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Characteristics of micro-hole machining of Al_2O_3 ceramics by ultrasonic longitudinal vibration

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Ultrasonic machining (USM) technology has been developed for the manufacturing of cost-effective and quality-assured precision parts. USM technology is available for several industrial applications such as in optics, semiconductors, aerospace, and automobiles. The past decade has seen a tremendous increase in the use of engineering ceramics in structural applications. The excellent thermal, chemical, and wear resistance properties of these materials can be realized because of recent improvements in the overall strength and uniformity of advanced ceramics. The USM process is an efficient and economical means for the precision machining of brittle materials. The process is non-thermal, non-chemical, and non-electric and hardly creates changes to the mechanical properties of brittle materials. This paper describes the characteristics of the micro-hole machining of Al_2O_3 ceramics in the ultrasonic longitudinal vibration mode with a tungsten carbide tool. The effects of various parameters of USM, including abrasive particle and machining force on the material removal rate (MRR) and tool wear are presented and discussed.

Key Words: Ultrasonic machining, Material removal rate (MRR), Tool wear, Abrasive particle introduction.

Introduction

The demand for micro-holes with a high aspect ratio is increasing with the development of micro-electromechanical systems (MEMS). MEMS and micro-machines have been accepted as products with the greatest demand in the precision micro-machining fields. The development of an excellent machining technology capable of producing high precision products has thus become a major research goal. Micro-hole machining technology is one of the most fundamental microstructural technologies and is moving towards high precision and high aspect ratio for productivity enhancement. Micro-hole manufacturing is becoming increasingly more prominent in a variety of precision industries, such as for automotive fuel injection nozzles, watch and camera parts, medical needles, air bearings, etc. It is difficult to manufacture these micro-holes using a traditional machining process. There are several other methods for the manufacture of micro-holes: electro-discharge machining (EDM), laser beam machining (LBM) and ultrasonic machining (USM) [1]. Among these methods, EDM is the only one that can be used for an electrical conducting material. Craters and micro- cracks in the raw material lead to poor surface roughness and geometrical accuracy. Laser beam machining causes surface deterioration because it produces a heat affected zone (HAZ) and micro-cracks by the thermal stress on the machined surface. USM can be employed for brittle materials. The risk of thermal deformation is less in USM and the machining accuracy is high. USM can be used to manufacture high-precision micro-holes with a high aspect ratio (L/D), however, as well as requiring a long manufacturing time; in addition, USM is not suitable for ductile materials [2]. USM methods suffer from a number of difficulties. The low rigidity of the micro-tool frequently leads to tool fracture if the machining load increases during machining, which leads to production failure. To reduce this problem, in the proposed method, USM uses a higher (greater than 30kHz) frequency vibration tool to combine the rotating and feeding effects of the micro-tool system, in order to promote the flow of the abrasive particles through a very small gap between the tool and the micro-hole that is formed. The proposed USM equipment has been designed to finish micro-holes with high aspect ratios. During the entire machining process, there were no micro-tool eccentricity problems since the micro tool remained in the same fixture. This arrangement significantly enhanced the micro-hole machining precision.

To achieve high precision for micro-holes with a high aspect ratio (L/D), experimental parameters need to be monitored during the machining process and the machining conditions should be adjusted accordingly to improve accuracy and to reduce the deformation and wear of the micro-tool.

In this study, the effects of various parameters of USM,

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including abrasive particles and machining pressure on the MRR and tool wear are presented and discussed. The properties and micro-holes of workpiece materials on the MRR and the surface quality in USM of Al_2O_3 ceramics was investigated with the proposed USM equipment

Mechanism of ultrasonic machining

The process of ultrasonic machining (USM) is shown schematically in Fig. 1. USM is defined as an impact abrasive method of material removal, in which the machining process is carried out by means of a tool that strikes the surface of the workpiece about 30,000 times per second. The machining action occurs as the tool vibrates fine abrasive slurry, which flows through a very small gap (10-100 μm) and propels it against the workpiece material. The abrasive slurry is composed of water and fine abrasive particles; this is supplied between the tool and workpiece surface. Material removal occurs when the abrasive particles are supplied, and impact the workpiece surface by the down stroke motion of the vibrating tool. In the cutting zone, the cool abrasive slurry keeps the material from becoming heated and distorted and at the same time carries away the material to be removed.

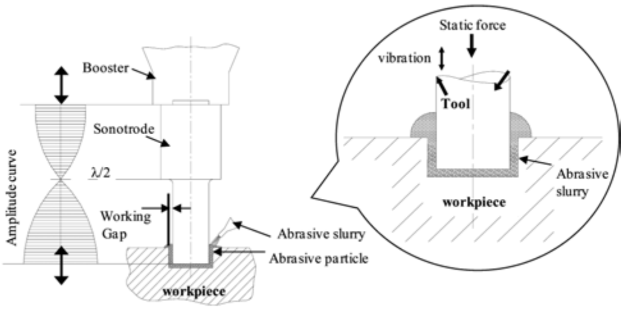


Fig. 1. Schematic diagram of ultrasonic machining.

The underlying principle of USM is the use of vibrating abrasive particles to creat micro-cracks on a material surface and to evaporate the material with a very high frequency and low amplitude. Since it is a non-contact machining process, USM is suitable for micro-hole machining and is suitable for producing microstructures of brittle materials in three dimensions and with a high aspect ratio. Thus, to obtain micro-holes, it is necessary to develop an ultrasonic machine and a series of key technologies, including the in-process manufacture of micro-tools, ultrasonic generation, and a controlled machining process.

Material removal mechanism

USM was used for machining Al_2O_3 ceramics. Fig. 1 shows a schematic illustration of the USM process. The tool (shaped like the desired hole or cavity) oscillates at a high frequency (typically 30 kHz) and is fed into the workpiece by a constant force. An abrasive slurry comprising water and fine abrasive particles is supplied between the tool tip and the workpiece surface. Material removal occurs when the abrasive particles, suspended in the slurry between the tool and the workpiece, impact the workpiece due to the down stroke of the vibrating tool. In the machining zone, the cool abrasive slurry keeps the material from becoming heated and distorted and at the same time carries away the material to be removed [3-6].

The dynamic motion of a micro-tool and abrasive particles is depicted in Fig. 2. The initiation and propagation of median as well as lateral cracks are considered to contribute greatly to material removal in the USM process. The

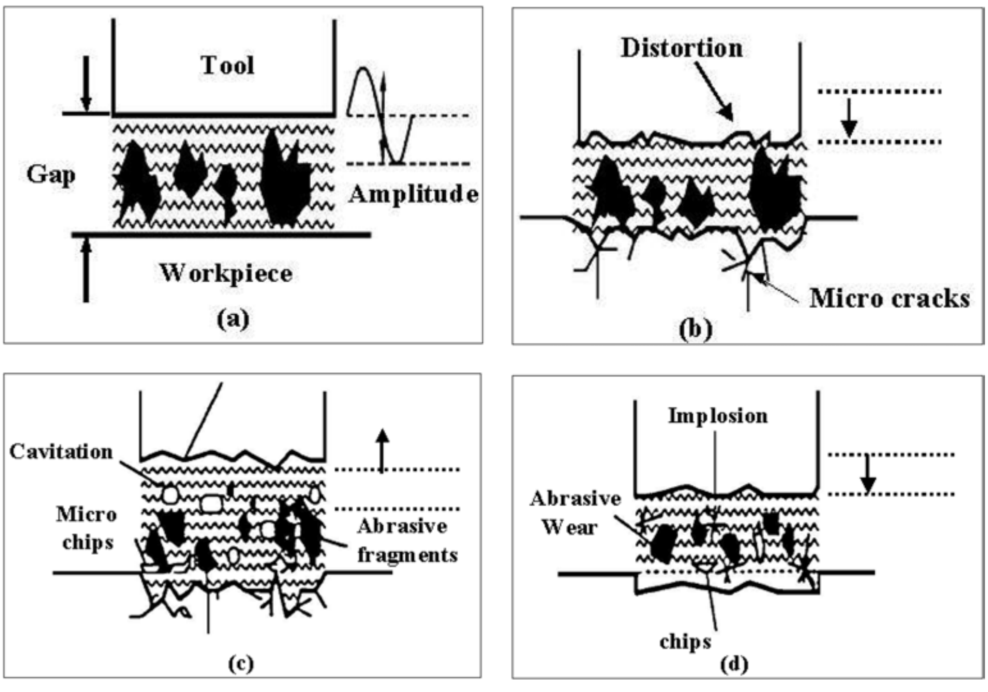


Fig. 2. Material removal mechanism.

sequence of crack propagation can be summarized as follows: (a) The rotating tool oscillates with a vibration amplitude of a few micrometers at about 30 kHz. At the beginning of the erosion period, the abrasive is propelled by the mechanical motion of the oscillating tool and it pummels the surface of the workpiece. (b) Because of the differences between the elastic properties of the tool and work surface, the abrasive hammers the surface of the workpiece. (c) As the gap increases, dynamic bubbles are formed and the slurry is accelerated, as shown in Fig. 2. (d) As the work gap between the tool and the workpiece expands and contracts periodically, an increased implosion in the fluid and refinishing of the machined surface take place, as shown in Fig. 2.

Experimental procedure

Most of the ultrasonic machines developed so far focus on the compact size and compensation for micro-tool wear along the vertical direction. However, we know that adding a longitudinal vibration or rotation onto the micro-tool during feeding is certainly beneficial in maintaining a stable and efficient machining process. Therefore, both equipment design and process techniques should be involved in the development of ultrasonic machine tools at the same time. The experimental equipment developed consisted of an ultrasonic machine, a three-axis control system, and an ultrasonic machining unit (as shown in Fig. 3). The three-axis control system was fixed onto the ultrasonic machine worktable. Here, the workpieces and alumina-based ceramics plate were moved along the front and back directions by motor Y and moved up and down by motor Z. Moreover, the micro-tool was clamped in a vertical ultrasonic unit that was rotated by a motor and directed left and right by motor X. To enable the easy removal of the debris from the micro-holes during USM, the machining operation was performed by ultrasonic vibration of the micro-tool. Furthermore, the ultrasonic vibration apparatus included an electronic generator, a transducer, and a horn-tool combination structure, in which the micro-tool was a cylinder rod screwed on the ultrasonic tip. The workpieces for the USM methods were horizontally fastened to the front end of the micro-tool. The ultrasonic vibration unit was generally attached to the machining micro-tool during the USM process.

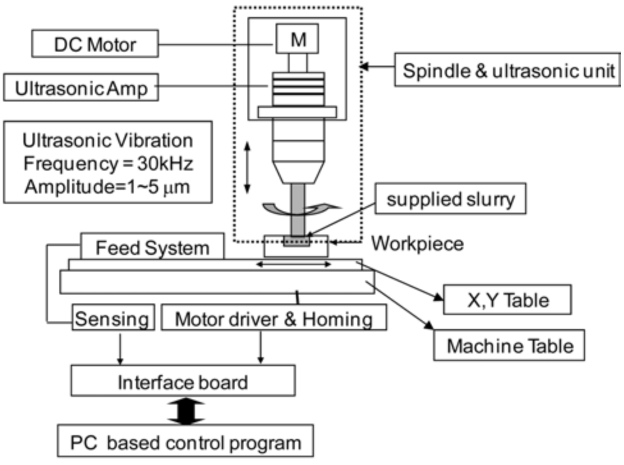


Fig. 3. Schematic diagram of the experimental system.

Al_2O_3 ceramics have many attractive properties such as high hardness, high thermal resistance and chemical stability, low electrical conductivity, etc. These properties make these ceramics suitable for a wide range of applications, such as in optics, semiconductors, aerospace, and automobile applications. However, the machining of ceramics is not easy, especially in micro-hole machining. The machining of ceramics by conventional machining processes is extremely laborious and time consuming. Tight tolerance and dimensions, together with acceptable surfaces finishes and minimal sub-surface damage are attainable only at great cost. Micro-holes in brittle materials such as ceramics have been machined using the ultrasonic vibration of the micro-tool with a small amplitude. To maintain precise micro-hole sizes and shapes, the micro-tools must have high wear resistance and rigidity. A circular tungsten carbide tool with a different diameter was selected as the USM tool. Micro-hole precision can be improved by using an abrasive slurry medium. Silicon carbide and diamond grains suspended in water were chosen as the working abrasive with concentration of 50% in the USM process. To achieve high precision micro-holes, the circular tungsten carbide tool was fixed in the vertical direction and rotated clockwise. The abrasive slurry was sprayed onto the working area at the beginning of the USM process. A micro-hole in the ceramics plate was manufactured by the micro-tool using the USM process. The machining mechanism utilized the abrasive particles to overlap the surface of the micro-holes with the rotated micro-tools. To allow the abrasive slurry to enter the gap between the micro-tool and micro-hole surface easily and produce a good manufacturing effect, a high frequency vibration of the ultrasonic equipment (about 30 kHz) was used with the machining tool. The ultrasonic vibration amplitudes were then set in the direction of the longitudinal vibration mode [7]. In all these USM processes, the micro-tools and workpieces were not removed from the jigs, thus managing to avoid the eccentricity problems of tools and micro-holes.

The experimental parameters for the USM process are listed in Table 1. With the micro-tool in the ultrasonic unit, a micro-hole was machined in the ceramic plate using

Table 1. Experimental parameters for the USM process

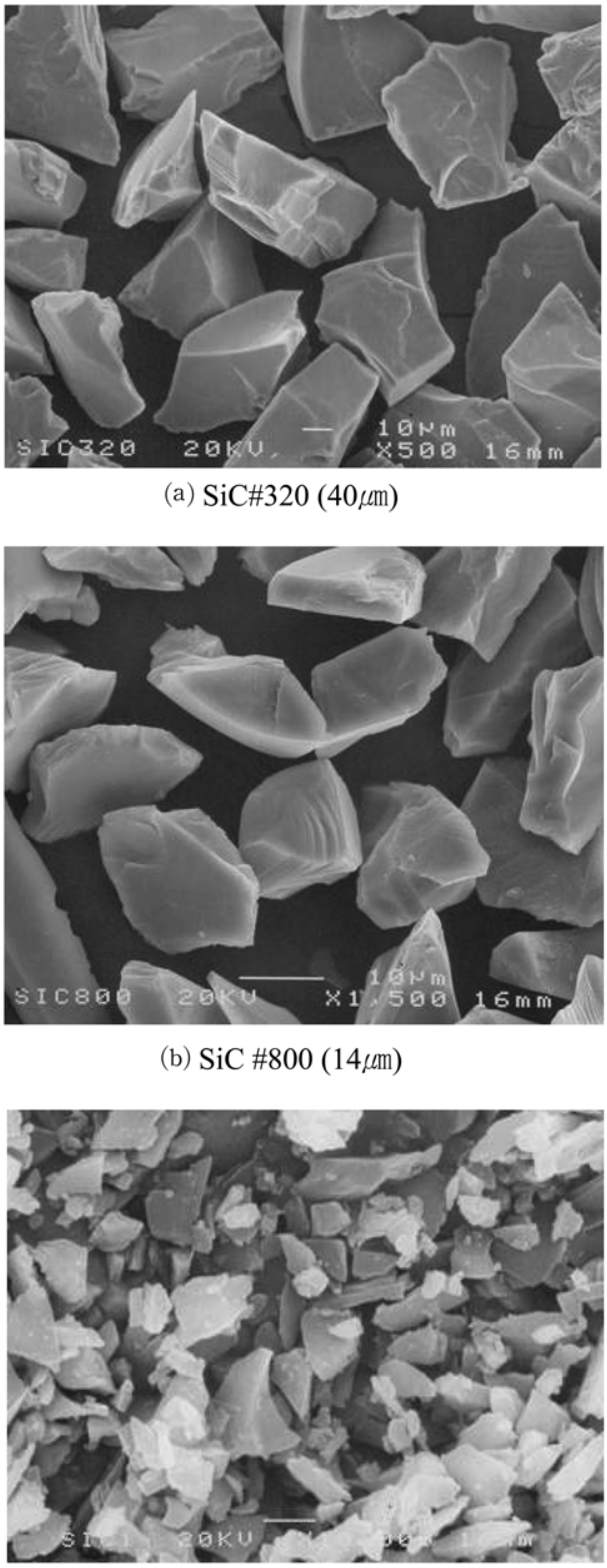
	Precision ultrasonic machine	
Machine specification	Stroke (X × Y × Z) Feed controller Step	140 × 120 × 100 motor (lead: 5 mm)
Ultrasonic unit	Frequency Amplitude Cooling	30 kHz 5-10 μm Air cooling
Abrasive Size	SiC #320(40 μm), #800(14 μm), #8000(1 μm)	
Workpiece material	Al_2O_3: t0.3, HR_V 1,500	
Slurry concentration	50 wt.% (water : abrasive)	
Machining conditions	Tool diameter 23, 30, 100 μm	

Table 2. Chemical composition of alumina (Al_2O_3) ceramics

Contents	Composition (At %)
Al_2O_3	99.8
SiO_2	0.05
Fe_2O_3	≤ 0.01
CaO	0.02
MgO	0.02
TiO_2	0.03
$Na_2O + K_2O$	0.05

ultrasonic longitudinal vibration. The micro-tool can not touch the workpiece before the machining process start, so there was exited about 0.1 mm between the micro-tool and ceramic surface when the machining process was began. The workpieces used in this research were alumina (Al_2O_3) ceramics. The chemical composition of the alumina (Al_2O_3) ceramics used in this study is presented in Table 2.

The abrasive particle is a key element of USM. Commonly, the abrasives used (boron carbide, silicon carbide, and aluminum oxide) are also suitable for the USM of a brittle material [8, 9]. The abrasive particle size largely affects the machining speed and the surface roughness. Silicon carbide is frequently used for materials such as glass, quartz, and sing1e crystal silicon. Boron carbide is recommended for machining engineering ceramics (silicon carbide, boron carbide, silicon nitride, aluminum oxide, zirconium oxide, etc) and metal parts. The abrasive is suspended in water, usually at a concentration of 20%-50% and is circulated constantly between the workpiece and micro-tool. A high volume of slurry cools the micro-tool and workpiece, supplies fresh abrasive to the cutting zone and removes the particles abraded. The fast motion of the micro-tool impacts the abrasive particle into the workpiece, thus chipping or grinding away the material. For deep cutting, vacuum assistance can be effective in getting the abrasive to the cutting zone. The abrasive particle size will determine the surface roughness and MRR, similar to the more conventional machining methods [10-12]. The abrasive particles used in this research were silicon carbide; their average abrasive sizes are shown in Fig. 4.



(a) SiC#320 (40㎛)

(b) SiC #800 (14㎛)

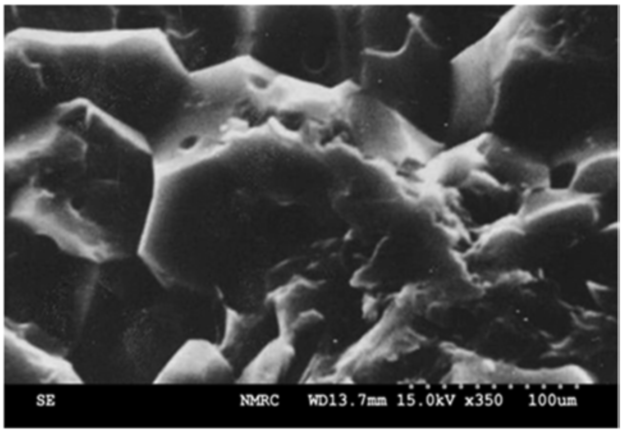
(c) SiC #8000 (1㎛)

Fig. 4. SEM images of the abrasive particles.

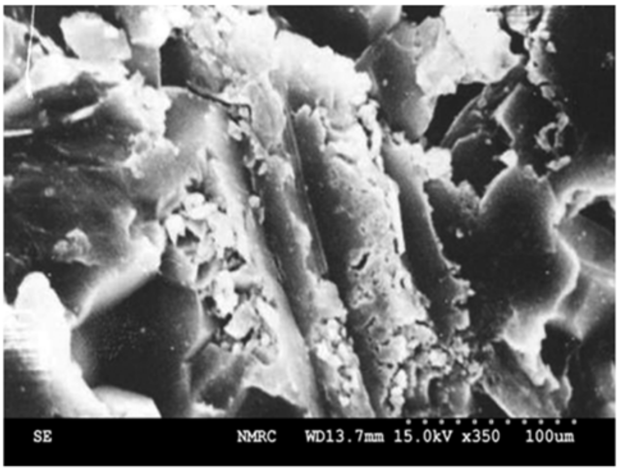
Experimental Results

In addition to evaluating the accuracy in size of high precision micro-holes with a high aspect ratio, the shape precision and surface roughness were investigated. Hence, the following discussion is organized into the following main parts: surface quality, MRR, tool wear and diameter variation between the entrance and exit. The factors affecting the precision of micro-holes include the abrasive particle size and the USM parameters.

The variations of surface roughness, roundness, and diameter between the entrance and exit are important for micro-hole quality. Because no equipment was available to measure the surface roughness of micro-holes in this research, SEM photographs are used to discuss the grain size effects. The diameter variation between the entrance and exit of the micro-hole (the ratio between the entrance and the exit diameters with respect to the hole depth) is



(a) Ultrasonic machined surface

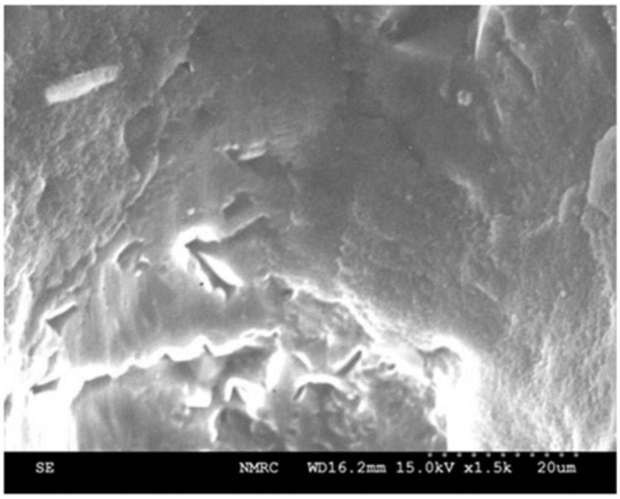


(b) Conventional machined surface

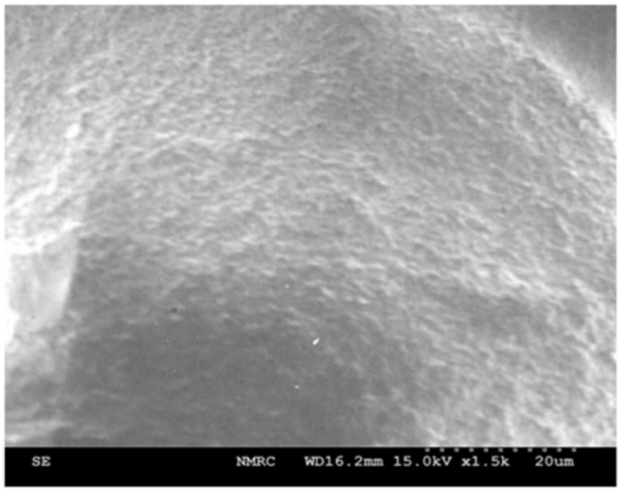
Fig. 5. Comparison of machined surface by different machining processes.

related to tool wear. Fig. 5 shows SEM images of the machined surfaces: Fig. 5 with ultrasonic vibration, and Fig. 5 without ultrasonic vibration. Fig. 5 gives a comparison of surface integrity and typical machined surfaces for USM and a conventional micro-drilling process. From the SEM images, it can be seen that the quality of the surface machined by the micro-drilling process is coarser than that machined by the USM process. The surface machined by a micro-drilling machining process is formed mostly by brittle fractures and is covered with irregular cracks due to severe plastic deformation and friction with the tool, while for the surface produced by the USM process far fewer brittle fractures are seen and a regular surface texture appear. Even the USM process does not perfectly remove brittle fractures on the machined surface, but it can make the magnitude of the fractures much smaller. In particular, the micro-hole of the machined surface with USM consists of streaks parallel to the machining direction, while the machined surface with the conventional machining process is rough and coarse, with severe defects on it, and consists of irregular fractures.

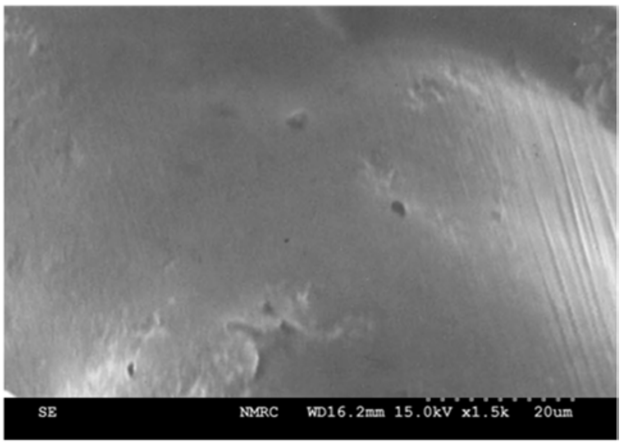
Fig. 6 shows cross section of micro-holes and the surfaces



(a) SiC #320 (40 μm)



(b) SiC #800 (14 μm)



(c) SiC #8000 (1 μm)

Fig. 6. SEM images of machined surface micro-hole wall a with different abrasive sizes.

of the micro-holes by USM. Fig. 6(a)-(c) show magnified SEM images of the hole surfaces when machined with different abrasive particle sizes. The surface of Fig. 6(a)

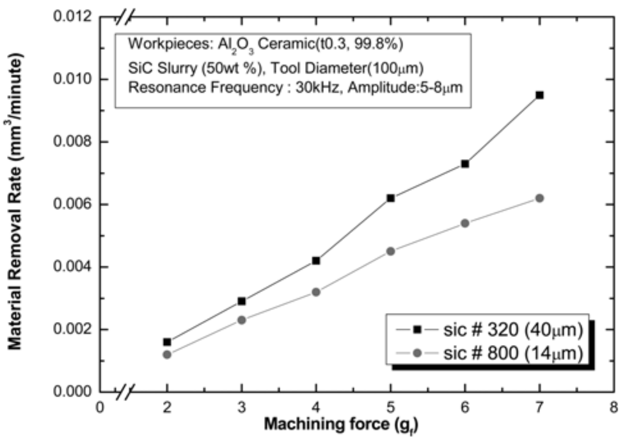


Fig. 7. Relation between machining force and MRR.

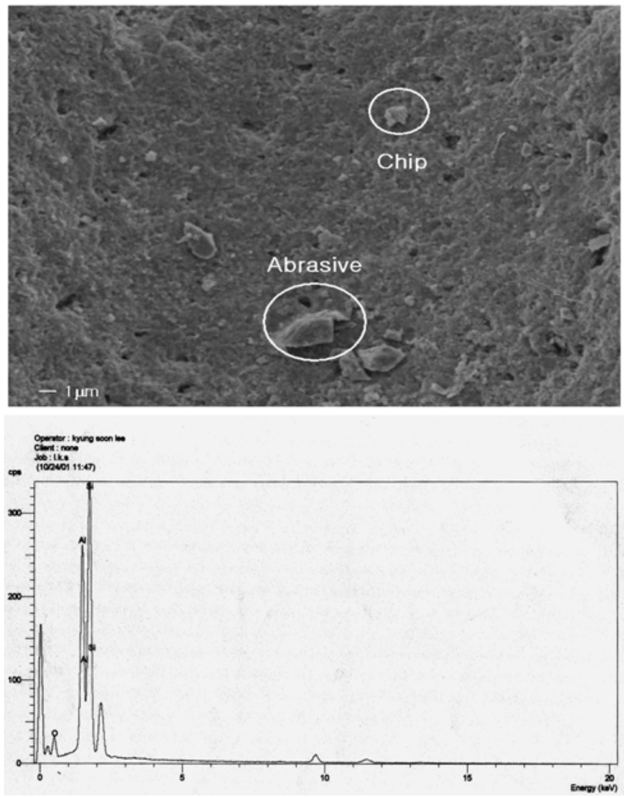


Fig. 8. SEM images and EDX spectrum of an abrasive particle and chip.

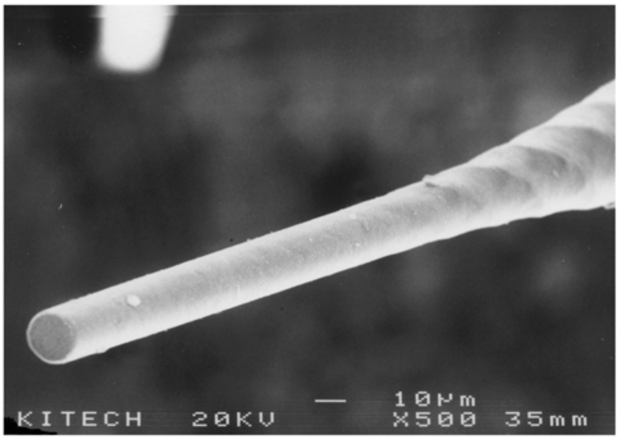
was machined using an average grain size of 40 µm; Fig. 6(b) was produced using an average grain size of 14 µm; Fig. 6(c) was produced using an average grain size of 1 µm. These three figures clearly illustrate that the working surface still has a few craters and is not very smooth when a large grain size is used. The surface is very smooth with almost no craters when the small grain size is applied, because the small abrasive particles are more uniformly suspended in the slurry and more easily enter the micro-hole than the larger ones. Hence, smaller abrasive particle sizes have a better effect on the micro-hole surface.

In this research, using Al_2O_3 as an example, the relations between the MRR and the experimental parameters have been predicted by the experiment and plotted in Fig. 7. As the machining pressure increases, the MRR increases almost proportionally. The abrasive particle size has a larger impact on removing material. The effects of abrasive particle size on the MRR are shown in Fig. 7. Coarser abrasive particles cause extensive damage of the material during the hammering by the of abrasives, and thus the MRR increases. However, increasing the size of the abrasives at the same level of the slurry concentration means a reduction in the number of the grit abrasive particles. The effects of abrasive particle size on MRR are shown in Fig. 7. From the figure, it is clear that the MRR will increase as the abrasive particle size increases. The reason for this can be explained as follows. As the abrasive particle size decreases, the cutting depth will increase and this will increase the intersection volume between the abrasive particles and the workpiece.

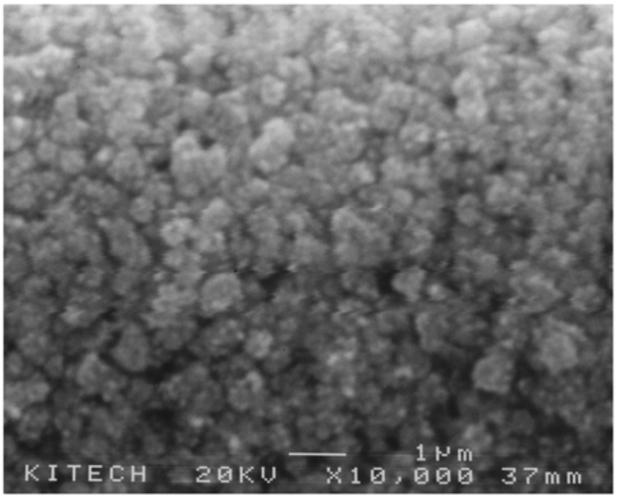
A machined surface is shown in Fig. 8. There are craters on the workpiece caused by abrasive particle hammering or impact. The ultrasonic machining consists of continual material removal in small craters. Fig. 8(a) illustrates the abrasive particles and chips after USM. Fig. 8(b) indicates that the major elements of the chip is Al and Si. The figure implies that chip removal by micro-cracks is indeed involved in USM. The size of the chip is about one tenth of that of the abrasive particle, or several micrometres. The chips are produced by the hammering or free impacting of the abrasive. Note that it is conceivable that micro-cracks take place both on a smaller scale and in using the large abrasive particle size; thus, a long time is needed for polishing. When the machining pressure is increased, on the other hand, the pressure exerted on the work surface by the abrasives through the vibrating tool also increases. Higher degrees of local stress, deformation, and MRR are expected.

Tool wear is the major intrinsic drawback of USM. Especially in the micro-machining with micro-tools, the longitudinal tool wear, namely, the length shortening of micro-tools for boring micro-holes to a given depth, becomes more serious and to some extent determines the accuracy of micro-machining. In this experiment, tungsten carbide was used as the tool material for boring micro-holes in 300 µm-thick Al_2O_3 ceramics. Fig. 9(a) shows an SEM image of the micro-tool. Fig. 9(b) represents the surface of the micro-tool with an average grain size of 0.7 µm.

Fig. 10 illustrates the typical tool wear length when boring 100 µm deep holes in Al_2O_3 ceramics with different abrasive particle sizes. As can be seen, the tool wear tends to increase when harder and coarser abrasives are used. However, in there experiments, no obvious variation in tool wear was observed within the limited working ranges for high-quality micro USM. Tool wear was maximized at a particular machining force which may be considered optimum for the point-of-view of maximum MRR. As a consequence, harder abrasives, such as diamond, cause higher tool wear than softer abrasives such as silicon



(a) Image of the micro-tool



(b) Surface of the micro-tool

Fig. 9. SEM photography of micro-tool

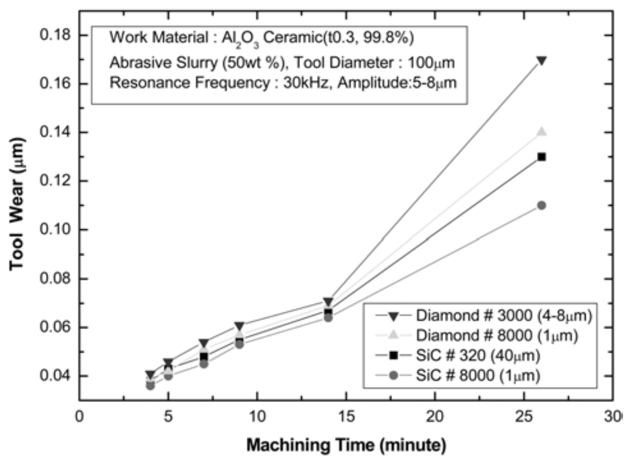
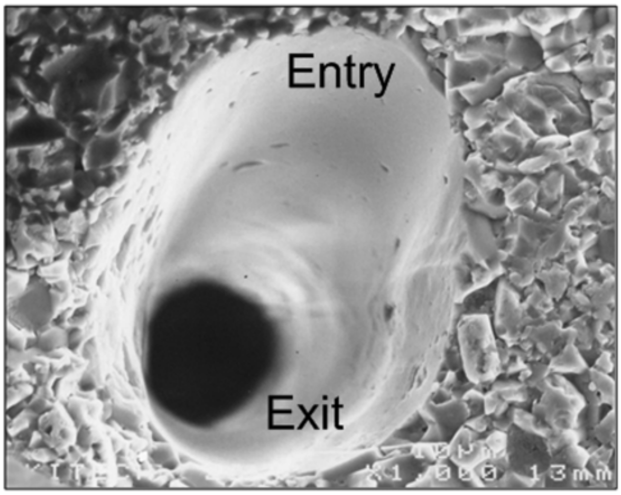
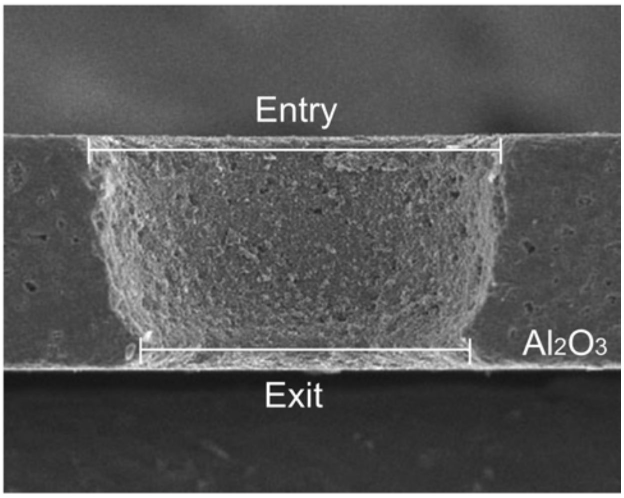


Fig. 10. Influence of different abrasive grit sizes on tool wear.

carbide for a tool of the same cross-sectional area. Tool wear is affected by workpiece hardness, and it can also be affected by the toughness of the workpiece. Thougher materials also tend to wear the abrasive at a higher rate



(a) Expansion of a micro-hole



(b) Cross section of a micro-hole

Fig. 11. Diameter variation between the entrance and exit of a micro-hole.

than when machining more conventional ceramics. If the hardness of the tool increases by work hardening, the penetration of the abrasive grains into the tool will decrease resulting in a higher workpiece MRR.

In USM processes, the micro-feeding method of the micro-tool was applied to manufacture the micro-holes. During the machining of micro-holes with high aspect ratios, the micro-tools can touch the walls of the micro-holes for a long time, which causes abrasion on the sides of the micro-tools or induces irregular expansion of the micro-holes (Fig. 11). These conditions result in the deterioration of the accuracy of the micro-holes.

Fig. 12 shows an example of micro-hole machining in Al_2O_3 ceramics, with an aspect ratios of 10. Some applications of these high-aspect-ratio micro-holes on ceramics and wafers lie in the sensor industry, where pressure sensors and flow sensors, etc. have a great need for micro-holes below 80 μm in diameter to further reduce

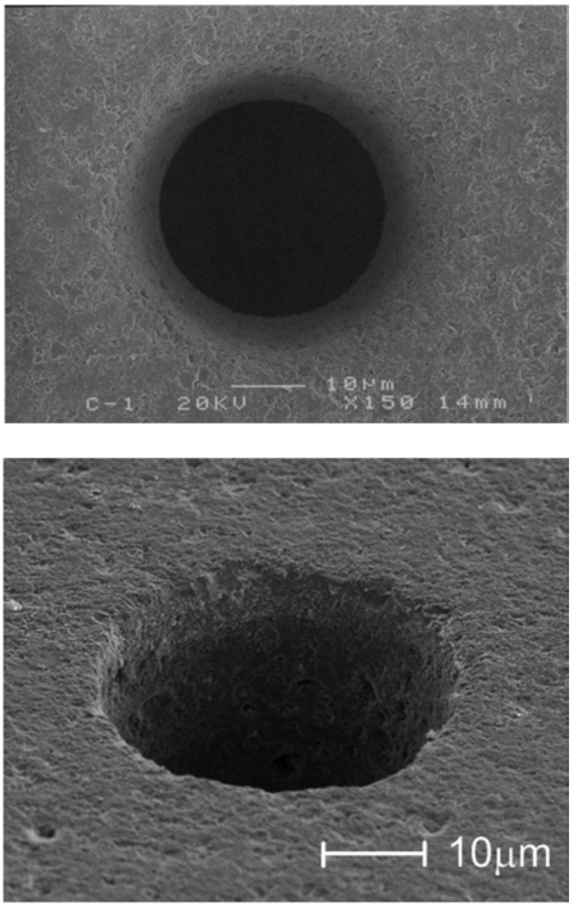
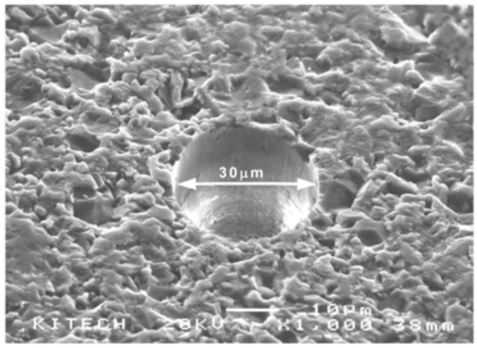
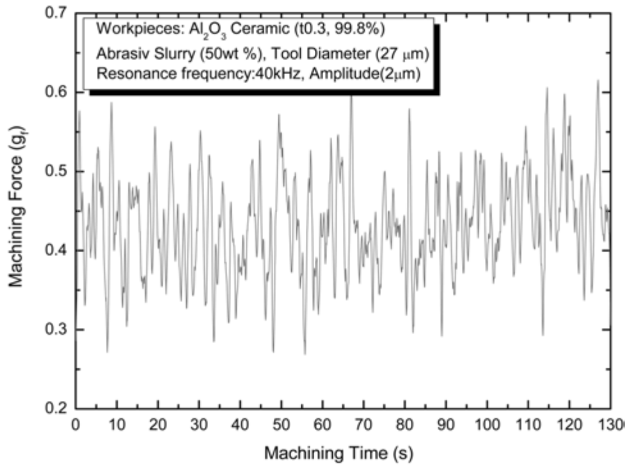


Fig. 12. Micro-hole made by USM in Al_2O_3 ceramics (SiC#8000, 50wt.%, depth: 300 μm, aspect ratio: 10).



(a) Micro-hole



(b) Machining pressure (300g/㎟)

Fig. 13. SEM image of micro-hole and a graph of machining pressure.

their package size. Another application is in micro-fluids, where high-aspect-ratio micro-holes with complex shapes are required for various micro-fluid components.

Fig. 13(a) shows an SEM image of a USM micro-hole with a diameter of 30 μm in a Al_2O_3 plate with a thickness of 0.3 mm. Fig. 13(b) shows the machining loads under the following conditions: resonance frequency: 30 kHz, vibration amplitude: 2 μm, depth of cut: 0.3 mm, abrasive slurry concentration: 50wt.%. It can be seen that the machining force jumped up and then gradually decreased. After some period of time, the loads reduced. This observation has at least two implications. Firstly, the feed rate might be further increased. This would increase the MRR. It is not necessary to wait until the loads completely reach zero and then send the next feed pulse. The feed rate can be increased as long as the forces are maintained below some critical value. Secondly, the force pattern exhibited by the process has provided an opportunity to utilize a variable feed rate control instead of a constant feed rate control. The machining forces may be monitored during the machining. As soon as the machining pressure decreases to some threshold value, the next feed pulse will be sent. In the USM process, the tool has the most significant effect on the machining pressure.

Conclusions

A prototype of an ultrasonic machine with a micro-feed mechanism, ultrasonic unit, and rotating spindle unit was developed. The micro-feed system is a response to maintaining a micro-gap between the micro-tool and workpiece during the machining process. In this ultrasonic machine equipment, the design of the ultrasonic horn must guarantee the required operation amplitude at the resonant frequency. The geometry of the ultrasonic horn model has been achieved by modal analysis. The machining experiments carried out on the USM verified some techniques to manufacture micro-holes in brittle materials such as Al_2O_3 ceramics. Because the micro-tool was not dismantled from the clamping equipment through a varied working process, a good tool concentricity level could be maintained in the machining procedure. Highly accurate micro-holes with a diameter of 27 μm and depth of 300 μm were manufactured via the USM process. The maximum aspect ratios of the micro-tool and micro-holes both exceeded 10, Moreover, the surface roughness of the micro-holes was clearly affected by the size of the abrasive particles. The results obtained show that a finer surface roughness could be obtained when smaller abrasive particle sizes were used. The experiments revealed that the MRR tool wear is influenced by the size of the abrasive particles. The diameter of the machined micro-hole is larger than the micro-tool owing to the flow of abrasive slurry along the sides of the micro-hole to the end face of the micro-tool. In order to secure accuracy and a good machined surface, it is better to use a smaller abrasive particle size or micro-tool feed rate, choosing the proper machining parameters.

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