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An Experimental Study on the Ultrasonic Machining Characteristics of Engineering Ceramics

Ik Soo Kang*
Department of Precision and Mechanical Engineering, Pusan Nationl University,
Jangjeon-Dong, Keumjung-Ku, Busan 609-735, Korea
Jeong Suk Kim
School of Mechanical Engineering, Pusan Nationl University,
Jangjeon-Dong, Keumjung-Ku, Busan 609-735, Korea
Yong Wie Seo
School of Mechanical and Automotive Engineering, Inje University,
Obang-Dong, Kimhae, Kyungnam 621-749, Korea
Jeon Ha Kim
ERC/NSDM, Pusan Nationl University,
Jangjeon-Dong, Keumjung-Ku, Busan 609-735, Korea

Engineering ceramics have many unique characteristics both in mechanical and physical properties such as high temperature hardness, high thermal, chemical and electrical resistance. However, its machinability is very poor in conventional machining due to its high hardness and severe tool wear. In the current experimental study, alumina (Al_2O_3) was ultrasonically machined using SiC abrasives under various machining conditions to investigate the material removal rate and surface quality of the machined samples. Under the applied amplitude of 0.02 mm, 27 kHz frequency, three slurry ratios of 1:1, 1:3 and 1:5 with different tool shapes and applied static pressure levels, the machining was conducted. Using the mesh number of 240 abrasive, slurry ratio of 1:1 and static pressure of 2.5 kg/cm^2, maximum material removal rate of 18.97 mm^3/min was achieved. With mesh number of 600 SiC abrasives and static pressure of 3.0 kg/cm^2, best surface roughness of 0.76 μm Ra was obtained.

Key Words : Ultrasonic Machining, Engineering Ceramics, Machinablility, Material Removal Rate, Alumina, Abrasives, Static Pressure

1. Introduction

In general, engineering ceramics have been widely used for parts for high temperatures as they have excellent characteristics and various functionalities like high hardness, high thermal resistance, chemical stability, low thermal conductivity and can maintain strength and stiffness at high temperatures. In particular, they are often used as material for parts like cylinder liners, bushings and bearings as they have excellent abrasion resistance. But the application of conventional machining to alumina ceramics entails technical and economic limitations because it is difficult to cut them and obtain precise measurements and surface roughness (Zeng et al., 2005 ; Lee et al., 1997 ; Zhang et al., 1999 ; Thoe et al., 1998).

Ultrasonic machining (USM) is a mechanical machining method that removes material by

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* Corresponding Author,
E-mail:iskang@pusan.ac.kr
TEL:+82-51-510-3079; **FAX**:+82-51-518-7207
Department of Precision and Mechanical Engineering, Pusan National University, Jangjeon-Dong, Keumjung-Ku, Busan 609-735, Korea. (Manuscript **Received** September 12, 2005; **Revised** December 23, 2005)

brittle fracture. Under the method, abrasives are supplied between the tool and workpiece and high frequency is applied to the tip of the tool; then the resulting pulse impact force causes fractures of micron level on the surface of the workpiece. In addition, USM can be applied irrespective of the chemical or electrical properties of a workpiece: this nontraditional machining can be applied to the machining of the high-hardness materials like non-metallic materials, tungsten and titanium carbide and the brittle materials such as glass, quartz and ceramics (Jeon et al., 2003; Kainth et al., 1978; Soundararajan et al., 1985; Pei et al., 1995).

Through ultrasonic machining of engineering alumina ceramics, this paper aims to investigate the ultrasonic machining characteristics of alumina ceramics by examining the machining conditions under which a good degree of surface precision and material removal rate (MRR) can be obtained.

2. Mechanism of Material Removal

In USM, high-hardness abrasives are supplied between the workpiece and the tool engraved with the desired form and tens of kHz of ultrasonic vibration are applied to cause fine impact to the surface of the workpiece. By doing so, material is removed by brittle fracture. By continuously providing the slurry made of abrasives and water to the machining part, the crushed particles are replaced with new particles and machining takes place by micro-chipping of a number of abrasives and the vibration of the tool.

The mechanism of material removal can be divided into hammering, throwing, cavitation erosion and a small amount of chemical reaction but hammering is known as the main factor. The abrasives at the tip of the tool apply impact to the surface of the workpiece and this impact causes brittle fracture on the workpiece surface, thus removing material. The abrasives on the workpiece surface are similar to the indenter of the micro-hardness tester and therefore it is possible to identify the mechanism of material removal by examining the indentation process of the brittle material. The material removal process of USM is shown in Fig. 1. The figure shows the building and relaxation of pressure to the workpiece surface by hammering of abrasives during a cycle of ultrasonic vibration. When the indentation by abrasives starts, cracks occur on the surface of the workpiece and spread to other areas, finally causing chipping of the brittle material. The six stages of the process are illustrated in the figure.

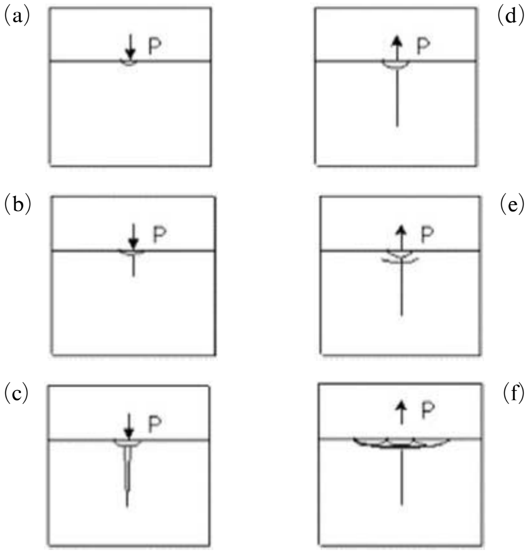


Fig. 1 Mechanism of material removal in USM

As the Fig. 1 demonstrates, a small area of inelastic deformation zone occurs when abrasives contact the workpiece surface through the vibrating tool (a). When the median cracks develop due to the increase in the deformation zone (b), the pressure increases and the median cracks grow (c). When the pressure decreases instantly upon relaxing the vibration, the median cracks are closed (d). When the lateral vents occur (e), the pressure is removed and the lateral vents continuously expand on the surface of the workpiece, causing chipping which in turn removes the material (f) (Zhang et al., 1999).

3. Experimental Setup and Method

3.1 Experimental setup

The ultrasonic machining machine used in this study consists of an amplifier with 0.02 mm of amplitude and 27 kHz of frequency, a transducer, a concentrator for amplification, a pressure device for the contact of the tool and workpiece and a supplier of the slurry which is a mixture of water and abrasives. Fig. 2 shows the schematic illustration of the setup used in this experiment.

To efficiently use the output of an amplifier, its frequency should be consistent with the natural frequency of the vibration system. But the natural frequency of the vibration system slowly changes due to the heat generated from the transducer during machining or the wear of the tool. Therefore, it is necessary to adjust the frequency of the amplifier to the variable natural frequency of the vibration system. It is known that the frequency control is easier in a transistor mode than the generator mode. The amplifier used in this experiment adopted an automatic frequency tracing system so that the frequency of the amplifier can tune in to the changes of the natural frequency of the vibration system during machining. When a power source of 60 Hz is inputted, it is transformed to electric energy of 27 kHz before being delivered to the transducer. The transducer transforms the electric energy of 27 kHz to a mechanical low-amplitude vibration energy.

The aluminum (A17075-T6) concentrator was used between the tool and transducer with the aim of amplification for a high efficiency of USM. Positioned at the tip of the concentrator, the tool delivers ultrasonic vibration to abrasives. The tool should have high wear-resistance and fatigue strength and material of high toughness so that cracks may not occur easily. In this experiment, stainless steel (SUS304) was used as the material of the tool.

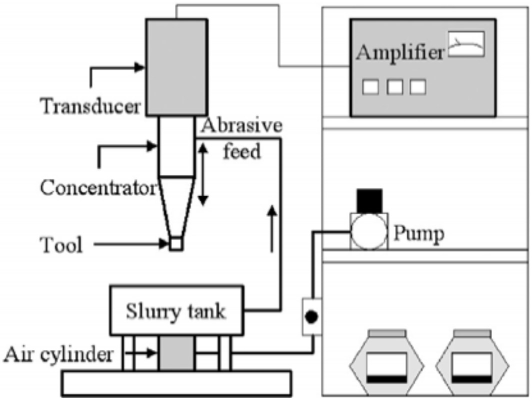


Fig. 2 Schematic illustration of experimental setup

3.2 Experimental method

A workpiece was put on the worktable which can move upward and downward. The workpiece was fixed to the worktable and then a specimen was prepared to approach the tool. A pressure device pushed the tool and the workpiece to each other so they can contact each other. Constant pressure is maintained between the two ends during machining so that the ultrasonic vibration generated from the tool can be effectively delivered to the workpiece. To facilitate material removal, the slurry was carried from the slurry tank to the abrasive supplier through the concentrator.

Using the slurry ratio, the size of abrasives and the static pressure as machining parameters, the experiment measured the material removal rate and the surface roughness. Square and rectangular section tools having the same cross-section areas were used to examine the influences of the tool's cross-section profiles on the material removal rate. The experimental conditions of USM are shown in Table 1.

The weights of the workpiece before and after machining were measured using an electronic balance to calculate the material removal rate.

Table 1 Experimental condition

USM machine	Frequency		27 kHz
	Amplitude		0.02 mm
Workpiece	Alumina (Al_2O_3) ceramics Hardness (Hv, kgf/mm^2), 1500		
Tool	Tool material		SUS304
	Tool dimension (mm)	Type A	Dia. 8.7
		Type B	12.85×5
		Type C	8×8
Abrasive	SiC #240, #400, #600 Hardness (Hv), 2500		
Slurry ratio (abrasive : water by weight)	1:1, 1:3, 1:5		
Static pressure	2.0, 2.5, 3.0 kg/cm^2		

The average surface roughness of the machined workpiece was measured with the cut of length (Lc) set at 0.25 mm. The machined surface were observed in SEM.

4. Experimental Results and Discussion

To examine the influences of the slurry ratio and static pressure on the material removal rate, machining was carried out with the slurry ratios set at 1:1, 1:3 and 1:5 and with the circular tool. The results are shown in Figs. 3∼5.

As shown in the figures, the material removal rate increased as the static pressure and the slurry concentration increased. This is because as the concentration increases, a greater amount of abrasives takes part in the material removal of the workpiece, contributing to more efficient material removal. Under the conditions that the slurry concentration is high and the sizes of abrasives are large, the material removal rate improves as the static pressure increases from 2.0 kg/cm^2 to 2.5 kg/cm^2 but the rate decreases when the pressure exceeds 3.0 kg/cm^2. This means that the pressure between the tool and the workpiece that maximizes material removal exists between 2.5 kg/cm^2 and 3.0 kg/cm^2. It appears that as the load increases, the impact force on abrasives increases and then the material removal rate decreases due to the fracture of abrasives themselves. The change of the material removal rate is small when the sizes of abrasives are #400 and #600 and the slurry ratios are 1:3 and 1:5. This implies that abrasives have little influence on the material removal rate when the sizes of abrasives are small and the slurry concentration is low.

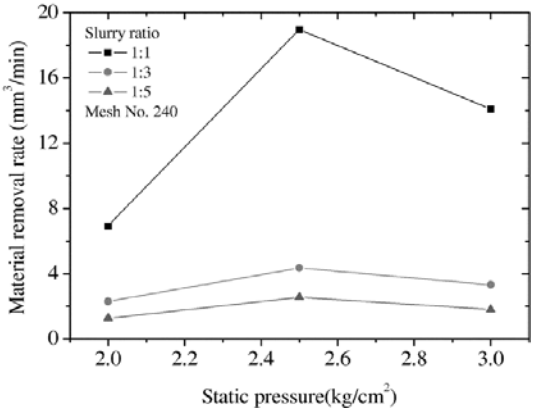


Fig. 3 Variation of material removal rate with slurry ratio in mesh No. 240

Figure 6 indicates the comparison of the material removal rates between the results of experiments conducted by Lee et al. (1997) and Zhang et al. (1999) and the results of this experiment conducted when the size of abrasives is #240 and the slurry ratio is 1:3. In the experiment conducted by Lee et al. (1997), the workpiece was ferrite ceramic, the material of the tool was mild steel, the shape was 5.4×20.3 mm^2 and #150 boron carbide (B$_4$C) was used as abrasives and

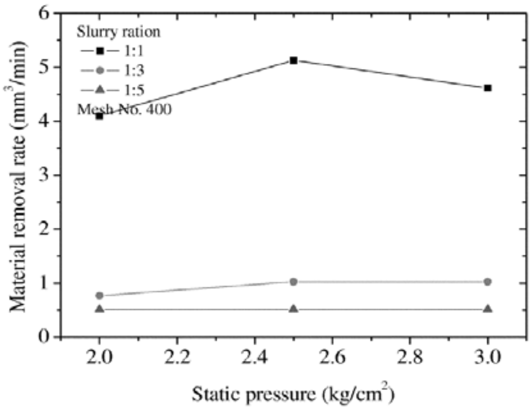


Fig. 4 Variation of material removal rate with slurry ratio in mesh No. 400

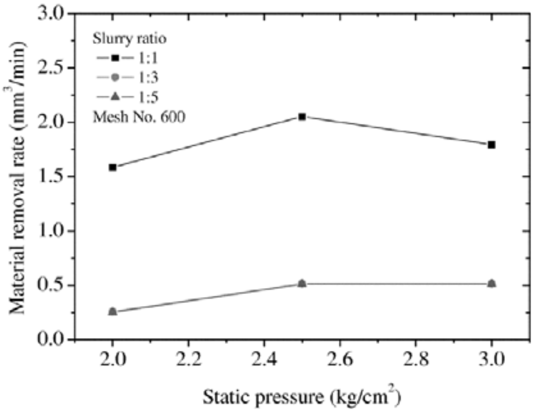


Fig. 5 Variation of material removal rate with slurry ratio in mesh No. 600

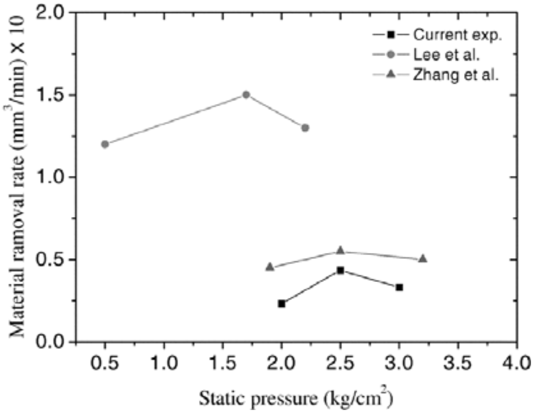


Fig. 6 Comparison of Material Removal Rate

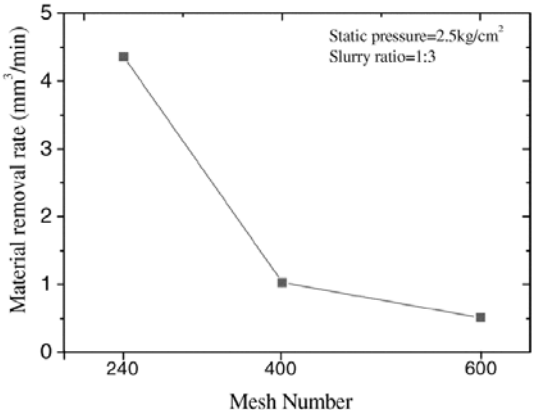


Fig. 7 Variation of material removal rate with abrasive size

the frequency and amplitude of the ultrasonic machinery were 19.3 kHz and 0.05 mm, respectively. Alumina was used as a workpiece and a low-carbon steel with a diameter of 10 mm was used as a tool; the slurry ratio of abrasives was 1:2.5 and boron carbide with a diameter of 150 μm was used as abrasives; the frequency and amplitude of the ultrasonic machinery were 20.3 kHz and 0.012 mm, respectively by Zhang et al. (1999).

In Fig. 6, the changes of the material removal rates depending on pressure are similar in the three experiments. The numerical differences in the material removal rates of the three experiments seem to have been caused by the differences in the types and sizes of abrasives, the materials and shapes of the tools and the amplitudes. Also it seems that the results of this experiment are consistent with those of the experiment by Zhang et al. (1999) because the machining conditions and the workpiece materials are similar to each other.

Figure 7 illustrates the changes in the material removal rates depending upon the sizes of abrasives. It shows that the material removal rates decrease as the sizes of abrasives get smaller (or the mesh number gets larger).

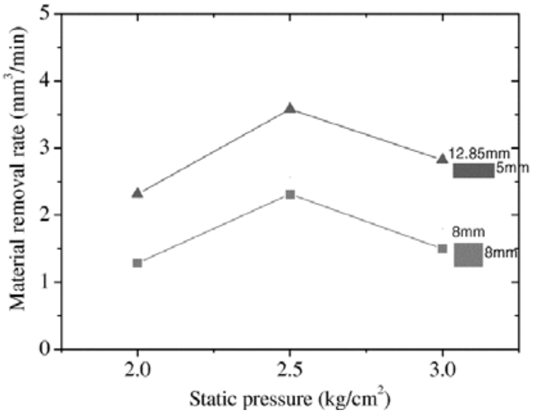


Fig. 8 Variation of material removal rate for the different tool shapes with same cross-sectional area

Figure 8 indicates the results of an experiment conducted with the tools that have the same cross-section areas but different shape when the size of abrasives is #240 and the slurry ratio is 1:5. The material removal rate was higher in the case of a rectangular tool than a square tool. This suggests that the outflow of the crushed chips and the incoming slurry takes place more smoothly when machining takes place with the shorter side of the rectangular tool than the square tool.

The influences of the size of abrasives on the surface roughness are shown in Fig. 9. The figure illustrates that the surface roughness improves as the size of abrasives gets smaller and that the smaller size of abrasives is more effective than the influence of the static pressure.

Figure 10 demonstrates the surface roughness obtained from this experiment and the experiments of Lee et al. (1997) and Kamaraiah et al. (1986). It shows that the surface roughness im-

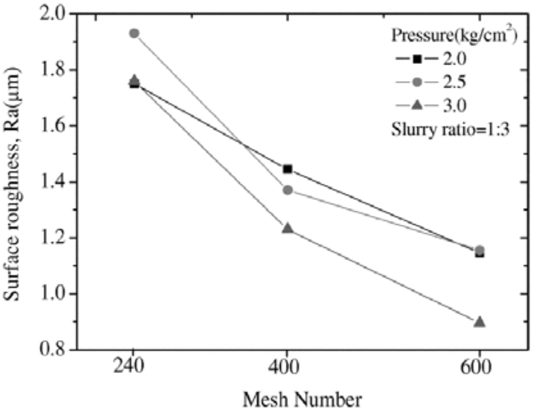


Fig. 9 Effect of surface roughness with abrasive size

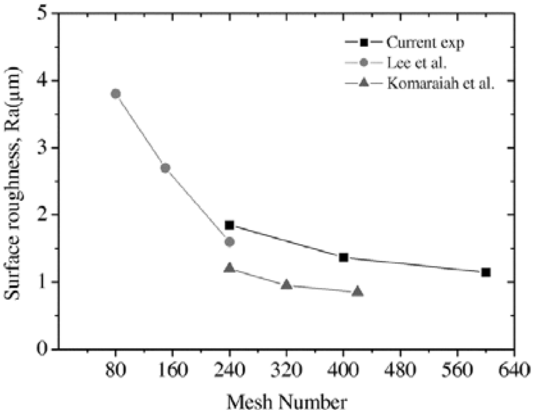
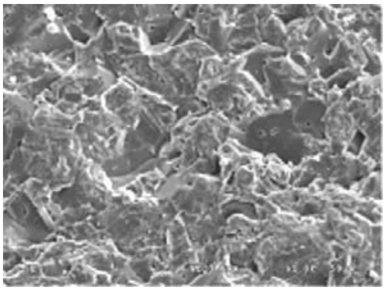


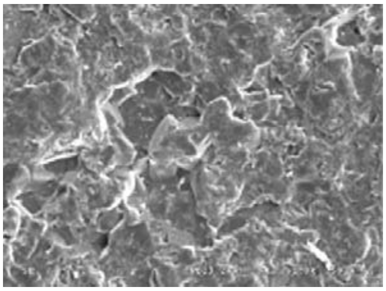
Fig. 10 Comparison of surface roughness

proves as the size of abrasives gets smaller. In the Lee et al. (1997)'s experiment, the frequency was 19.3 kHz, the amplitude was 0.15 mm and the workpiece was ferrite while in the Kamaraiah et al. (1986)'s experiment, the frequency was 22 kHz, the amplitude was 0.0375 mm and the workpiece was aluminum. The results of these two experiments were similar to those of this experiment in terms of tendencies and figures.

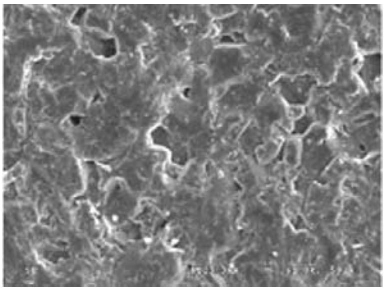
The machined surface was observed with SEM to examine the surface characteristics depending on the sizes of abrasives. The pictures taken by SEM are shown in Fig. 11. The surface machined with large-size abrasives (#240) shows non-uniform state. This is the characteristic of micro-chipping which is caused because unlike other general mechanical machining, USM is done by abrasives. But as the size of abrasives gets smaller, the surface profiles become more precise and the surface state in the figure also improves like the surface roughness measured. Accordingly, it is concluded that the size of abrasives is one of the major factors that determine the surface roughness.



(a) Mesh No. 240 (mean size=58.5 μm)



(b) Mesh No. 400 (mean size=35.0 μm)



(c) Mesh No. 600 (mean size=25.8 μm)

Fig. 11 SEM photographs of the ultrasonic machined surfaces (×1000)

5. Conclusions

USM with SiC abrasives was conducted on alumina ceramics with the size of abrasives, the slurry ratio and the static pressure set as the machining parameters. The results are as follows :

(1) When the mesh number was 240, the slurry

ratio was 1:1 and the static pressure was 2.5 kg/cm^2, a maximum material removal rate of 18.97 mm^3/min. was obtained. When the static pressure increased to 3.0 kg/cm^2, the material removal rate rather decreased. Also, the material removal rate decreased as the size of abrasives got smaller.

(2) When the tools had the same cross-section areas, the material removal rate was higher when the sectional profiles were rectangular than when the sectional profiles were square. This suggests that the outflow of the crushed chips and the incoming slurry took place more smoothly when the shorter side of the rectangular sectional tool carried out machining.

(3) Machining with the abrasives of mesh number 600 resulted in an improved surface roughness of about 0.76 μm Ra. It was demonstrated that in the case of a greater static pressure, the material removal rate decreased but the surface roughness improved.

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