192 *Int. J. Manufacturing Technology and Management, Vol. 7, Nos. 2/3/4, 2005*

Rotary ultrasonic machining of ceramics: design of experiments

Yue Jiao*, Ping Hu and Z.J. Pei

Department of Industrial and Manufacturing Systems
Engineering, Kansas State University, Manhattan,
KS 66506, USA
E-mail: yuejiao@ksu.edu E-mail: phu3388@ksu.edu
E-mail: zpei@ksu.edu
*Corresponding author

Clyde Treadwell

Sonic-Mill, Inc., 7500 Bluewater Road, Albuquerque,
NM 87121, USA
E-mail: contact@sonicmill.com

Abstract: Rotary ultrasonic machining is one of the nontraditional machining processes for advanced ceramics. Currently available in literature are publications on theoretical and experimental studies on material removal rates in rotary ultrasonic machining. However, there is no report on the systematic study of the cutting force in rotary ultrasonic machining. Furthermore, the effects of some process parameters on material removal rates and surface roughness have not been reported. This paper presents the results of designed experiments on rotary ultrasonic machining of a ceramic material (92% alumina). The designed experiments have revealed the main effects as well as the interaction effects of the process parameters (spindle speed, ultrasonic power, feedrate and grit size) on cutting force, material removal rate, and surface roughness.

Keywords: ceramics; cutting force; design of experiment; material removal rate; rotary ultrasonic machining; surface roughness.

Reference to this paper should be made as follows: Jiao, Y., Hu, P., Pei, Z.J. and Treadwell, C. (2005) 'Rotary ultrasonic machining of ceramics: design of experiments', *Int. J. Manufacturing Technology and Management*, Vol. 7, Nos. 2/3/4, pp.192–206.

Biographical notes: Yue Jiao holds a Master of Engineering degree and Bachelor of Engineering degree in automatic control engineering from Tsinghua University, Beijing, China and a PhD in industrial and manufacturing Systems Engineering from Kansas State University. She is currently a Postdoctoral Researcher at the University of Massachusetts Dartmouth. Her research areas include operations research, fuzzy modelling, and nontraditional machining methods.

Ping Hu is currently a graduate student in the Industrial and Manufacturing Systems Engineering Department at Kansas State University, Manhattan, KS, USA. He has published several papers on rotary ultrasonic machining of ceramics.

Dr Z.J. Pei received his PhD in mechanical engineering from the University of Illinois at Urbana-Champaign. He is currently an assistant professor in the Department of Industrial and Manufacturing Systems Engineering at Kansas State University. He holds three US patents and has published over 20 journal papers and over 50 papers at international conferences. His current research activities include analysis and modelling of silicon wafering processes and traditional and nontraditional machining processes.

Clyde Treadwell is the President of Sonic Mill. He has over 20 years of experience in designing and making ultrasonic machines, and developing innovative machining processes with ultrasonic technology.

1 Introduction

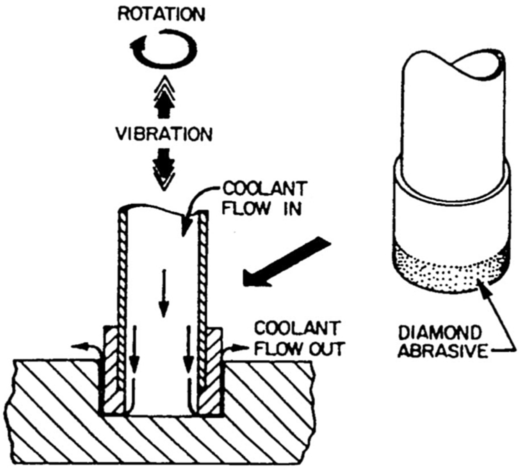
Advanced ceramics have found a variety of engineering applications owing to their superior properties, such as high hardness, high strength, and rigidity at elevated temperatures; wear resistance; low thermal conductivity; and low chemical inertness. However, these properties also make it difficult to shape and machine ceramics into a precise size and shape, which has impeded their widespread application. Thus, the reliable and cost-effective machining techniques for advanced ceramics are required.

Among the non-traditional machining methods being currently proposed for machining advanced ceramics, such as laser processing, electrical discharging machining, Rotary Ultrasonic Machining (RUM), also called ultrasonic assisted grinding, is a relative low-cost, environment-benign process and easily fits within the infrastructure of the traditional machining environment. Due to the combination of material removal mechanisms of both the diamond grinding and the ultrasonic machining, RUM can achieve a higher material removal rate (MRR) than those obtained by either diamond grinding or ultrasonic machining. The experiments with calcium aluminium silicate and magnesia-stabilised zirconia have shown that MRR obtained from RUM is 6 to 10 times higher than that from a conventional grinding process under similar conditions (Khanna et al., 1995; Pei, 1995; Pei et al., 1995; Prabhakar, 1992). In comparison with ultrasonic machining, RUM is about ten times faster; it is easier to drill deep holes with rotary ultrasonic machining than with ultrasonic machining, and the hole accuracy is improved (Cleave, 1976; Graff, 1975; Tyrrell, 1970). Other advantages of RUM include superior surface finish and low tool pressure (Cleave, 1976; Petrukha et al., 1970; Spur et al., 1999a).

The RUM process is illustrated in Figure 1. A rotating core drill with metal bonded diamond abrasives ultrasonically vibrates along its axial direction and is fed towards the workpiece. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill and keeps it cool.

Since the inception of RUM in 1964 (Legge, 1964), many researchers have reported studies, which range from the experimental investigation and theoretical analysis, and cover the effects of process parameters and modelling of material removal mechanisms.

Figure 1 Illustration of RUM



Effects of RUM parameters (rotational speed, ultrasonic vibration amplitude and frequency, diamond type, size and concentration, bond type, etc.) on its performances (MRR, tool wear, surface roughness, etc.), have been investigated experimentally (Kubota et al., 1997; Legge, 1964, 1966; Markov and Ustinov, 1972; Markov et al., 1977). The major conclusions are summarised by Pei and Ferreira (1998). As for the modelling of the RUM process, it has been demonstrated that there exist two material removal modes in the RUM of ceramic materials: brittle fracture mode and ductile mode (Pei, 1995). Two RUM models accounting for brittle fracture have been developed (Pei, 1995; Prabhakar et al., 1993). An approach to the modelling of the ductile mode has also been developed (Pei and Ferreira, 1998). Material removal and tool wear in RUM have been investigated through a single grit scratching test (Spur and Hall, 1997). Extensions of RUM to face milling (Pei et al., 1995; Pei and Ferreira, 1999), disk grinding (Khanna et al., 1995), and complex contour machining (Ardelt et al., 1999; Uhlmann et al., 1999; Ya et al., 2001) have been developed. The mechanism of RUM under a CNC system has been analysed (Ya et al., 2001). Furthermore, in their comprehensive review paper on ultrasonic machining, Thoe et al. (1998) discussed the effects of some process parameters on MRR, tool wear and workpiece accuracy in RUM. Spur and co-workers (Spur et al., 1999b, 2001) provided a review on the principles of RUM, the machinability of various ceramics, as well as the effects of the process parameters on the process outputs for different kinematics' modifications.

However, systematic studies on the cutting force in RUM have not been reported. It was noticed that the grinding force could be reduced by at least 40% in ultrasonic assisted grinding (Spur et al., 1999a). The effects of five process parameters (rotational speed, ultrasonic vibration amplitude, feedrate, grit size of cutting tool, and depth of cut) on cutting force have been experimentally investigated (Pei, 1995; Pei and Ferreira, 1999) for rotary ultrasonic face milling which, however, is different from RUM.

As for MRR and surface roughness, significant efforts have been expended by researchers to study the effects of process parameters. However, the process parameters discussed, the ranges of these factors covered, the materials studied, and even the processes investigated are not exactly the same as those investigated in this study. For instance, in Prabhakar's study (Prabhakar, 1992), the effects of the spindle speed and the feedrate on MRR and surface roughness for the core drilling of RUM were not revealed. Similarly, Pei and his colleagues (Pei, 1995; Pei and Ferreira, 1999) experimentally investigated the effects of five process parameters (such as rotational speed, ultrasonic vibration amplitude, feedrate, grit size of cutting tool, and depth of cut) on MRR and surface roughness, but their process was for rotary ultrasonic face milling. In addition, the material studied in the work of both Prabhakar's and Pei's was magnesia-stabilised zirconia.

This paper, for the first time, reports the results of a systematic study on the cutting force in RUM of 92% alumina. It is important to study the cutting force in RUM of advanced ceramics since too high a cutting force can damage the ceramic parts, the tool or the machine spindle. Furthermore, the relationship between the cutting force and the RUM parameters obtained experimentally will be useful for the modelling of RUM. In this paper, a 2^4 (two-level, four-factor) full factorial design is used to investigate experimentally the relationship between the performance parameters (cutting force, MRR, and surface roughness) and the process parameters (spindle speed, ultrasonic power, feedrate, and grit size) for the RUM of a ceramic material (92% alumina). This study provides the main effects of these variables, the effects of two-factor interactions and three-factor interactions among these variables. The results will shed more light on the study of the RUM of alumina regarding the process performance in terms of the cutting force, MRR, and surface roughness.

2 Design of experiments

In this section, the experimental setup is described. The effects of the process parameters (spindle speed, ultrasonic power, feedrate, and grit size) on the performance parameters (cutting force, MRR, surface roughness) are investigated experimentally.

2.1 Experimental conditions

The RUM machine (Sonic-Mill 10 series, Sonic-Mill, Albuquerque, NM) used in the experiments is shown in Figure 2.

The ultrasonic spindle kit system comprises an ultrasonic spindle that is uniquely designed and coupled to an ultrasonic transducer, an ultrasonic power supply and a motor speed controller. The ultrasonic power supply converts conventional line voltage (50 Hz) into high frequency (20 KHz) electrical energy. This high-frequency electrical energy is provided to a piezoelectric converter located in the ultrasonic spindle that changes the high-frequency electrical energy into mechanical motion. The ultrasonic motion from the converter is amplified and transmitted to the rotary spindle. This causes the diamond tool attached to the spindle to vibrate, perpendicular to the tool face, thousands of times per second. The amplitude of ultrasonic vibration can be adjusted by changing the setting of the output control of the power supply. The motor attached atop the ultrasonic spindle supplies the rotational motion of the tool and different speeds can be obtained by adjusting the motor speed controller.

Figure 2 RUM machine (Sonic-Mill 10 series)

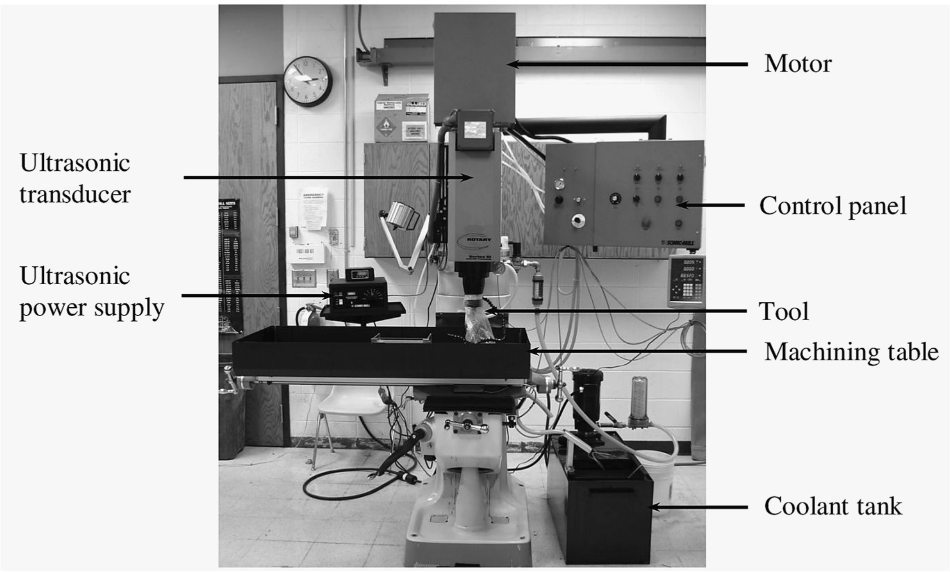


Figure 3 schematically illustrates the experimental setup. The experimental conditions are summarised in Table 1. In the experiments, the cutting tools used are metal-bonded diamond abrasives core drills (NBR Diamond Tool Corp, La Grangeville, NY, USA), with an outer diameter of 9.5 mm (3/8″). Workpieces are 25.4 mm × 25.4 mm × 6.35 mm (1″ × 1″ × 1/4″) 92% alumina samples (Endura) (Ferro Corp, Shreve, OH, USA). Their mechanical properties are listed in Table 2. The coolant used in the RUM process is a water-based coolant with 20:1 dilution of water soluble cutting oil (Mobilmet S 122, Mobil Oil Corp, Fairfax, VA, USA). The supporting platform (fixture) has a hole with a diameter of 13.4 mm (0.53″).

Figure 3 Illustration of experimental setup

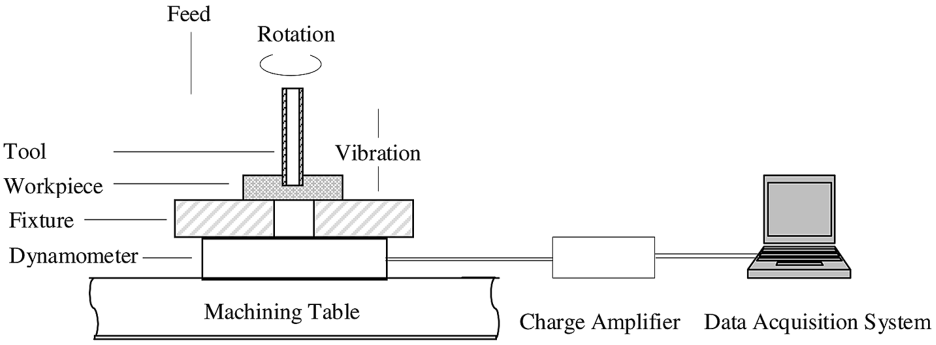


Table 1 Experimental conditions

Item	*Description*
Tool	9.525 mm (3/8″) outer diameter diamond-impregnated metal-bonded core drills (NBR Diamond Tool Corp, La Grangeville, NY)
Workpiece	92% alumina (Al_2O_3) (Endura, Ferro Corp, Shreve, OH)
Coolant	Water-based coolant: 20:1 dilution of water soluble cutting oil (Mobilmet S 122, Mobil Oil Corp, Fairfax, VA)

Table 2 Mechanical properties of workpiece

Property	*Value*
Elastic modulus (GPa)	190
Compressive strength (MPa)	1751
Tensile strength (MPa)	129
Vickers hardness (VHN)	1190
Fracture toughness (MPa/m^2)	4.2

2.2 Design of experiments

A 2^4 (two-level four-factor) full factorial design is employed, which results in 16 unique experiment conditions. Based on the experience from preliminary experiments and due to the limitations of the experimental set-up, the experiments focus on the study of the following four process parameters or machining parameters:

- spindle speed: rotational speed of cutting tool
- ultrasonic power: percentage of power from ultrasonic power supply, which controls the ultrasonic vibration amplitude
- feedrate: feedrate of cutting tool
- grit size: abrasive particle size of cutting tool.

Table 3 shows these variables and the values of the corresponding high and low levels. The levels represent the typical high and low settings for the process parameters according to the preliminary experiments. Furthermore, considering the variations associated with machining experiments involving ceramics, two tests were conducted for each of the 16 unique experiment conditions, bringing the total number of tests to 32. Software called Design-Expert (version 5.0, Stat-Ease Corporation, Minneapolis, MN, USA) is used to generate the testing order as well as to assist in processing the experimental data. The test matrix is shown in Table 4. The output variables, or the process performance parameters, studied include cutting force, material removal rate, and surface roughness.

Table 3 Low and high levels of process parameters

Process parameters	*Unit*	*Low level* (−)	*High level* (+)
Spindle speed	rpm	1000	3000
Ultrasonic power	%	30	45
Feedrate	mm/s	0.09	0.155
Grit size	mesh	140/170	270/325

Table 4 Experimental results

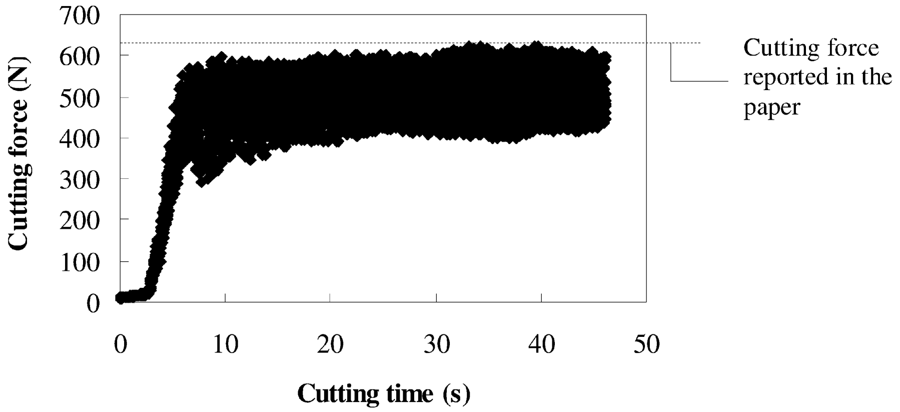
Test order	*Spindle speed*	*Ultrasonic power*	*Feedrate*	*Grit size*	*Cutting force (N)*	*MRR* (mm^3/s)	*Ra* (μm)
30	−	−	−	−	704	2.11	0.55
23	−	−	−	−	658	2.12	0.55
2	+	−	−	−	483	2.17	0.35
5	+	−	−	−	367	2.18	0.42
9	−	+	−	−	473	2.26	0.81
24	−	+	−	−	630	2.16	0.53
18	+	+	−	−	384	2.34	0.61
14	+	+	−	−	146	2.38	0.50
3	−	−	+	−	1057	3.30	0.97
11	−	−	+	−	763	3.60	1.02
27	+	−	+	−	494	3.85	0.81
10	+	−	+	−	409	3.84	0.46
7	−	+	+	−	1021	3.61	0.70
25	−	+	+	−	785	3.56	0.68
1	+	+	+	−	623	2.06	0.84
28	+	+	+	−	519	3.74	0.71
19	−	−	−	+	654	1.91	0.61
31	−	−	−	+	569	2.18	0.49
17	+	−	−	+	294	2.03	0.69
13	+	−	−	+	352	2.12	0.57
8	−	+	−	+	540	2.18	0.57
29	−	+	−	+	493	2.09	0.39
15	+	+	−	+	407	2.12	0.40
20	+	+	−	+	341	2.20	0.57
12	−	−	+	+	796	3.41	0.60
22	−	−	+	+	873	3.19	0.53
32	+	−	+	+	519	3.50	0.47
6	+	−	+	+	411	3.80	0.41
16	−	+	+	+	855	3.49	0.52
4	−	+	+	+	536	3.85	0.63
21	+	+	+	+	585	3.30	0.64
26	+	+	+	+	443	3.67	0.60

2.3 Measurement of output variables

A quartz three-component dynamometer (model 9257B, Kistler Instrumente AG, Winterthur, Switzerland) was used to measure the cutting force. The dynamometer is capable of measuring forces ranging from −5000 N to +5000 N in the X-, Y- and Z-directions above the top surface. The charge signals from the dynamometer are converted into output voltage signals that are proportional to the forces and amplified using a KISTLER dual mode charge amplifier (model 5010B). Data acquisition system is controlled by LabView™ software package (Version 5.1, National Instruments Corporation, Austin, TX, USA). See Figure 3 for reference. Due to the noises generated by the rotary ultrasonic machine during the machining process, some preliminary tests were conducted to obtain the appropriate setting of LabView™ for this process. The scanning rate was set to be 100 samples per second.

The maximum value of the cutting force in the tool axial direction is chosen to represent the cutting force in this study. For an illustration, Figure 4 shows the curve of the cutting force vs. the cutting time.

Figure 4 Cutting force vs. cutting time



The material removal rate for any machining operation is computed by:

$$\text{MRR} = \frac{\text{Volume of Material Removed}}{\text{Time}}$$

So, for the hole drilling process in RUM, MRR can be calculated by the following equation:

$$MRR = \frac{\pi \cdot [(D_h/2)^2 - (D_r/2)^2]\cdot L}{T},$$

where, D_h is the diameter of the drilled hole, D_r diameter of the machined rod, L the length of the drilled hole, and T is the time it takes to drill the hole.

Surface roughness is measured on the cylindrical surfaces of machined rods along the feed direction. A Surftest-402 Profilometer (Mitutoyo Corporation, Japan) is used with the tested range being set as 0.25 mm. The surface roughness in this study is characterised by R_a, average surface roughness.

3 Results and discussion

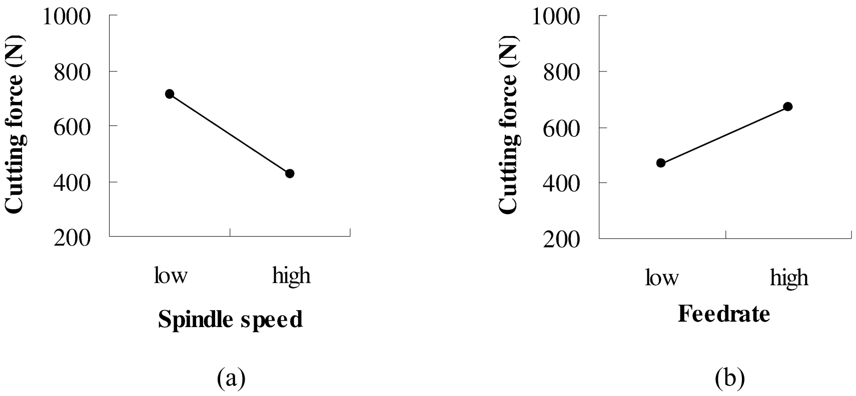
In the previous section, the design of experiments is described. This section provides the experimental results which are summarised in Table 4, as well as some discussions. ANOVA (analysis of variance) was performed for each of the three output variables, to identify the significant effects on cutting force, MRR, and surface roughness at the significance level $\alpha=0.1$. In the following discussion, only these significant effects will be presented.

3.1 Results on cutting force

The spindle speed and the feedrate have significant effects on the cutting force, with P-value<0.0001 and P-value$=0.0001$, respectively. P-value is the smallest level of significance that would lead to rejection of the null hypothesis with the given data. More information about the P-value approach can also be found in statistics textbooks such as the one by Montgomery and Runger (2003).

The geometric representation is shown in Figure 5. The cutting force decreases as the spindle speed increases. It is interesting to notice that this observation is different from those previously reported (Pei, 1995; Pei and Ferreira, 1999) for rotary ultrasonic face milling. This is due to the fundamental difference between these two processes: the rotary ultrasonic hole drilling in this study rather than the rotary ultrasonic face milling. In addition, the cutting force increases as the feedrate increases. For the two-level four-factor factorial design, six two-factor interactions can be obtained, none of them has significant effects on the cutting force at the significance level $\alpha=0.1$. Four three-factor interactions can be obtained for the two-level four-factor factorial design, again, none of the three-factor interactions on the cutting force is significant at $\alpha=0.1$.

Figure 5 Significant main effects on cutting force

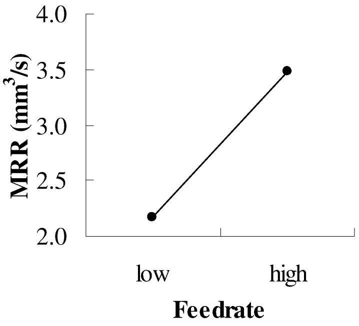


(a) (b)

3.2 Results on MRR

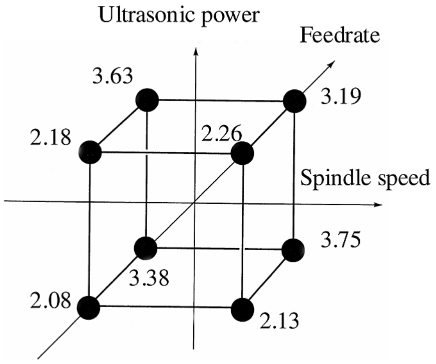
The main effects of four process parameters (spindle speed, ultrasonic power, feedrate, and grit size), two-factor interactions, and three-factor interactions on MRR are studied. The geometric representation of the significant effects on MRR at the significance level $\alpha=0.1$ is provided in Figures 6 and 7. Among the parameters investigated, the feedrate has the significant effects on MRR with P-value <0.0001. As the feedrate increases, MRR increases, as shown in Figure 6.

Figure 6 Significant main effects on MRR



The remaining process factors such as the spindle speed, the ultrasonic power and the grit size have no significant effects on MRR at the significance level $\alpha=0.1$. In addition, ANOVA shows that the six two-factor interactions do not have significant effects on MRR at the significance level $\alpha=0.1$. It can be observed that the three-factor interaction of the spindle speed, the feedrate, and the ultrasonic power on MRR is significant (P-value $=0.0889$). As shown in Figure 7, the combination for the highest MRR is higher spindle speed, smaller ultrasonic power, and larger feedrate.

Figure 7 Significant three-factor interaction effects on MRR (mm^3/s)



3.3 Results on surface roughness

The main effects of four machining parameters (spindle speed, ultrasonic power, feedrate, and grit size), two-factor interactions, and three-factor interactions on surface roughness are studied, with the geometric representation of the significant effects at the significance level $\alpha=0.1$ being depicted in Figures 8, 9, and 10. The spindle speed, the feedrate, and the grit size have significant effects on the surface roughness with P-value=0.0755, P-value=0.0040, and P-value=0.0073, respectively. The surface roughness becomes lower as the spindle speed increases and the feedrate decreases. In addition, the surface roughness becomes lower as the tool changes from the low level of grit size (mesh 140/170) to the high level of grit size (mesh 270/325) in this process, which is consistent with the observation by Prabhakar (1992). However, it is interesting to notice that this observation is different from those previously reported (Pei, 1995; Pei and Ferreira, 1999) for rotary ultrasonic face milling. This is due to fundamental difference of these two processes.

Figure 8 Significant main effects on surface roughness

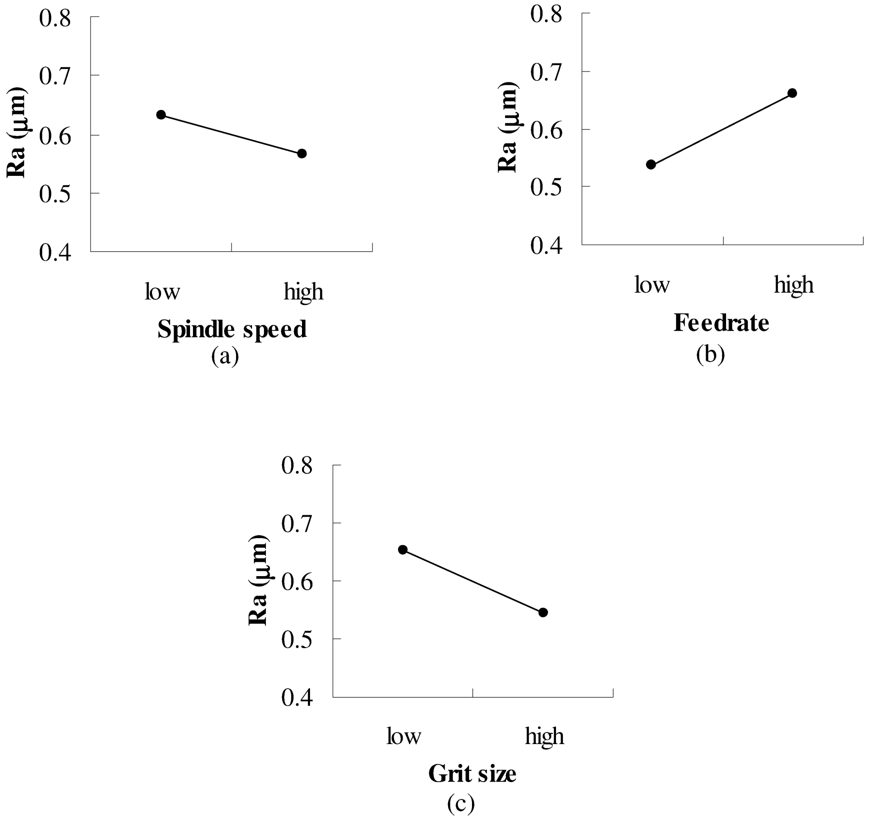


Figure 9 Significant two-factor interaction effects on surface roughness

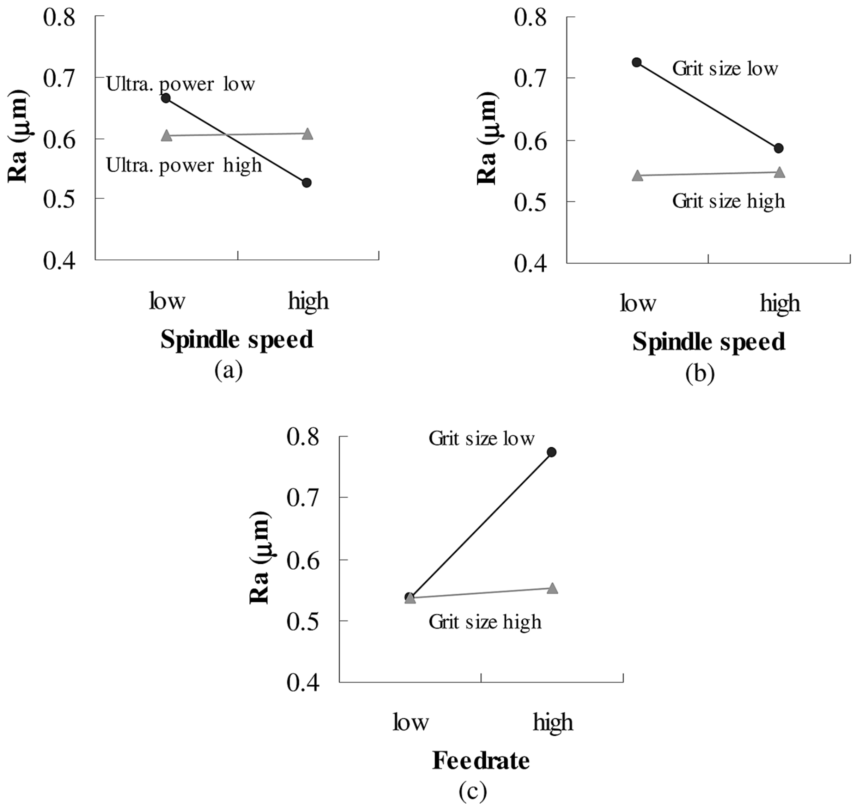
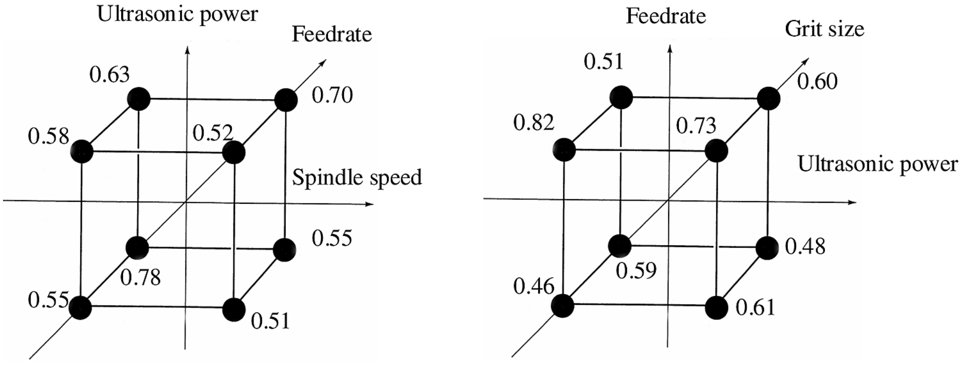


Figure 10 Significant three-factor interaction effects on surface roughness (μm)



(a) (b)

Six two-factor interactions effects on the surface roughness can be obtained some of which are significant. The following are the two-factor interactions between the spindle speed and the ultrasonic power (P-value=0.0625), between the spindle speed and the grit size (P-value = 0.0732), and between the feedrate and the grit size (P-value = 0.0084). As shown in Figure 9(a), at the low level of the ultrasonic power, the change in spindle speed causes a larger change in the surface roughness than at the high level of the ultrasonic power. In Figure 9(b), at the low level of the grit size (mesh 140/170), the change in spindle speed causes a larger change in the surface roughness than at the high level of the grit size (mesh 270/325). And in Figure 9(c), at the low level of the grit size, the change of the feedrate causes a larger change in the surface roughness than at the high level of the grit size.

For the three-factor interactions on surface roughness, it can be observed that the interaction of the spindle speed, the ultrasonic power, and the feedrate (P-value = 0.0423), and the interaction of the ultrasonic power, the feedrate, and the grit size (P-value = 0.0097), have significant effects on the surface roughness. As shown in Figure 10(b), the best combination with respect to the surface roughness is less ultrasonic power, lower feedrate, and lower level of grit size, which yields the least surface roughness.

4 Conclusions

In this paper, a 2^4 (two-level, four-factor) full factorial design is employed to study the relationship between the output variables (cutting force, material removal rate, and surface roughness) and four process parameters (spindle speed, ultrasonic power, feedrate, and grit size) in rotary ultrasonic core drilling on a ceramic material (92% alumina). Based on the experimental results, the main effects, two-factor interactions and three-factor interactions of these four process parameters on these performance parameters are obtained and discussed.

According to the experiments, the following conclusions can be drawn:

- The cutting force is one of the important output variables in RUM. For the first time, a systematic study on the effects of process parameters on the cutting force for 92% alumina in RUM is performed and reported.
- For cutting force, the spindle speed and the feedrate have significant effects on the cutting force; higher spindle speed and lower feedrate result in a smaller cutting force. Some two-factor interactions, and three-factor interactions have significant effects on cutting force as well.
- Only feedrate has significant effects on MRR.
- The feedrate, the spindle speed and the grit size have significant effects on surface roughness.
- Some two-factor and three-factor interactions also have significant effects on MRR and surface roughness.

Acknowledgements

This work was supported in part by the Society of Manufacturing Engineers through a research initiation grant and by the Advanced Manufacturing Institute at Kansas State University. The authors would like to thank Mr Bruno Renzi at NBR Diamond Tool

Corporation for providing the diamond tools, Mr Todd Cohn at Lighthouse Lubricant Solutions for providing the coolant, Mr James Jaskowiak at the Ferro Corporation for providing the workpiece materials, Mr Timothy Deines at Kansas State University for providing technical assistance in setting up the machine, and Professor Shuting Lei and Mr Gregory Oundjian at Kansas State University for providing assistance in the measurement of cutting force and surface roughness.

References

Ardelt, T., Uhlmann, E. and Spur, G. (1999) 'Machining of complex contours by ultrasonic assisted grinding', *3rd International Machining and Grinding Conference*.

Cleave, D.V. (1976) 'Ultrasonic gets bigger jobs in machining and welding', *Iron Age*, September 13, pp.69–72.

Graff, K.F. (1975) 'Ultrasonic machining', *Ultrasonics*, May, pp.103–109.

Khanna, N., Pei, Z.J. and Ferreira, P.M. (1995) 'An experimental investigation of rotary ultrasonic grinding of ceramics disk', *Technical Papers of the North American Manufacturing Research Institute of SME*, pp.67–72.

Kubota, M., Tamura, Y. and Shimamura, N. (1997) 'Ultrasonic machining with a diamond impregnated tool', *Bulletin Japan Society of Precision Engineering*, Vol. 11, No. 3, pp.127–132.

Legge, P. (1964) 'Ultrasonic drilling of ceramics', *Industrial Diamond Review*, Vol. 24, No. 278, pp.20–24.

Legge, P. (1966) 'Machining without abrasive slurry', *Ultrasonics*, pp.157–162.

Markov, A.I. and Ustinov, I.D. (1972) 'A study of the ultrasonic diamond drilling of non-metallic materials', *Industrial Diamond Review*, March, pp. 97–99.

Markov, A.I. et al. (1977) 'Ultrasonic drilling and milling of hard non-metallic materials with diamond tools', *Machine and Tooling*, Vol. 48, No. 9, pp.45–47.

Montgomery, D.C. and Runger, G.C. (2003) *Applied Statistics and Probability for Engineers*, New York, NY: John Wiley & Sons, Inc.

Pei, Z.J. (1995) 'Rotary ultrasonic machining of ceramics', *PhD Thesis*, University of Illinois at Urbana-Champaign.

Pei, Z.J. and Ferreira, P.M. (1998) 'Modeling of ductile mode material removal in rotary ultrasonic machining', *International Journal of Machine Tools and Manufacture*, Vol. 38, Nos. 10–11, pp.1399–1418.

Pei, Z.J. and Ferreira, P.M. (1999) 'An experimental investigation of rotary ultrasonic face milling', *International Journal of Machine Tools and Manufacture*, Vol. 39, No. 8, pp.1327–1344.

Pei, Z.J., Kapoor, P.M. and Haselkorn, S.G. (1995) 'Rotary ultrasonic machining for face milling of ceramics', *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 7, pp.1033–1046.

Petrukha, P.G. et al. (1970) 'Ultrasonic diamond drilling of deep holes in brittle materials', *Russian Engineering Journal*, Vol. 50, No. 10, pp.70–74.

Prabhakar, D. (1992) 'Machining advanced ceramic materials using rotary ultrasonic machining process', *MS Thesis*, University of Illinois at Urbana-Champaign.

Prabhakar, D., Pei, Z.J., Ferreira, P.M. and Haselkorn, M. (1993) 'A theoretical model for predicting material removal rates in rotary ultrasonic machining of ceramics', *Transactions of the North American Manufacturing Research Institution of SME*, Vol. 21, pp.167–172.

Spur, G. and Holl, S.E. (1997) 'Material removal mechanisms during ultrasonic assisted grinding', *Production Engineering*, Vol. 4, No. 2, pp.9–14.

Spur, G., Uhlmann, E. and Holl, S.E. (1999b) 'Ultrasonic assisted grinding of ceramics', *Proceedings of the World Ceramics Congress, Ceramics: Getting into the 2000's – Part D*, pp.181–191.

Spur, G., Uhlmann, E. and Holl, S.E. (2001) 'Ultrasonic assisted grinding of ceramics', *Industrial Ceramics*, Vol. 21, No. 3. pp.177–181.

Spur, G., Uhlmann, E., Holl, S.E. and Daus, N.A. (1999a) 'Influences on surface and subsurface during ultrasonic assisted grinding of advanced ceramics', *Proceedings of the 14th Annual Meeting, the American Society for Precision Engineering*, pp.481–484.

Thoe, T.B., Aspinwall, D.K. and Wise, M.L.H. (1998) 'Review on ultrasonic machining', *International Journal of Machine Tools and Manufacture*, Vol. 38, No. 4, pp.239–255.

Tyrrell, W.R. (1970) 'Rotary ultrasonic machining', *SME Technical Paper*, MR70-516.

Uhlmann, E., Spur, G. and Holl, S.E. (1999) 'Machining of complex contours by ultrasonic assisted grinding', *SME Technical Paper*, MR99-284.

Ya, G., Qin, H.W., Xu, Y.W. and Zhang, Y.S. (2001) 'An experimental investigation on rotary ultrasonic machining', *Key Engineering Materials*, Vols. 202–203, pp.277–280.