flow rate, and cutting direction on different panels were studied (Kvietková *et al.* 2014). Gerencsér and Bejó (2007) concluded that kerf width is a significant index of AWJ efficiency and used it to evaluate kerf quality. Barcík and Kvietková (2011) evaluated the impact of material thickness on the angle of the cut sides and found that increasing the thickness of the material causes an initial decrease of the angle before an increase in angle. Alberdi *et al.* (2013) cut composites with AWJ, and their results indicated that the taper decreased as the thickness increased.

Pressure, feed rate, and abrasive mass flow rate were selected as input parameters in this study. The aim was to study the effect of these parameters on the efficiency in the form of the kerf width and the geometry of the kerf. The distance from nozzle to the cut surface was fixed because it was difficult to adjust. Response surface methodology (RSM) was used to design the experiment and analyze the results. The upper kerf width (UK), lower kerf width (LK), and the ratio of the upper kerf to lower kerf width for various combinations of input parameters can be predicted accurately by the models that were developed in this study.

EXPERIMENTAL

Materials

Recombinant bamboo samples with a thickness of 5 mm, 10 mm, and 15 mm were supplied by the Hunan Taohuajiang Industries Co., Ltd. (China). Experiments were carried out with an abrasive water jet cutter (Dadi DWJ3020, China) with a high pressure output pump operating up to 500 MPa. The diameter of the nozzle was 1 mm, and the distance from the jet nozzle to the work piece surface was 2 mm. The abrasive particles were garnet, and the grain size of the abrasive particles was 80-mesh. The setup of the equipment is illustrated in Fig. 1.

Fig. 1. Equipment setup: (a) recombinant bamboo and (b) nozzle

Methods

The UK and LK were measured using an optical microscope (JNOEC XS213, China), as shown in Fig. 2. The ratio of UK divided by LK was calculated to evaluate the performance of the kerf. This ratio was generally above 1, but when the ratio approached 1, it indicated excellent kerf characteristics.

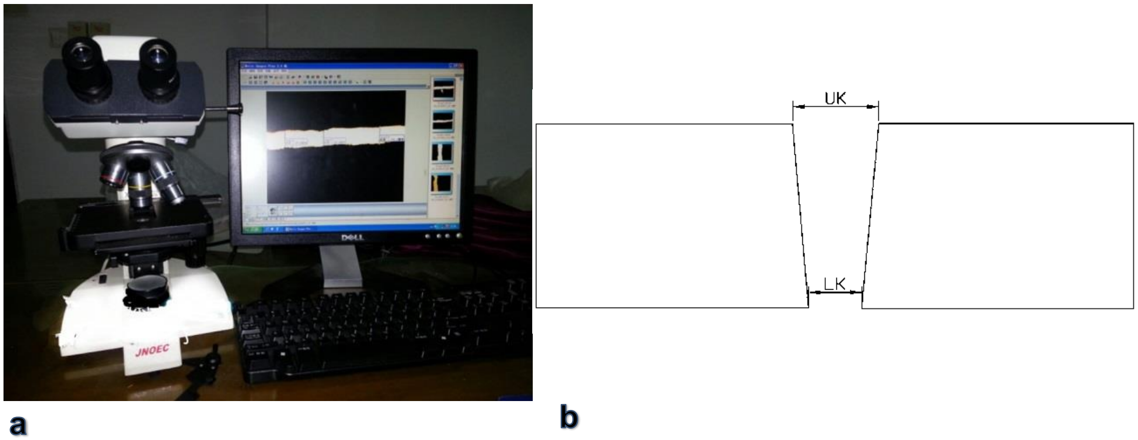

Fig. 2. (a) Optical microscope used to measure kerf width; (b) sketch diagram for UK and LK

Design of experiments

The interrelationship between the input and output parameters are complex, and analysis using conventional experimental methods is inefficient and expensive (Karakurt *et al.* 2014). Fortunately, RSM is a well-known approach for the creation, analysis, and optimization of models of the relationships between input and output parameters (Asiltürk and Neseli 2012).

In this study, RSM using a Box-Behnken design (Box and Behnken 1960) was applied. Version 8.0.6 of the Design-Expert Software (Stat-Ease Inc., USA) was used to develop the experimental plan for RSM and also for analysis of the experimental data. Input parameters (*i.e.*, pressure, feed rate, and abrasive mass flow rate) were set to three levels for different thicknesses. Table 1 shows the input parameter combinations and the assignments to the corresponding levels.

Table 1. Process Variables and Experiment Design Levels

Parameters	Code	Unit	Level								
			-1			0			1		
			Thickness (mm)			Thickness (mm)			Thickness (mm)		
			5	10	15	5	10	15	5	10	15
Pressure	A	MPa	70	100	200	120	150	250	170	200	300
Feed rate	B	m/min	0.2	0.2	0.2	0.4	0.4	0.4	0.6	0.6	0.6
Abrasive mass flow rate	C	g/min	200	200	200	300	300	300	400	400	400

RESULTS AND DISCUSSION

During the experiments, the UK and LK were measured and the ratio UK/LK was calculated. Tables 2, 3, and 4 show the UK, LK, and UK/LK ratios for all experiments. The numbering of results in Tables 2 to 4, shown divided in the two leftmost columns, refers to the fact that experiments were conducted in the order denoted [b] (random way) and the results were input into the RSM software in the order shown in column [a] (standard way).

Table 2. Design Matrix and Experimentally Recorded Data for 5-mm Thickness

Standard[a]	Run[b]	Factors			Responses		
		Pressure (MPa)	Feed rate (m/min)	Abrasive flow (g/min)	UK (mm)	LK (mm)	Ratio
1	12	70	0.2	300	1.18	1.06	1.11
2	10	170	0.2	300	1.43	1.40	1.02
3	3	70	0.6	300	1.03	0.82	1.25
4	5	170	0.6	300	1.23	1.09	1.13
5	2	70	0.4	200	1.01	0.88	1.15
6	4	170	0.4	200	1.19	1.13	1.05
7	17	70	0.4	400	1.50	1.24	1.21
8	16	170	0.4	400	1.63	1.46	1.12
9	13	120	0.2	200	1.13	1.10	1.03
10	11	120	0.6	200	1.07	1.00	1.07
11	9	120	0.2	400	1.74	1.64	1.06
12	14	120	0.6	400	1.56	1.22	1.28
13	1	120	0.4	300	1.23	1.16	1.06
14	8	120	0.4	300	1.24	1.17	1.06
15	7	120	0.4	300	1.23	1.17	1.05
16	6	120	0.4	300	1.23	1.16	1.06
17	15	120	0.4	300	1.25	1.19	1.05

[a] The experiment plan, as expressed in a standardized arrangement
[b] The experiment plan, as actually run (in a randomized order)

Table 3. Design Matrix and Experimentally Recorded Data for 10-mm Thickness

Standard[a]	Run[b]	Factors			Responses		
		Pressure (MPa)	Feed rate (m/min)	Abrasive flow (g/min)	UK (mm)	LK (mm)	Ratio
1	2	100	0.2	300	1.39	1.15	1.21
2	7	200	0.2	300	1.56	1.36	1.15
3	4	100	0.6	300	1.26	0.91	1.39
4	17	200	0.6	300	1.35	1.00	1.35
5	13	100	0.4	200	1.21	0.95	1.27
6	16	200	0.4	200	1.33	1.13	1.18
7	6	100	0.4	400	1.39	1.06	1.31
8	5	200	0.4	400	1.61	1.30	1.24
9	9	150	0.2	200	1.38	1.16	1.19
10	3	150	0.6	200	1.30	0.98	1.32
11	12	150	0.2	400	1.69	1.37	1.23
12	10	150	0.6	400	1.34	0.92	1.45
13	14	150	0.4	300	1,28	1.02	1.26
14	8	150	0.4	300	1.27	1.01	1.26
15	11	150	0.4	300	1.28	1.02	1.26
16	1	150	0.4	300	1.27	1.02	1.25
17	15	150	0.4	300	1.28	1.02	1.26

[a] The experiment plan, as expressed in a standardized arrangement
[b] The experiment plan, as actually run (in a randomized order)

Table 4. Design Matrix and Experimentally Recorded Data for 15-mm Thickness

Standard[a]	Run[b]	Factors			Responses		
		Pressure (MPa)	Feed rate (m/min)	Abrasive flow (g/min)	UK (mm)	LK (mm)	Ratio
1	9	200	0.2	300	1.50	1.23	1.22
2	12	300	0.2	300	1.72	1.47	1.17
3	16	200	0.6	300	1.34	0.96	1.39
4	4	300	0.6	300	1.51	1.19	1.27
5	7	200	0.4	200	1.32	1.03	1.28
6	1	300	0.4	200	1.49	1.32	1.13
7	3	200	0.4	400	1.80	1.34	1.34
8	17	300	0.4	400	1.95	1.57	1.24
9	11	250	0.2	200	1.46	1.30	1.12
10	8	250	0.6	200	1.41	1.17	1.21
11	6	250	0.2	400	2.08	1.82	1.14
12	13	250	0.6	400	1.89	1.38	1.37
13	14	250	0.4	300	1.57	1.33	1.18
14	15	250	0.4	300	1.56	1.32	1.18
15	10	250	0.4	300	1.55	1.32	1.17
16	5	250	0.4	300	1.55	1.34	1.16
17	2	250	0.4	300	1.56	1.32	1.18

[a] The experiment plan, as expressed in a standardized arrangement
[b] The experiment plan, as actually run (in a randomized order)

Analysis of Variance

Analysis of variance (ANOVA) is a statistical methodology used to analyze the differences between group means and their associated parameters (Ali *et al.* 2014). To avoid confusing the reader, only the most important information is presented in Table 5. This table shows the adequacy measures R^2, adjusted R^2, and predicted R^2. When R^2 approaches a value of 1, it indicates a good correlation between the experimental and predicted values.

Table 5. Summary of ANOVA Information

Thickness (mm)	Response	Degrees of Freedom	Probability (F model)	R^2	Adjusted R^2	Predicted R^2
5	UK	9	<0.0001 (Sig.)	0.9890	0.9748	0.8298
	LK	9	<0.0001 (Sig.)	0.9940	0.9863	0.9183
	Ratio	9	<0.0001 (Sig.)	0.9822	0.9593	0.7333
10	UK	9	<0.0001 (Sig.)	0.9880	0.9725	0.8135
	LK	9	<0.0001 (Sig.)	0.9890	0.9749	0.8267
	Ratio	9	<0.0001 (Sig.)	0.9865	0.9692	0.7967
15	UK	9	<0.0001 (Sig.)	0.9915	0.9806	0.8699
	LK	9	<0.0001 (Sig.)	0.9930	0.9840	0.8919
	Ratio	9	<0.0004 (Sig.)	0.9869	0.9701	0.8323

Regression Equations

The final mathematical models are provided by Eqs. 1 through 9 below, where A is the pressure in MPa, B is the feed rate in m/min, and C is the abrasive mass flow rate in g/min.

Equations 1 through 3 show models for 5-mm-thick recombinant bamboo.

$$UK=1.24+0.095\times A-0.074\times B+0.25\times C-0.013\times A\times B-0.013\times A\times C-0.030\times B\times C-0.031\times A^2+0.012\times B^2+0.13\times C^2 \quad (1)$$

$$LK=1.17+0.13\times A-0.13\times B+0.18\times C-0.019\times A\times B-9.85E\text{-}003\times A\times C-0.081\times B\times C-0.070\times A^2-7.34E\text{-}003\times B^2+0.076\times C^2 \quad (2)$$

$$Ratio=1.06-0.050\times A+0.063\times B+0.046\times C-7.06E\text{-}003\times A\times B+2.50E\text{-}003\times A\times C+0.045\times B\times C+0.048\times A^2+0.025\times B^2+0.029\times C^2 \quad (3)$$

Equations 4 through 6 show models for 10-mm-thick recombinant bamboo.

$$UK=1.28+0.075\times A-0.096\times B+0.10\times C-0.020\times A\times B+0.025\times A\times C-0.068\times B\times C+0.036\times A^2+0.078\times B^2+0.073\times C^2 \quad (4)$$

$$LK=1.01+0.089\times A-0.15\times B+0.054\times C-0.029\times A\times B+0.016\times A\times C-0.069\times B\times C+0.044\times A^2+0.045\times B^2+0.052\times C^2 \quad (5)$$

$$Ratio=1.26-0.032\times A+0.091\times B+0.034\times C+5.00E\text{-}003\times A\times B+5.00E\text{-}003\times A\times C+0.022\times B\times C-0.015\times A^2+0.032\times B^2+7.25E\text{-}003\times C^2 \quad (6)$$

Equations 7 through 9 show models for 15-mm-thick recombinant bamboo.

$$UK= 1.56+0.089\times A-0.076\times B+0.26\times C-0.013\times A\times B-5.00E\text{-}003\times A\times C-0.035\times B\times C-0.055\times A^2+0.015\times B^2+0.14\times C^2 \quad (7)$$

$$LK=1.33+0.12\times A-0.14\times B+0.16\times C-3.91E\text{-}003\times A\times B-0.015\times A\times C-0.077\times B\times C-0.11\times A^2-6.07E\text{-}003\times B^2+0.097\times C^2 \quad (8)$$

$$Ratio=1.17-0.052\times A+0.074\times B+0.044\times C-0.018\times A\times B+0.013\times A\times C+0.035\times B\times C+0.063\times A^2+0.025\times B^2+0.011\times C^2 \quad (9)$$

Adequacy of the Developed Models

The adequacies of the developed models (Eqs. 1 through 9) were tested by three validation experiments. Predicted values for UK, LK, and their ratio were calculated for these validation experiments using the point prediction option of the Design-Expert software. Input parameters, actual experimental values, predicted output values, and their percent errors are presented in Table 6. The errors are in the range of 1 to 2.4%, indicating that the models are statistically significant and accurate.

Upper Kerf Width (UK)

Figure 3 shows the main effects of input cutting parameters on UK for all thicknesses tested. Figure 3 shows similar trends for UK values of samples of all three thicknesses. An increase in pressure resulted in an increase in UKs for all thicknesses. The UK values also increased as the feed rate was decreased. This result may be due to UKs being associated with jet energy levels per area, which increases as the feed rate decreases.

Table 6. Validation Experiments

Thickness (mm)	Factors			Values	Responses		
	A (MPa)	B (m/min)	C (g/min)		UK (mm)	LK (mm)	Ratio
5	130	0.35	250	Actual	1.17	1.14	1.03
				Predicted	1.18	1.15	1.02
				Error (%)	-0.9	-0.9	1.0
10	120	0.45	310	Actual	1.23	0.97	1.27
				Predicted	1.24	0.95	1.30
				Error (%)	-0.8	2.1	-2.4
15	250	0.5	290	Actual	1.52	1.23	1.24
				Predicted	1.50	1.24	1.21
				Error (%)	1.3	-0.8	-2.4

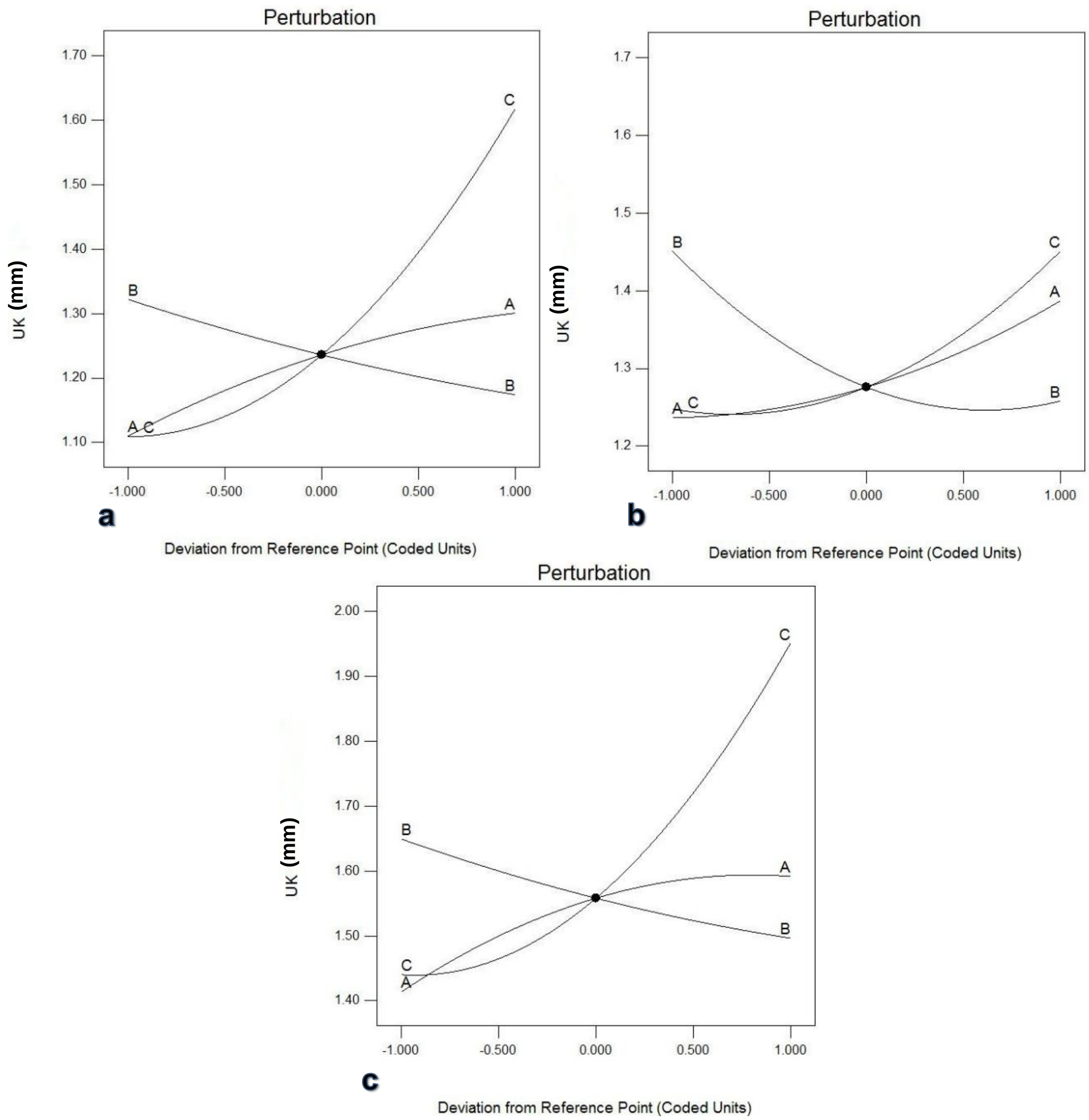

Fig. 3. The effects of (A) pressure, (B) feed rate, and (C) abrasive mass flow rate on UK for thicknesses of (a) 5 mm, (b) 10 mm, and (c) 15 mm. In coded units, -1 represents the lowest value, 0 represents the medium value, and 1 represents the highest value; see Table 1

Low jet energy per area results in a low material removal rate (Karakurt *et al*. 2014). The experimental results show that abrasive mass flow rate had a significant effect on UKs and that the UKs increased as the abrasive mass flow rate increased. This result is reasonable since more abrasive particles within a certain area lead to an increased material removal rate and increased UKs.

Lower Kerf Width (LK)

Figure 4 shows the effect of the input parameters on the LKs. The LKs increased as the pressure and abrasive mass flow rate increased for all thicknesses. Higher abrasive mass flow rate leads to more abrasive particles per unit area and time at a certain point. Feed rate had a major effect on LKs. The LKs decreased dramatically as the feed rate increased. This may be because the jet energy per area decreases when the feed rate increases, in much the same way it does for UKs.

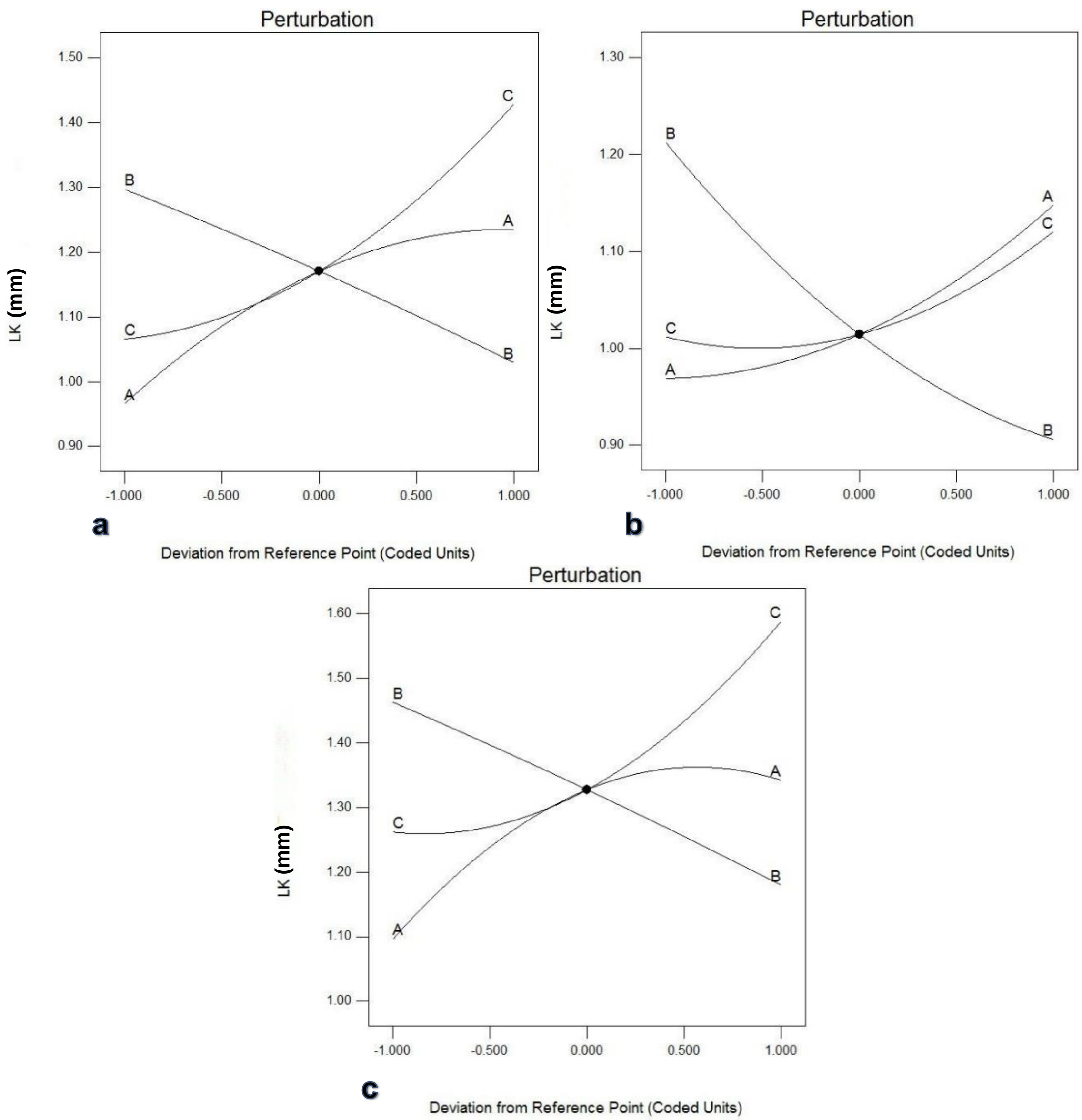

Fig. 4. The effects of (A) pressure, (B) feed rate, and (C) abrasive mass flow rate on LK for thicknesses of (a) 5 mm, (b) 10 mm, and (c) 15 mm. In coded units, -1 represents the lowest value, 0 represents the medium value, and 1 represents the highest value; see Table 1

Ratio

Figure 5 reveals the effect of varying input parameters on the UK/LK ratio. Feed rate had a major effect on the ratio, and the ratio increased as the feed rate increased for all thicknesses. For the other two factors, the ratio increased as the pressure decreased and/or the abrasive mass flow increased. The ratio of UK/LK is an important index for evaluating kerf quality. When the ratio approaches a value of 1, it indicates a good-quality kerf.

Figure 6 is a response surface graph showing the effect of pressure and feed rate on ratio for each of the thicknesses tested. These figures are useful in identifying the area in which the ratio approaches the value 1.

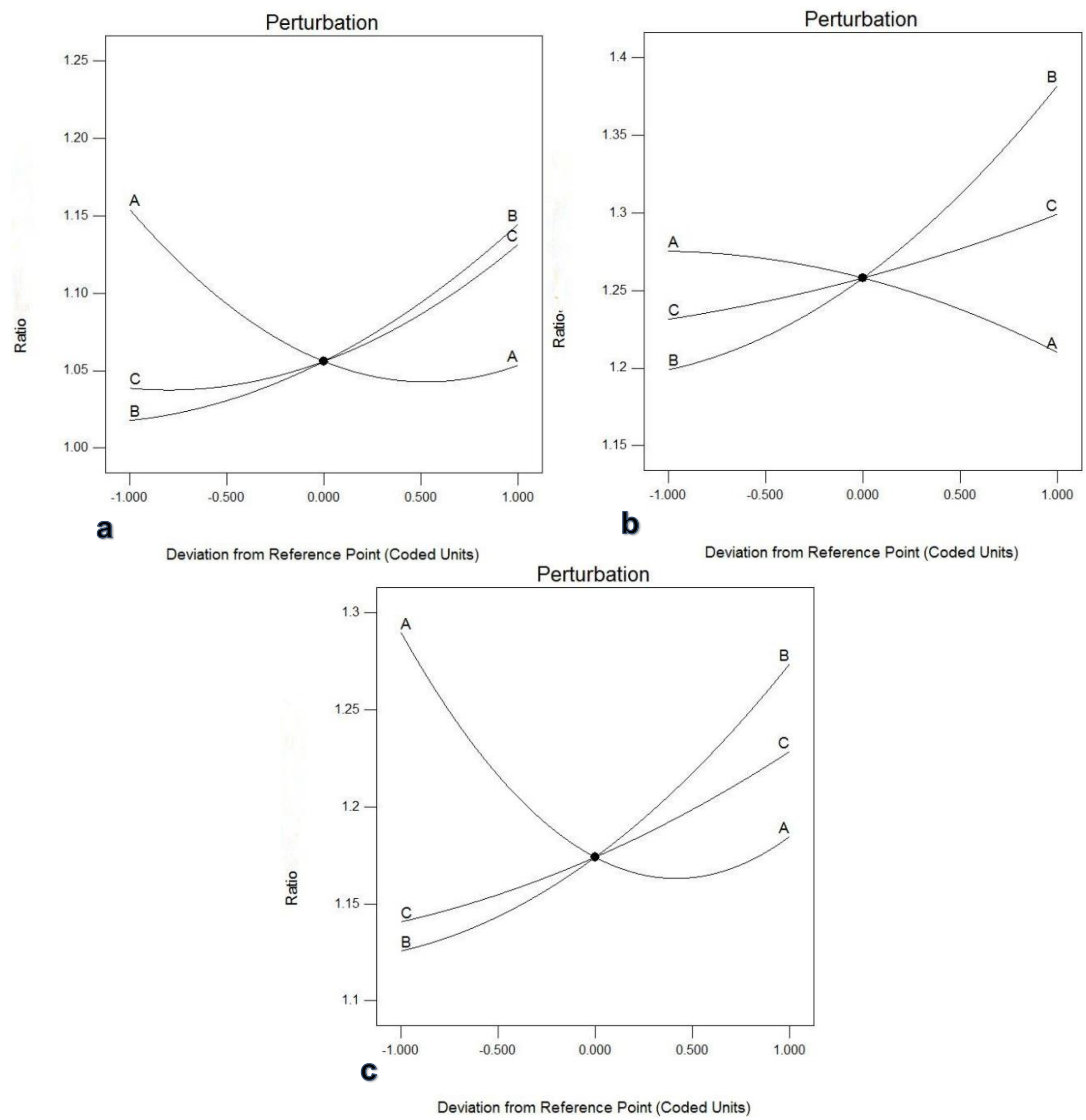

Fig. 5. The effects of (A) pressure, (B) feed rate, and (C) abrasive mass flow rate on the ratio for thicknesses of (a) 5 mm, (b) 10 mm, and (c) 15 mm. In coded units, -1 represents the lowest value, 0 represents the medium value, and 1 represents the highest value; see Table 1

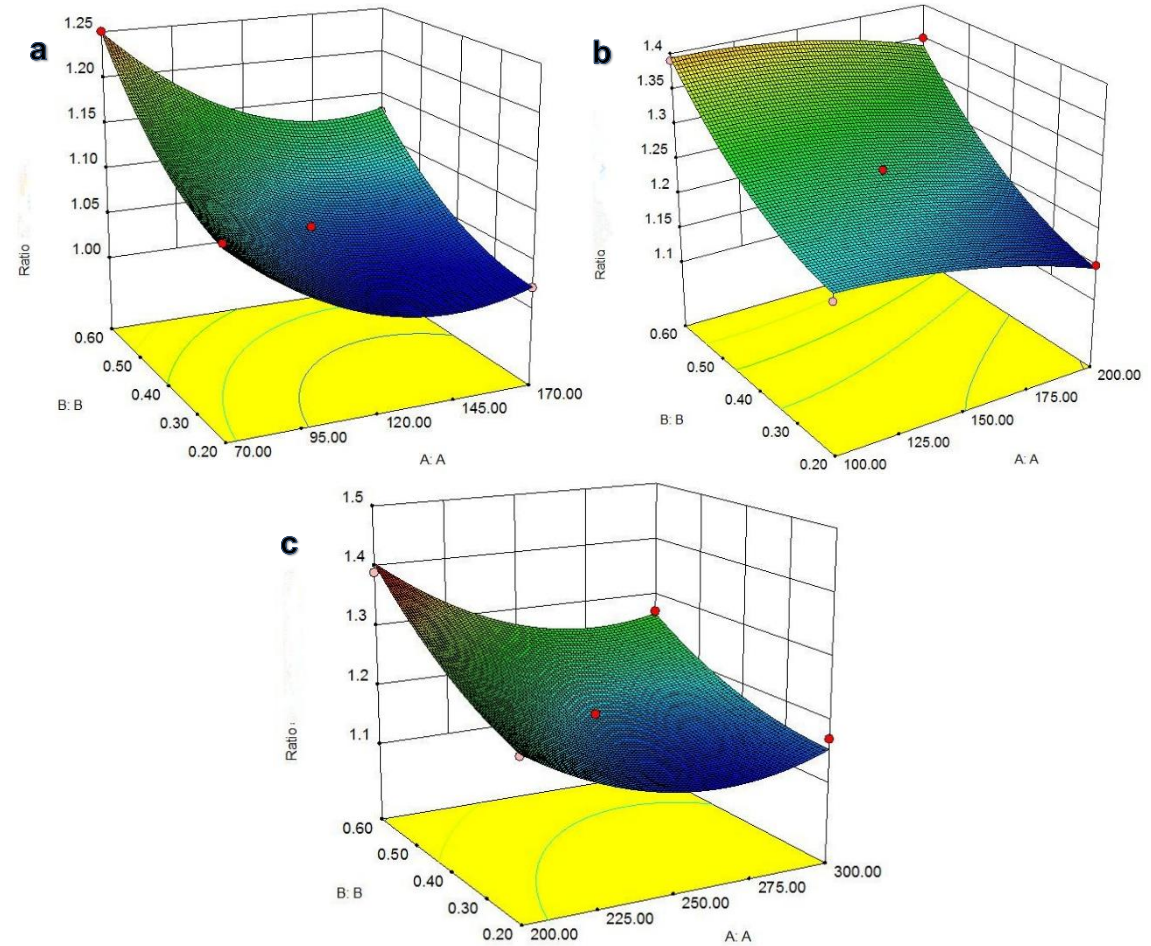

Fig. 6. Ratio as a function of (A) pressure and (B) feed rate for thicknesses of (a) 5 mm, (b) 10 mm, and (c) 15 mm. Units for A and B are MPa and m/min, respectively; see Table 1

CONCLUSIONS

1. The considered input parameters had significant effects on the kerf widths and ratio. The trends were similar for all three thicknesses tested.
2. The abrasive mass flow rate had a major effect on UKs. The UKs increased with increasing abrasive flow. The UKs also increased as the feed rate was decreased and as the pressure was increased.
3. The LKs increased as the pressure and abrasive flow were increased and decreased as the feed rate was increased. These observations are the same as those of the UKs.
4. The feed rate had a major effect on the UK/LK ratio. The ratio increased dramatically as the feed rate was increased. It also increased as the abrasive flow increased and decreased as the pressure increased.
5. The modeling results show that the prediction values from the models were in accordance with experimental data. This means that the models were statistically significant and that the responses can be accurately modeled using this method.

ACKNOWLEDGMENTS

The authors are grateful for funding from the Priority Academic Program Development of the Jiangsu Higher Education Institutions (PAPD) and the National Sci-tech Support Plan of China (No. 2012BAD24B01).

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Article submitted: September 5, 2014; Peer review completed: November 14, 2014; Revisions accepted: November 18, 2014; Published: November 25, 2014.