Rotary ultrasonic machining of silicon carbide: designed experiments

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Abstract: Silicon carbide (SiC) has found a variety of engineering applications due to its superior properties. However, it is still desirable to study cost-effective processes to machine silicon carbide. This paper presents the results of a designed experimental investigation into Rotary Ultrasonic Machining (RUM) of silicon carbide. A four-variable two-level full factorial design was employed to reveal main effects as well as interaction effects of four process variables (spindle speed, feedrate, ultrasonic power and grit size). The process outputs studied include cutting force, surface roughness and chipping size.

Keywords: ceramic; chipping size; cutting force; design of experiments; grinding, machining; Rotary Ultrasonic Machining (RUM); surface roughness.

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Dustin C. Shorter is currently an undergraduate student for a Bachelor's degree in the Industrial and Manufacturing Systems Engineering Department at Kansas State University, USA. He has conducted a research on rotary ultrasonic machining.

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

1 Introduction

Silicon carbide (Sic) has superior properties such as high strength at elevated temperatures, resistance to chemical degradation, wear resistance, low density, high stiffness, low coefficient of thermal expansion and superior creep resistance. The combination of these properties makes them attractive in many engineering applications such as high-temperature engines, nuclear fusion reactors, chemical process equipment and aerospace components (Anonymous, 1966; Datta and Chaudhari, 2003; Datta et al., 2004; Gopal and Rao, 2003; Yin et al., 2004).

Reported studies on machining of Silicon carbide (Sic) include electrical-discharged machining (Luis et al., 2005; Puertas and Perez, 2003), machining with abrasive paste (Dolotov et al., 1986), grinding with diamond wheels (Gopal and Rao, 2003; Gopal and Rao, 2004; Kibble and Phelps, 1995; Yin et al., 2004), ion beam milling (Hylton et al., 1993), lapping/polishing (Chandler et al., 2000) and micro machining with ultrashort laser pulses (Rice et al., 2002). However, the literature review states that difficulty, high cost and long time associated with machining of Silicon carbide (SiC) limit the use of Silicon carbide (SiC) in industry. Therefore there is a need to develop more cost effective machining methods for silicon carbide.

Among non-traditional machining processes being currently proposed for machining hard-to-machine materials, Rotary Ultrasonic Machining (RUM) is a relatively low-cost, environment-benign process that easily fits in with the infrastructure of the traditional machining environment (Cleave, 1976; Graff, 1975; Hu et al., 2003; Kumabe, et al., 1989; Pei et al., 1995; Petrukha, 1970). In RUM, a rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated in the axial direction and fed towards the workpiece at a constant feedrate or constant force. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill and keeps it cool. This process is illustrated in Figure 1.

Table 1 summarises reported work on RUM process since it was invented in 1960s. It can be seen that RUM has been employed to machine many types of materials. However, no systematic studies have been published on RUM of silicon carbide.

This paper reports the results of a study on RUM of Silicon carbide (SiC) using designed experiments. It presents and discusses the main and interaction effects of process variables (spindle speed, feedrate and ultrasonic power) on cutting forces, surface roughness and chipping size.

Figure 1 Illustration of rotary ultrasonic machining

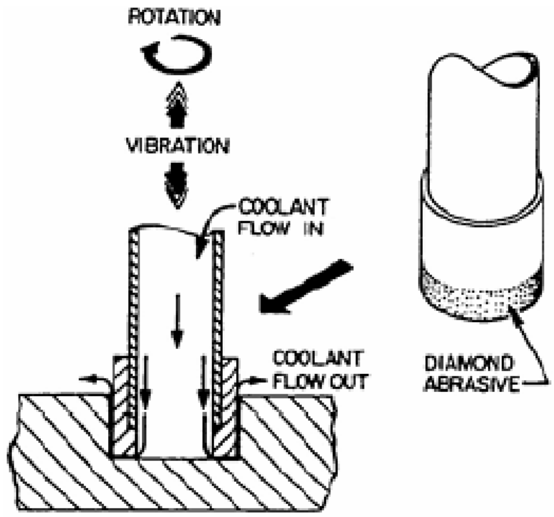


Table 1 Summary of workpiece materials machined by RUM

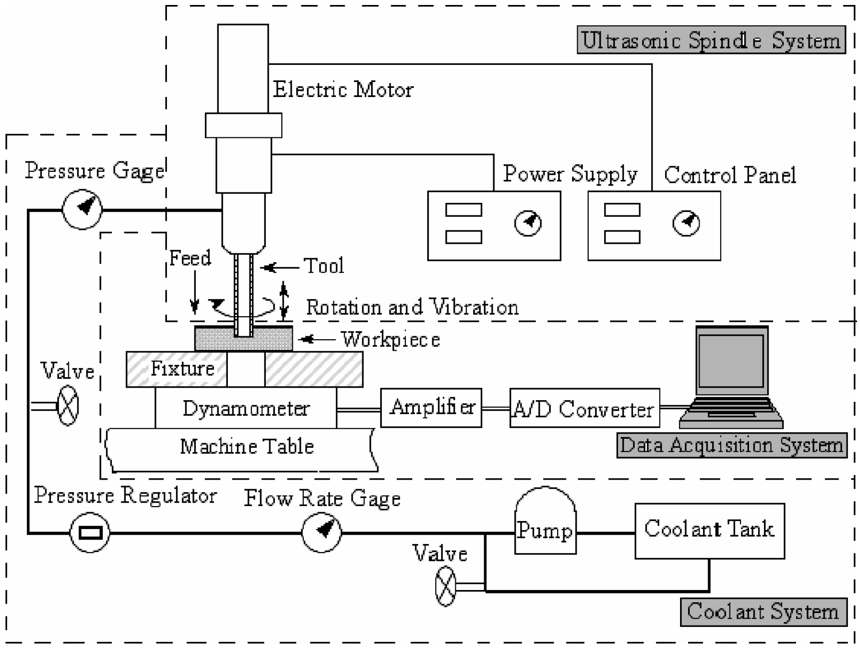
Workpiece material	*Reference*
Alumina	Hu et al. (2003), Li et al. (to appear), Anantha et al. (1989), Zeng et al. (2004), Jiao et al. (to appear) and Jiao et al. (2005)
Canasite	Khanna et al. (1995)
Ceramic composite matrix	Li et al. (2005)
Glass	Jana and Satyanarayana (1973), Treadwell and Pei (2003), Anonymous (1973) and Anonoymous (1966)
Polycrystalline Diamond Compacts	Li et al. (2004)
Silicon carbide	Zeng et al. (2005)
Silicon Nitride	Dam et al. (1995)
Titanium Boride	Dam et al. (1995)
Zirconia	Anantha et al. (1989), Pei et al. (1995), Prabhakar (1992), Pei (1995), Pei et al. (1995) and Pei and Ferreira (1998)

2 Experimental conditions and procedure

2.1 Experimental set-up and conditions

Machining experiments were performed on a machine of Sonic Mill Series 10 (Sonic-Mill^R, Albuquerque, NM, USA). The experimental set-up is schematically illustrated in Figure 2. It mainly consists of an ultrasonic spindle system, a data acquisition system and a coolant system. The ultrasonic spindle system comprises of an ultrasonic spindle, a power supply and a motor speed controller. The power supply converts 60 Hz electrical supply to high frequency (20 kHz) AC output. This is fed to the piezoelectric transducer located in the ultrasonic spindle. The ultrasonic transducer converts electrical input into mechanical vibrations. 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 Experimental set-up



Mobilemet® S122 water-soluble cutting oil (MSC Industrial Supply Co., Melville, NY, USA) was used as the coolant (diluted with water at 1–20 ratio).

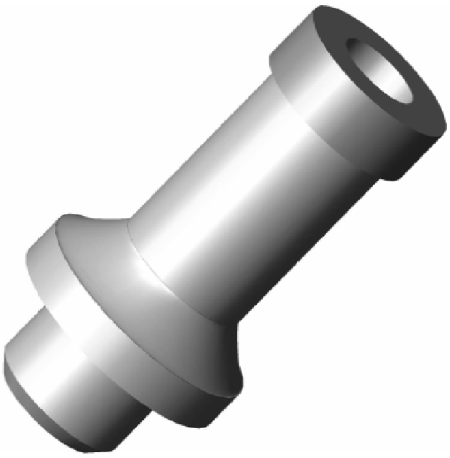
The workpiece material was Silicon carbide (SiC) provided by Saint-Gobain Ceramics (Niagara Falls, NY). The mechanical properties are given in Table 2. The size of workpiece was 120 mm × 50 mm × 6 mm.

Table 2 Properties of silicon carbide (SiC)

Property	*Unit*	*Value*
Tensile strength	MPa	3440
Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$	120
Melting point	K	56
Density	$Kg \cdot m^{-3}$	3100
Coefficient of thermal expansion	$in \cdot in^{-1}\ F^{-1}$	2.2×10^{-6}
Vickers hardness		2150

Figure 3 illustrates the diamond drills used. They were provided by N.B.R. Diamond Tool Corp. (LaGrangeville, NY, USA). The outer and inner diameters of the core drills were 9.6 mm and 7.8 mm respectively.

Figure 3 Illustration of the cutting tool for rotary ultrasonic machining



2.2 Design of experiments

A 2^4 (two-level four-factor) full factorial design was employed. There were 16 unique experimental conditions. Based on preliminary experiments and due to the limitations of the experimental set-up, the following four process variables were studied:

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

Table 3 gives the low and high levels of the process variables. Test matrix is given in Table 4. The high and low levels of the process variables were determined according to the preliminary experiments. Furthermore, considering the variations associated with ceramic machining experiments, two tests were conducted for each of the 16 unique experiment conditions, bringing the total number of tests to 32. The output variables studied include cutting force, surface roughness and chipping size.

Table 3 Low and high levels of process variables

Process Variable	*Unit*	*Low level (−)*	*High level (+)*
Spindle speed	$rev\cdot s^{-1}$	33.3	66.6
Feedrate	$mm\cdot s^{-1}$	0.008	0.015
Ultrasonic power*	%	25	50
Grit size	mesh	60/80	80/100

* To control ultrasonic vibration amplitude.

Table 4 Test matr

Test #	*Test order*		*Spindle speed*	*Vibration power*	*Feedrate*	*Grit size*
	Test 1	*Test 2*				
1	1	14	–	–	–	–
2	10	8	+	–	–	–
3	4	3	–	+	–	–
4	5	16	+	+	–	–
5	3	10	–	–	+	–
6	7	2	+	–	+	–
7	2	9	–	+	+	–
8	16	15	+	+	+	–
9	6	1	–	–	–	+
10	12	11	+	–	–	+
11	11	5	–	+	–	+
12	13	12	+	+	–	+
13	9	4	–	–	+	+
14	8	7	+	–	+	+
15	15	6	–	+	+	+
16	14	13	+	+	+	+

2.3 Measurement procedure

During RUM, the cutting force along the feedrate direction was measured by a KISTLER 9257 dynamometer (Kistler Instrument Corp, Amherst, NY, USA). The dynamometer was mounted atop the machine table and beneath the workpiece, as shown in Figure 2. The electrical signals from the dynamometer were transformed into numerical signals by an A/D converter. Then the numerical signals to measure the cutting force were displayed and saved on the computer with the help of LabVIEW™ (Version 5.1, National Instruments, Austin, TX, USA). The sampling frequency to obtain the cutting force signals was 100 Hz. A typical curve of cutting force versus time is shown in Figure 4. The cutting force reported in this paper is the maximum cutting force on the cutting force curve, as illustrated in Figure 4.

The surface roughness was measured on the machined hole surface with a surface profilometer (Mitutoyo Surftest-402, Mitutoyo Corporation, Kanagawa, Japan).

A digital video microscope of Olympus DVM-1 (Olympus America Inc., Melville, NY, US) was utilised to inspect the chippings at the exit side of the machined hole. The hole quality is quantified by the size of the edge chipping formed on the machined rod as illustrated in Figure 5. The chipping size was measured with a vernier caliper (Mitutoyo IP-65, Mitutoyo Corporation, Kanagawa, Japan).

Figure 4 Measurement of maximum cutting force

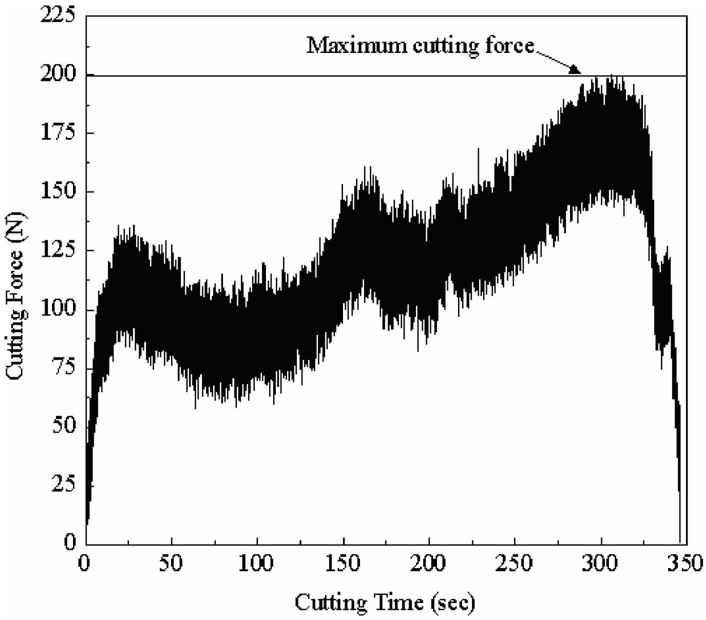
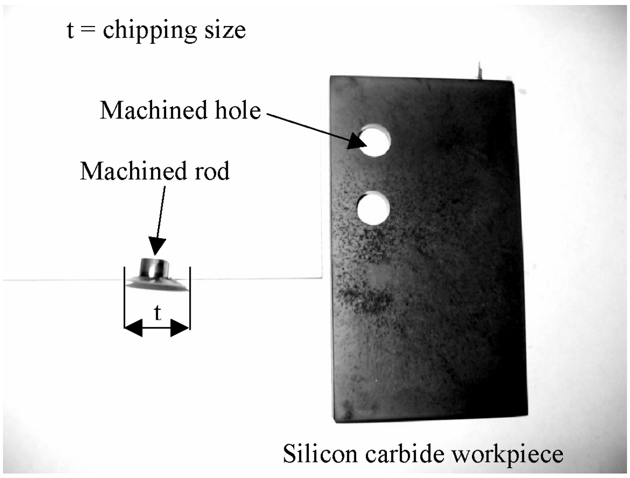


Figure 5 Illustration of chipping size



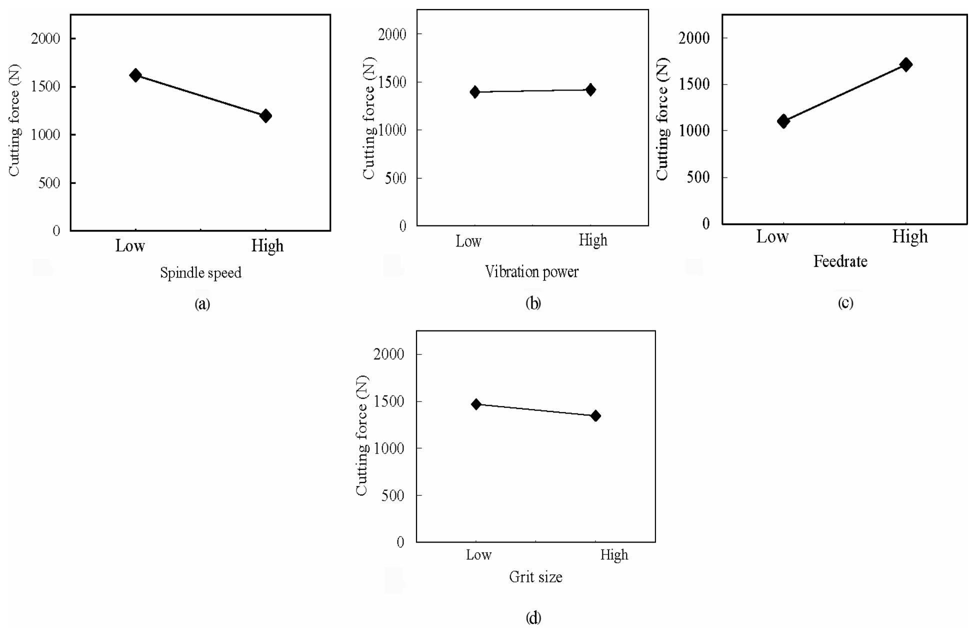
3 Experimental results

Table 5 displays the experimental data. The software called MINITAB Statistical Software (Version 13.31, Minitab Inc., State College, PA, USA) was used to process the data and to obtain the main effects, two-factor interaction and three-factor interaction effects. Geometric representations of these effects are presented in Figures 6–11. Analysis of Variance (ANOVA) has been conducted to determine the significance of each effect. However, ANOVA, tables are omitted in this paper.

Table 5 Experimental result

Test #	*Cutting force (N)*		*Chipping size (mm)*		*Surface roughness Ra (μm)*	
	Test 1	*Test 2*	*Test 1*	*Test 2*	*Test 1*	*Test 2*
1	1400	1350	14	16	0.38	0.40
2	1010	980	10	11	0.32	0.35
3	1230	1205	16	18	0.33	0.37
4	990	950	13	12	0.27	0.29
5	1930	1965	17	16	0.49	0.51
6	1420	1450	15	17	0.41	0.43
7	2120	2145	20	22	0.41	0.42
8	1650	1710	19	20	0.36	0.38
9	1290	1230	13	13	0.29	0.29
10	970	950	9	10	0.24	0.27
11	1090	1060	14	13	0.25	0.27
12	850	900	12	14	0.23	0.23
13	1810	1770	15	16	0.38	0.40
14	1340	1390	14	14	0.36	0.37
15	2080	2180	17	16	0.34	0.37
16	1340	1310	15	16	0.30	0.33

Figure 6 Main effects on cutting force



3.1 Main effects

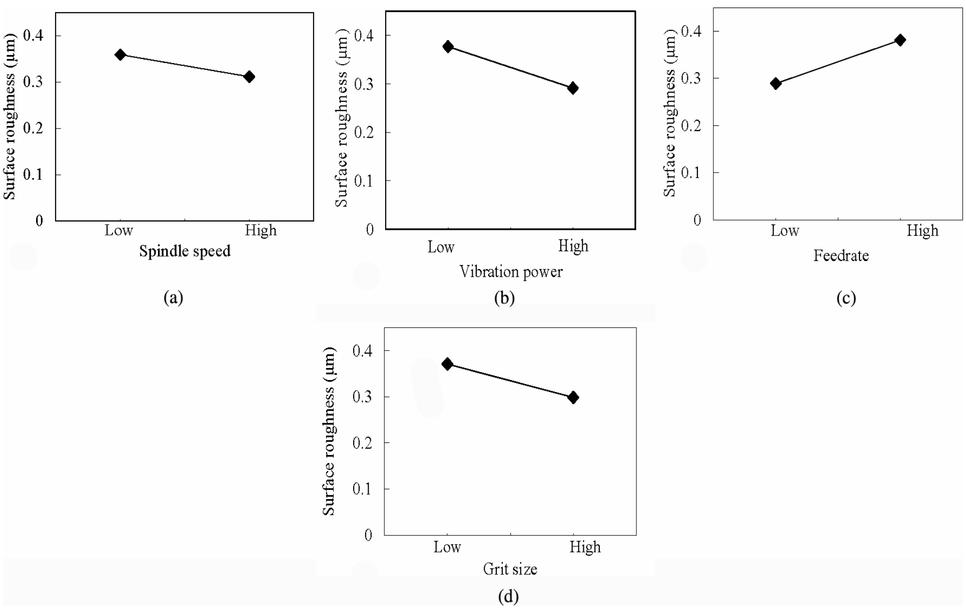
3.1.1 On-cutting force

The main effects of the four process variables (spindle speed, feedrate, vibration power and grit size) on cutting force are shown in Figure 6. The effect of feedrate is the most significant (with *P*-value = 0.031). The second significant effect is spindle speed (*P*-value = 0.045). It can be seen that, as spindle speed decreases and feedrate increases, cutting force will increase. These trends are consistent with those observed by Jiao et al. (2005) for RUM of alumina and by Li et al. (2005) for RUM of ceramic matrix composites.

3.1.2 On-surface roughness

The main effects of the four process variables (spindle speed, feedrate, vibration power and grit size) on surface roughness are shown in Figure 7. The effect of feedrate is the most significant (with *P*-value = 0.069). The second significant effect is grit size (*P*-value = 0.087) followed by spindle speed (*P*-value = 0.132), and vibration power (*P*-value = 0.132). As it can be seen, surface roughness (Ra) decreases as spindle speed, vibration power and grit size increases and as feedrate decreases. These trends are consistent with those reported by Jiao et al. (2005) for RUM of alumina.

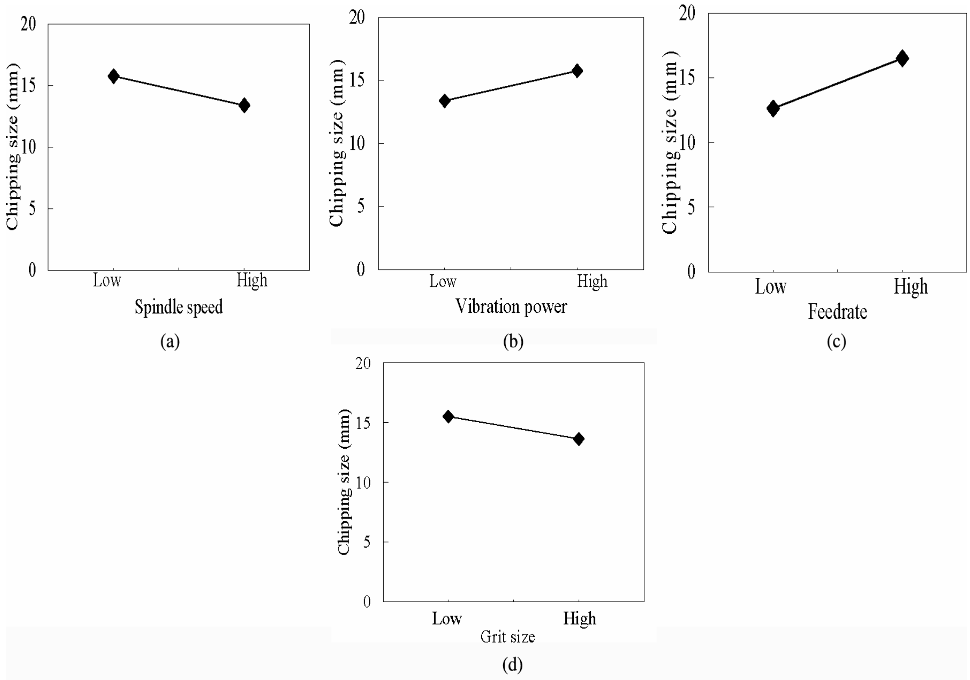
Figure 7 Main effects on surface roughness



3.1.3 On-chipping size

The main effects of the four process variables (spindle speed, feedrate, vibration power and grit size) on chipping size are shown in Figure 8. The effect of feedrate is the most significant (with *P*-value = 0.061). The secondly significant effects are spindle speed and vibration power (both have *P*-value = 0.1). As it can be seen, as spindle speed and grit size increase or feedrate decreases, chipping size decreases. These trends are consistent with those reported by Jiao et al. (2005) for RUM of alumina and by Li et al. (2005) for RUM of ceramic matrix composite.

Figure 8 Main effects on chipping size



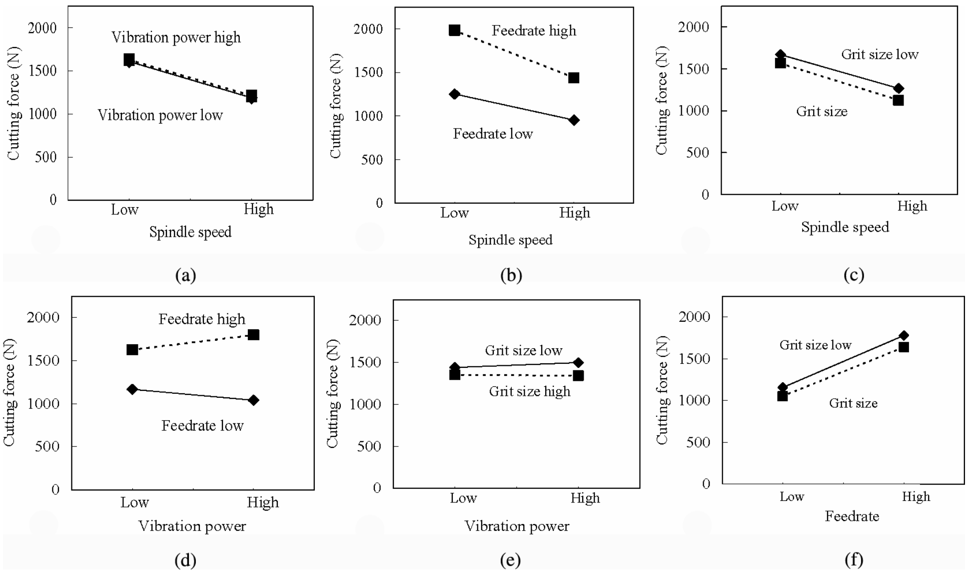
3.2 Two-factor interactions

3.2.1 On-cutting force

For the four-factor two-level factorial design, six two-factor interactions can be obtained. The results are shown in Figure 9. The interactions between spindle speed and feedrate (*P*-value = 0.15) as shown in Figure 9 (b), between vibration power and feedrate (*P*-value = 0.126) as shown in Figure 9 (d), between vibration power and grit size (*P*-value = 0.151) as shown in Figure 9 (e), are significant on cutting force at a significance level of $\alpha = 0.2$.

As shown in Figure 9 (b), at the high level of feedrate, the change of spindle speed causes a larger change in cutting force than at the low level of feedrate. As shown in Figure 9 (d), at the high level of feedrate, the cutting force increases with the change of vibration power from low level to high level, whereas, at the low level of feedrate, the cutting force decreases with the change of vibration power from low level to high level. As shown in Figure 9 (e), at low level of grit size, the cutting force increases with change of vibration power from low level to high level, whereas, at high level of grit size, the cutting force remains about the same with change of vibration power from low level to high level.

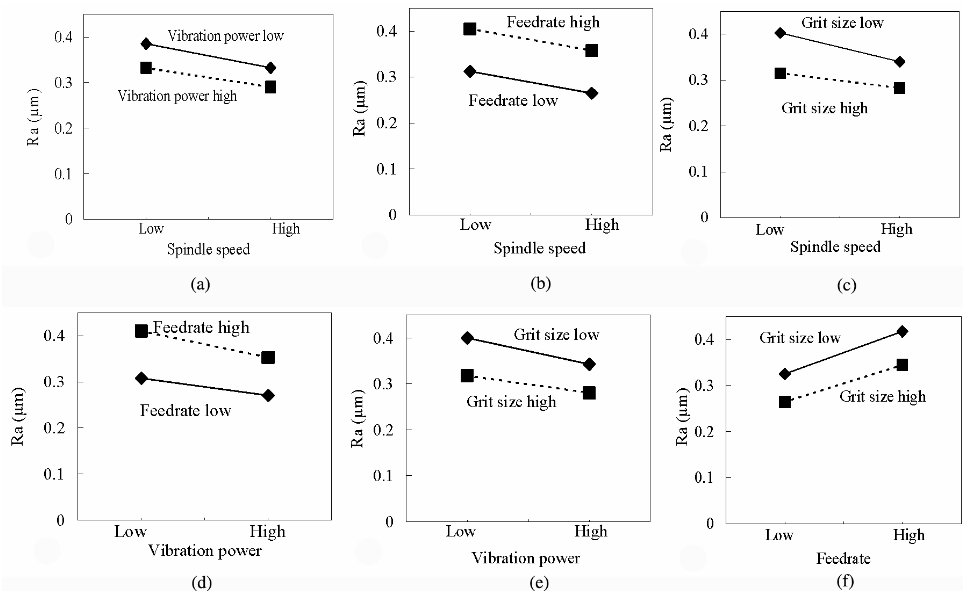
Figure 9 Two factor interactions on cutting force



3.2.2 *On-surface roughness*

The six two-factor interaction effects on surface roughness are shown in Figure 10. The interaction effect between spindle speed and grit size (*P*-value = 0.174) as shown in Figure 10 (c) is significant at a significance level of $\alpha = 0.2$. It can be seen that at the low level of grit size, the change of spindle speed causes a larger change in surface roughness than at the high level of grit size.

Figure 10 Two factor interactions on surface roughness

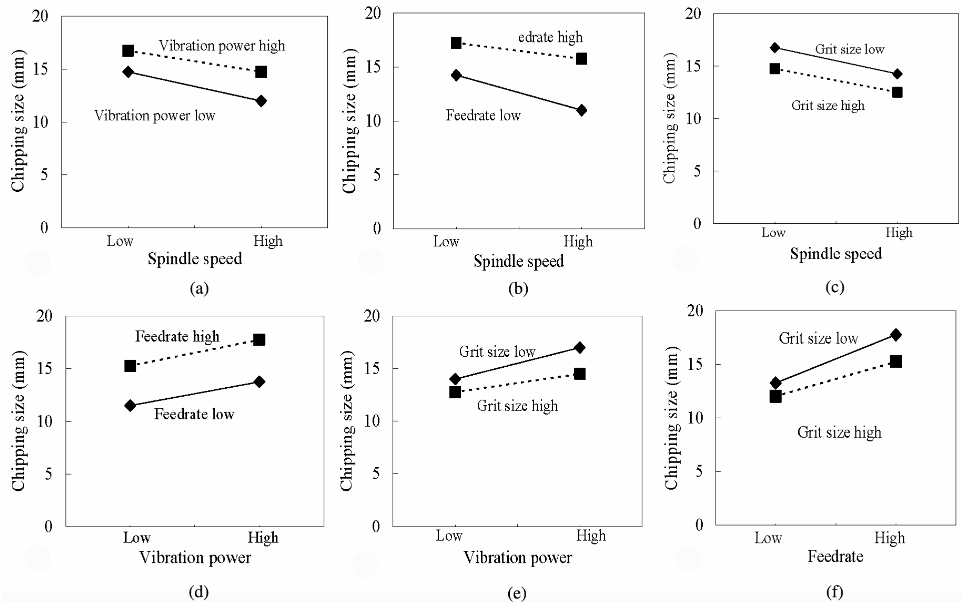


3.2.3 On-chipping size

The six two-factor interaction effects on chipping size are shown in Figure 11. The interaction effect between spindle speed and vibration power (*P*-value = 0.2) as shown in Figure 11 (a), is significant at a significance level of $\alpha = 0.2$.

It can be seen that at the high level of vibration power, the change of spindle speed causes a smaller change in chipping size than at the low level of vibration power.

Figure 11 Two factor interactions on chipping size



3.3 *Three-factor interactions*

At the significance level of α = 0.3, none of the three-factor interactions is significant. Therefore, their geometric representations and discussion are omitted in this paper.

4 Conclusions

A four-factor two-level factorial design is used to study the relationships between the outputs (cutting force, surface roughness and chipping size) and the four process variables (spindle speed, feedrate, vibration power and grit size). The following conclusions are drawn from this study:

1. The main effects of spindle speed and feedrate have significant effects (α = 0.05) on the cutting force. As spindle speed decreases and feedrate increases, cutting force increases.
2. Spindle speed, vibration power, feedrate and grit size have significant effects on surface roughness (Ra), it decreases as spindle speed, vibration power and grit size increases and as feedrate decreases.

3 Spindle speed, feedrate and vibration power have significant effects on chipping size, as spindle speed and grit size increase or feedrate and vibration power decreases, chipping size decreases.

4 Some of the two-factor interactions are also significant.

Acknowledgements

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