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## ROTARY ULTRASONIC DRILLING AND MILLING OF CERAMICS

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### ABSTRACT

An experimental study of the rotary ultrasonic drilling of ceramics is first presented. The influence of different process parameters on the material removal rate for machining of magnesia stabilized zirconia is examined. Then a mechanistic approach to modeling the material removal rate during rotary ultrasonic drilling of ceramics is proposed and applied to predicting the material removal rate for the case of magnesia stabilized zirconia. Finally, a new method to extend rotary ultrasonic drilling process to face milling of ceramics is proposed. The development of the experimental setup is described and preliminary experimental results are presented and discussed.

### INTRODUCTION

Possessing many superior properties, such as high strength at elevated temperatures, resistance to chemical degradation, wear resistance, and low density, advanced ceramics have been expected to find more and more applications in the near future. One of the reasons for hindering market expansion of ceramic materials is due to the high cost of machining with current technology compared to other materials. Of the total production costs for ceramic components, machining can account for 30%--60% and sometimes even up to 90% [1]. Therefore, there is a crucial need for the development of nonconventional machining processes applicable to advanced ceramic materials.

Ultrasonic machining (USM) is considered as "probably the most frequently used machining method for advanced ceramics" next to grinding [2]. A schematic illustration of USM is shown in Figure 1. The tool (shaped conversely to the desired hole or cavity) oscillates at high frequency (typically 20 kHz) and is fed into the workpiece by a constant force. An abrasive slurry comprising water and small abrasive particles is supplied between the tool tip and the workpiece. Material removal occurs when the abrasive particles, suspended in the slurry between the tool and workpiece, are struck by the downstroke of the vibrating tool.

Ultrasonic machining of ceramics has the following advantages. Both conductive and nonconductive materials can be machined, complex three-dimensional contours can be

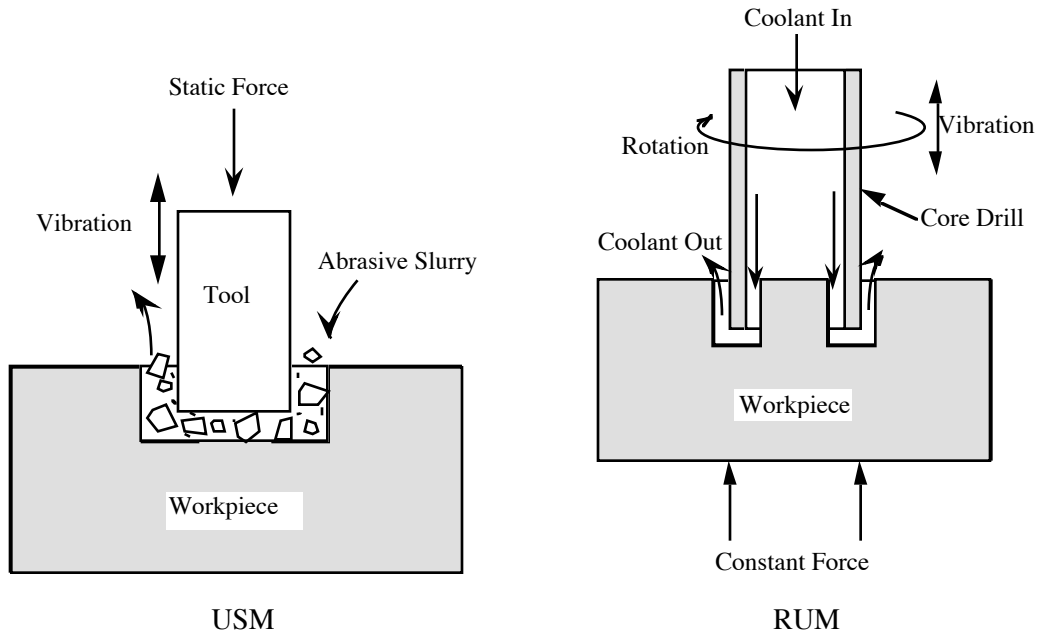


Figure 1 Schematic Illustration of USM and RUM

manufactured as quickly as simple ones. The process does not cause heat affected zone and any chemical or electrical alterations on workpiece surface. A shallow, compressive residual stress generated on the workpiece surface may increase the high cycle fatigue strength of the machined part [3].

In USM, the slurry has to be fed to and removed from the gap between tool and workpiece. This fact limits material removal rate (MRR) and makes it difficult to drill deep holes. The presence of a slurry also limits the accuracy, particularly for small holes.

One modification of USM to overcome its disadvantages is rotary ultrasonic machining (RUM). In RUM, the slurry has been abandoned. A rotating core drill with metal bonded diamond abrasives is ultrasonically vibrated while the workpiece being fed towards the core drill at a constant pressure. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill and keeps it cool. This is illustrated in Figure 1. Experimental results have shown that machining rate obtained from RUM is about 6-10 times higher than that from conventional grinding process under similar conditions [4]. In comparison to USM, RUM is about 10 times faster [5]. It is easier to drill deep holes with RUM than with USM. Improved hole accuracy is also reported [6]. The major disadvantage of RUM is that only circular holes can be machined because of the rotational motion of the tool. Hence, RUM is also called rotary ultrasonic drilling (RUD).

Research on RUM has been conducted for five years at University of Illinois. Three portions of this work will be presented in this paper: (1) an experimental study of rotary ultrasonic drilling of ceramics; (2) a mechanistic approach to modeling MRR during rotary ultrasonic drilling of ceramics; (3) a new method to extend rotary ultrasonic

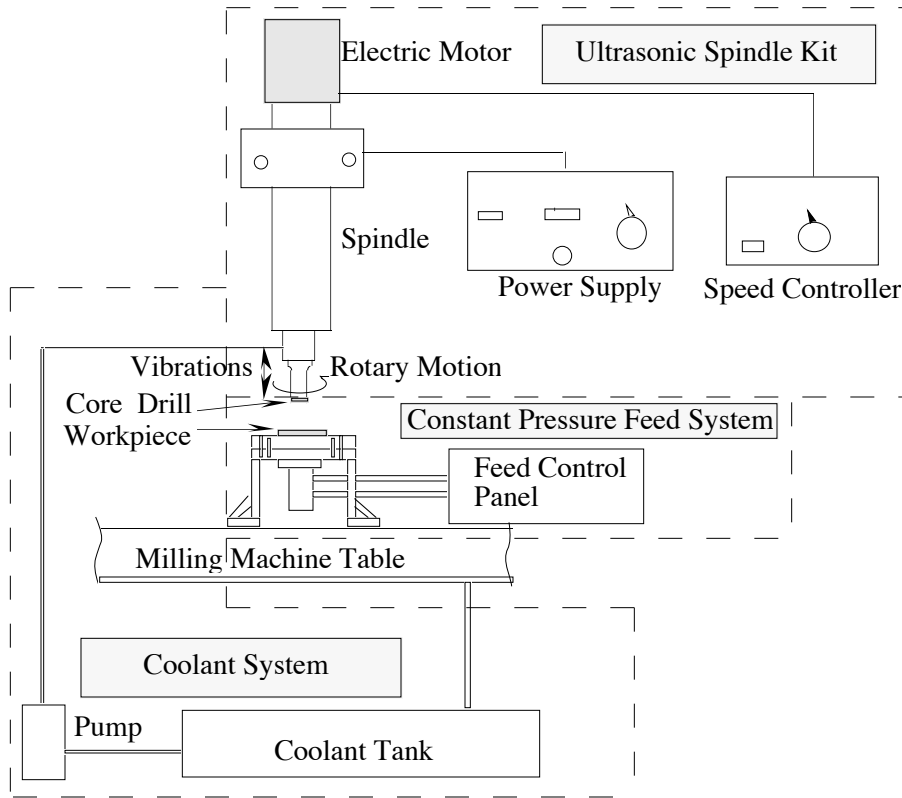


Figure 2 Schematic Illustration of Rotary Ultrasonic Drilling Setup

drilling process to face milling of ceramics.

#### EXPERIMENTAL STUDY OF ROTARY ULTRASONIC DRILLING

Parametric experiments were performed to identify the effects on MRR of different process control variables and to observe the effects of interactions among control variables.

The rotary ultrasonic drilling setup is schematically illustrated in Figure 2. It consists of an ultrasonic spindle kit, a constant pressure feed system and a coolant system. For further details of the setup, its calibration, measurement of variables, etc., the reader is referred to [4, 7].

The design of experiments involved five process control variables shown in Table I. Therefore, for a two-level full-factorial design, at least 32 experiments are needed. Each test was replicated once bringing the total number of tests to 64. The levels shown in Table I represent the typical high and low settings for control variables.

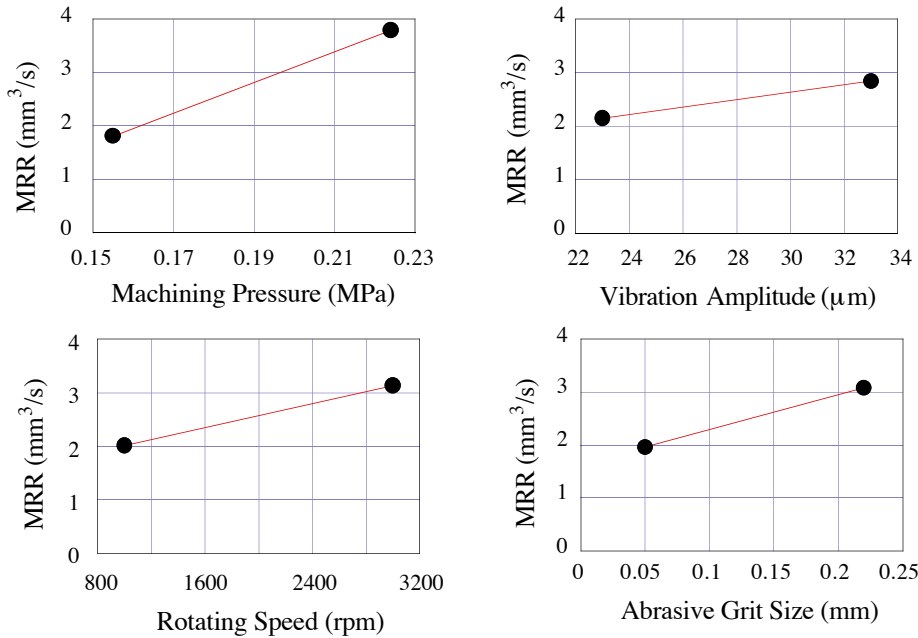


Figure 3 Influence of Control Variables on MRR at Primary Level

Table I Control Variables And Their Levels In Experiments

| Control Variable         | Low level    | High Level  |
|--------------------------|--------------|-------------|
| Machining Pressure (MPa) | 0.155        | 0.244       |
| Vibration Amplitude (mm) | 0.023        | 0.033       |
| Rotational Speed (rpm)   | 1000         | 3000        |
| Abrasive Bond Type       | Brass-copper | Iron-nickel |
| Abrasive Grit Size (mm)  | 0.05         | 0.22        |

The following variables were held constant during all test runs.

Workpiece Material: Magnesia Stabilized Zirconia (Young's modulus  $E = 205\,000$  MPa, Poisson's ratio  $\nu = 0.31$ );

Coolant: A water based semi-synthesis emulsifier;

Abrasive: Diamond particles impregnated on the core drill.

Figures 3 shows the influence of major control variables on MRR. As can be seen, at the levels tested, machining pressure has the greatest effect on MRR. Experiments also showed that all control variables except abrasive bond type had significant effects at primary level on MRR. Bond type, however, played a significant role at interaction levels. An empirical model for predicting MRR (mm<sup>3</sup>/s) was developed statistically from the experimental results.

$$\text{MRR} = 3.24 + 0.30X_2 + 0.32X_3 + 0.13X_4 + 0.56X_5 - 0.08X_1X_3 + 0.08X_1X_4 - 0.075X_1X_5 + 0.09X_2X_5 - 0.11X_3X_4 + 0.12X_3X_5 + 0.105X_1X_4X_5$$

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$$-0.075X_1X_4X_5 - 0.10X_2X_4X_5 - 0.075X_1X_2X_4X_5 + 0.085X_1X_3X_4X_5 - 0.12X_2X_3X_4X_5$$

where

- X<sub>1</sub> -- Abrasive bond type;
- X<sub>2</sub> -- Abrasive grit size;
- X<sub>3</sub> -- Rotational speed of drill;
- X<sub>4</sub> -- Amplitude of ultrasonic vibration;
- X<sub>5</sub> -- Machining pressure.

## MODELING OF MRR IN ROTARY ULTRASONIC DRILLING

Rotary ultrasonic drilling has been around for more than twenty years [8--11] and many investigators have reported their studies on it [12--17]. However, these studies have been primarily experimental with little or no attempt to develop a model governing material removal mechanism. Attempts to develop theoretical models to predict the MRR for rotary ultrasonic drilling are desirable since they would help in understanding the mechanism of rotary ultrasonic drilling and in the optimization of parameters to obtain required performance from the process.

Rotary ultrasonic drilling might be considered as a combination of the ultrasonic machining process and the diamond grinding process. Hence, there are two principal approaches to developing a model for predicting MRR for rotary ultrasonic drilling: one considers the process as being predominantly ultrasonic machining and superimposes the effect of rotational motion of the tool, the other reverses the two primary processes. The first approach was used to develop the following model.

The model was based on several simplifications: the workpiece material was an ideally brittle material; the material was removed by Hertz fracture; the diamond abrasive particles were assumed to be rigid spheres of the same size, and all the particles were assumed to take part in cutting during each ultrasonic cycle.

By this model, the MRR is given by:

$$MRR = knf\pi \left(1 + \frac{L}{d}\right) \left(\frac{d}{2} - \frac{\delta}{3}\right) \delta^2 \quad (1)$$

where,

- k -- constant of proportionality determined experimentally;
- n -- number of active abrasive particles across the tool face;
- f -- frequency of ultrasonic vibration;
- L -- distance moved by abrasive particles during penetration into the workpiece due to rotary motion of the tool;
- d -- diameter of abrasive particles;
- δ -- indentation depth.

The following equation can be used to calculate L:

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$$L = \frac{DS}{60f} \left\{ \frac{\pi}{2} - \arcsin\left(1 - \frac{\delta}{A}\right) \right\} \quad (2)$$

where,  
 D -- tool diameter;  
 S -- rotational speed;  
 A -- amplitude of ultrasonic vibration.

The indentation depth,  $\delta$ , can be solved from the following two equations:

$$\delta = \left( \frac{9}{16} \frac{(F/n)^2}{d/2} \left( \frac{1-\nu^2}{E} \right)^2 \right)^{1/3} \quad (3)$$

$$F = \frac{\pi F_s}{\left( \frac{\pi}{2} - \arcsin\left(\frac{\delta}{A}\right) \right)} \quad (4)$$

where,  
 F -- maximum contact force between tool and workpiece;  
 $\nu$  -- Poisson's ratio of workpiece material;  
 E -- Young's modulus of workpiece material;  
 F<sub>s</sub> -- static force;

For the purpose of estimating k, experimental data were used from the parametric study described in the preceding section. k was estimated as the slope of the least-squares straight line passing through the origin and relating observed MRR for each experiment with corresponding  $n f \pi \left(1 + \frac{L}{d}\right) \left(\frac{d}{2}\right)^2 \delta$  value for the experiment. The value of k was determined to be 0.618 for the workpiece material used.

Detailed derivation of the model was published elsewhere [18]. The model was applied to predict the relations between MRR and different process variables for rotary ultrasonic drilling of magnesia stabilized zirconia. The predicted relations were compared with the trends observed experimentally by other researchers.

Figure 4 shows the predicted relation between MRR and amplitude of ultrasonic vibration as well as the variation of different intermediate parameters with variation in amplitude. Specifically, indentation force/indenter, depth of indentation and distance moved by an indenter when in contact with workpiece (length of contact) due to rotational motion of tool are shown in this figure. Finally volume of indentation and MRR are also shown. Two important effects are visible. First, indentation force and depth increase at a decreasing rate with amplitude. Second, length of contact decreases with increasing amplitude. These two effects cause MRR to increase at a decreasing rate, suggesting that at some amplitude the curve will flatten and possibly begin to drop. The experimental data reported in [14] showed that further increases of ultrasonic amplitude above a certain value would result in a reduction in MRR. The reason for this was explained as "due to an excessive increase in alternate loading on the diamond grits and a weakening of the bond" and further increase of ultrasonic amplitude might "result in complete failure of the diamond core bits as a result of the high cycle stresses". This is certainly true, however, our model (which does not consider wear) suggests that in addition, the process mechanics, explained above, is also responsible for such a behavior.

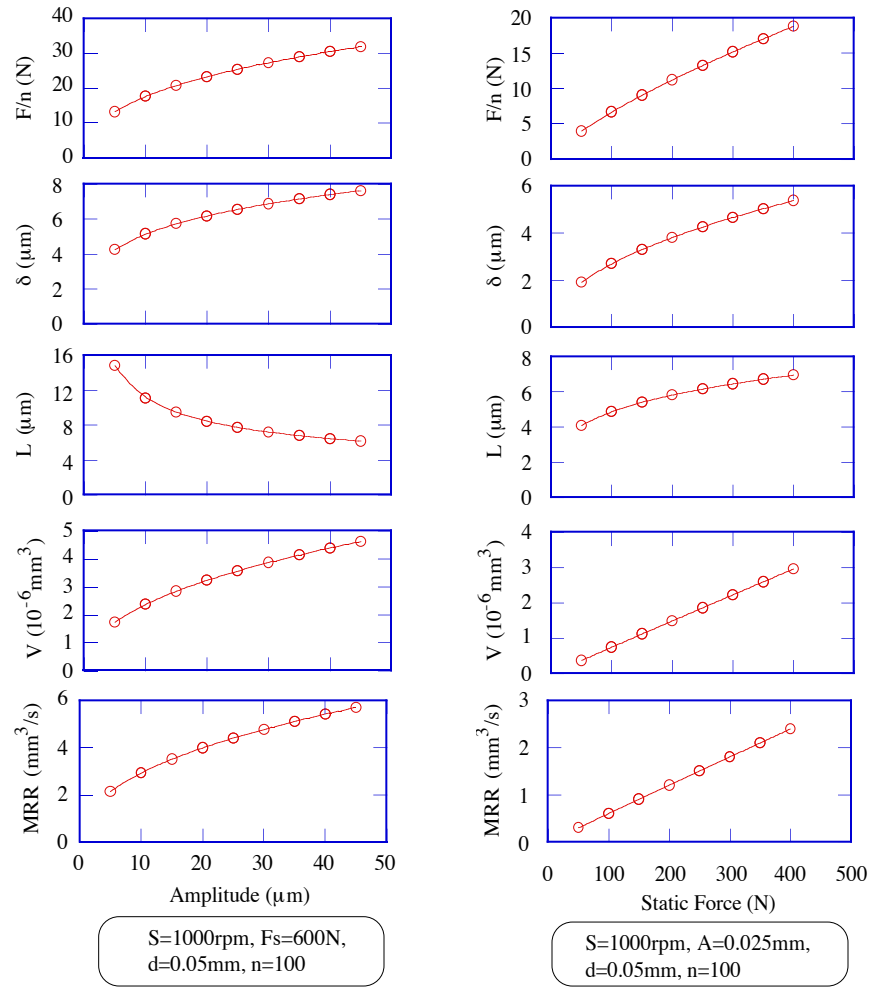


Figure 4 Influence of Amplitude and Static Force

The relation between MRR and static force is also shown in Figure 4. It can be seen that the predicted MRR will always increase with static force. The experimental data reported in [14] also showed that MRR first increased with static force until reaching a certain value, and then decreased with static force. No explanation was given for this phenomenon in [14]. According to our analysis, it might be also due to rapid wear of core drill. Over the region of comparable forces, the trends predicted by model and the experimental trends are similar. The difference at higher values is due to the fact that our model does not account for such factors as tool wear. Figure 4 also shows variation of different intermediate parameters with static force. The almost linear trend is due to the fact that both indentation depth and contact length increase with static force causing indentation volume to increase steadily.

The predicted relations between MRR and other process variables (rotational speed, grit number, and grit diameter) were also compared with the experimental trends. Detailed

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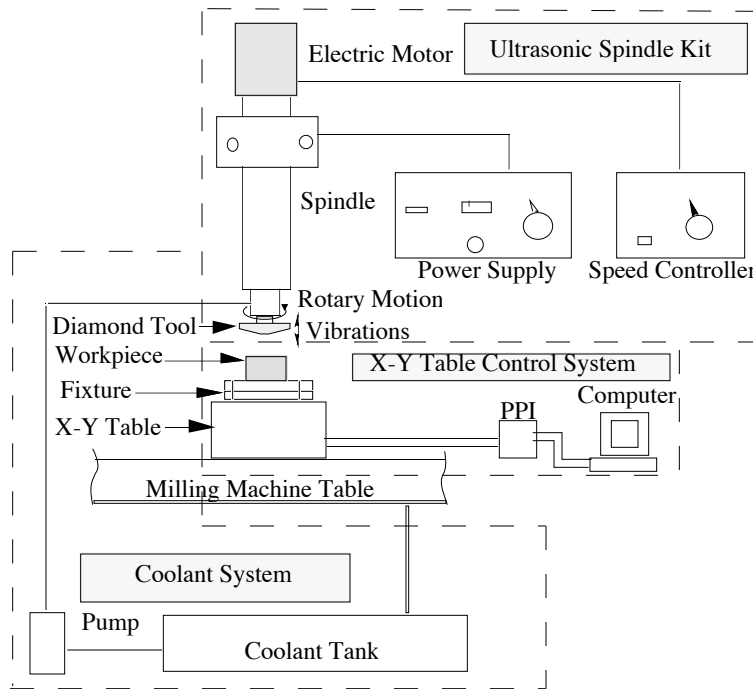


Figure 5 Schematic Illustration of Rotary Ultrasonic Face Milling Setup

description can be found in [18].

#### EXTENSION OF ROTARY ULTRASONIC DRILLING TO FACE MILLING

The limitation of rotary ultrasonic drilling is that only circular holes can be machined. Attempts have been made by others to extend the rotary ultrasonic drilling process to machining flat surfaces or milling slots. However, these extensions either changed the involved material removal mechanisms or have some severe drawbacks. The new approach to extend rotary ultrasonic drilling to face milling of ceramics proposed in this section has the following advantages over the other existing approaches: (1) material removal mechanisms are kept the same as those of rotary ultrasonic drilling; (2) flat surface on large workpieces can be machined; (3) it is easy to realize on commercially available machine tools by incorporating some modifications.

The experimental setup is schematically illustrated in Figure 5. It consists of an ultrasonic spindle kit, a feed system and a coolant system. The ultrasonic spindle kit and the coolant system are the same as in the experimental setup for rotary ultrasonic drilling. The feed system consists of a X-Y table (containing Rapidsys 23D-6204C stepper motors), a control link Programmable Preset Indexer (PPI), and a computer (IBM PS/2 386). On the top of the X-Y table is mounted a fixture which holds the ceramic workpiece. A dynamometer may be mounted between the fixture and the X-Y table to measure machining forces.

The following machining conditions were used for the preliminary experiments:



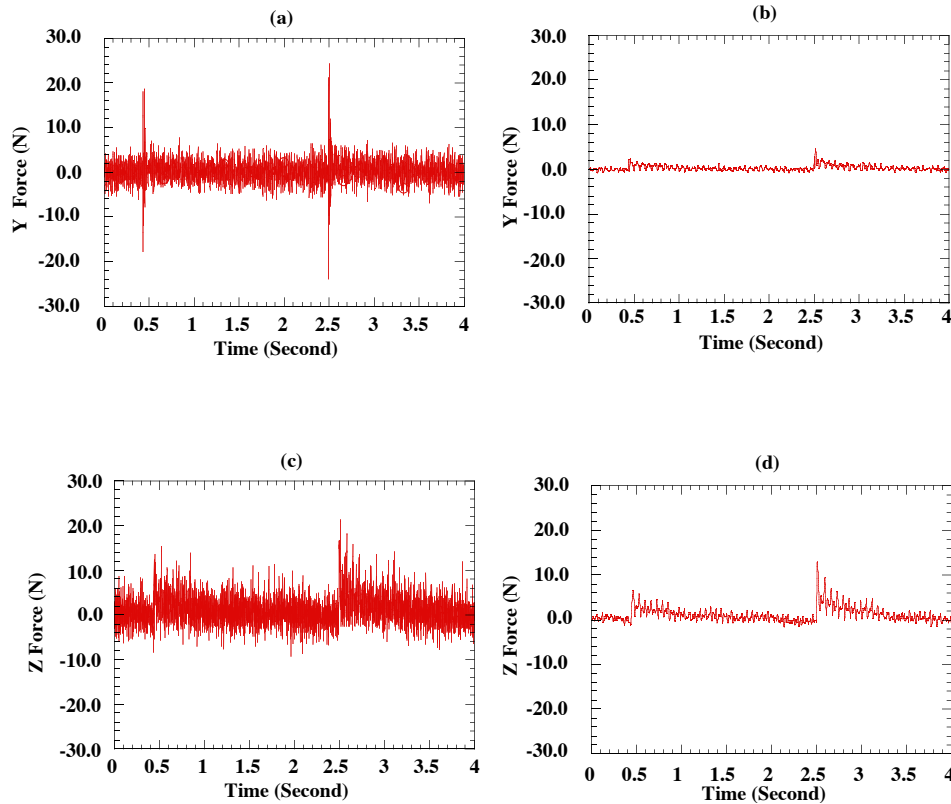


Figure 6 Forces for Machining Magnesia Stabilized Zirconia ( $v = 0.5$  BLU/s)  
 (a) Collected Y Forces; (b) Filtered Y Forces;  
 (c) Collected Z Forces; (d) Filtered Z Forces.

Workpiece material: Magnesia stabilized zirconia, Reaction-bonded silicon nitride, and Hot-pressed silicon nitride;

Coolant: Water;

Rotational speed:  $S = 3000, 1000$  rpm;

Vibration amplitude:  $A = 0.023, 0.033$  mm;

Depth of cut:  $a_p = 0.1, 0.35, 1$  mm;

Feedrate:  $v = 0.5, 1, 2, 4, 8$  BLU/s ( $= 0.381, 0.762, 1.524, 3.048, 6.096$  mm/min.).

Under all these machining conditions, the flat surfaces on ceramic workpieces have been machined successfully. Material removal rates corresponding to the above machining conditions are in the range of  $1.7\text{--}77.4$  mm<sup>3</sup>/min.. It seemed that higher MRR was possible for the process. However, since excessive feedrate may cause excessive forces which may damage the cutting tool and even the spindle, only the feedrates less than 8 BLU/s were used in the preliminary experiments. The upper limit of feedrate for the experimental setup is under investigation.

Cutting forces in two directions,  $F_y$  and  $F_z$ , were measured by Kistler milling

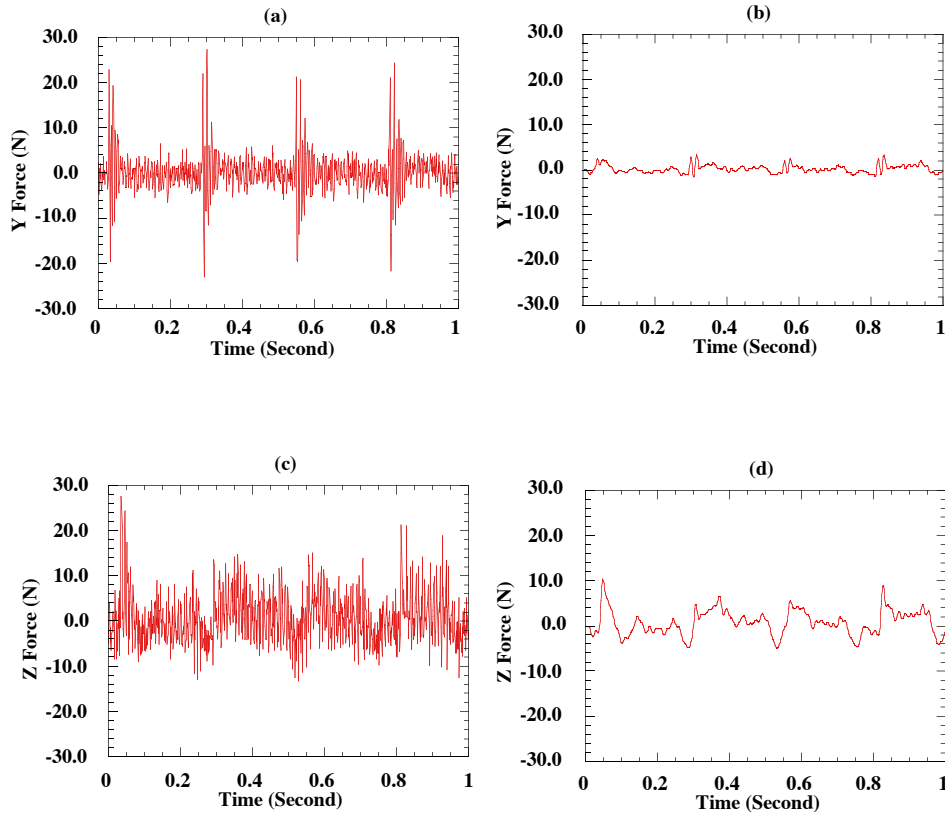


Figure 7 Forces for Machining Magnesia Stabilized Zirconia ( $v = 4$  BLU/s)  
 (a) Collected Y Forces; (b) Filtered Y Forces;  
 (c) Collected Z Forces; (d) Filtered Z Forces.

dynamometer.  $F_y$  was in feedrate direction and  $F_z$  in tool axial direction. Shown in Figures 6, 7 and 8 are  $F_y$  and  $F_z$  forces under three conditions for milling magnesia stabilized zirconia. Rotational speed  $S = 3000$  rpm, vibration amplitude  $A = 0.023$  mm and depth of cut  $a_p = 1$  mm for all the three figures. Feedrate  $v = 0.5$  BLU/s for Figure 6,  $v = 4$  BLU/s for Figure 7 and  $v = 8$  BLU/s for Figure 8. Butterworth lowpass filter was used to process the collected force data and the filtered data are also shown in these figures.

It can be seen that for every feed step (the X-Y table moves forward one BLU), the forces jump up and then gradually decrease. After certain period of time, the forces reduce to near zero. From this observation, two conclusions may be got. Firstly, the feedrate may be further increased. This will increase MRR. It is not necessary to wait until the forces completely reach zero and then send next feed pulse. Feedrate 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 feedrate control instead of constant feedrate control. Forces may be monitored during machining. Next feed pulse can be sent as soon as forces decrease to some threshold value.

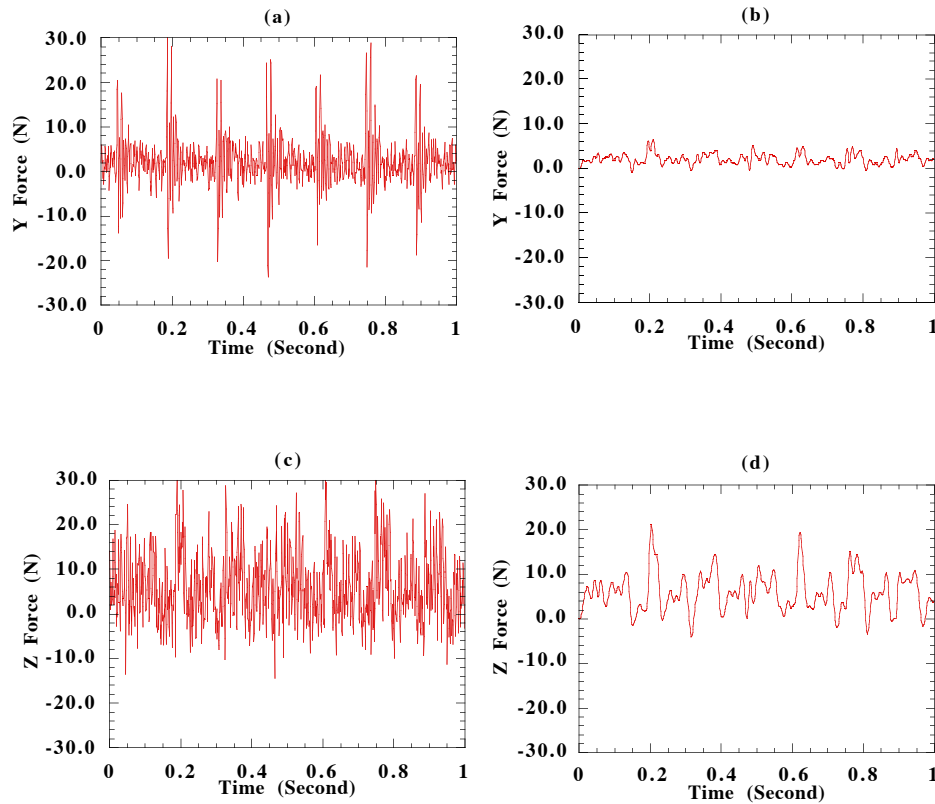


Figure 8 Forces for Machining Magnesia Stabilized Zirconia ( $v = 8$  BLU/s)  
(a) Collected Y Forces; (b) Filtered Y Forces;  
(c) Collected Z Forces; (d) Filtered Z Forces.

## CONCLUSIONS

A two-level full-factorial design was employed to undertake experiments on rotary ultrasonic drilling of magnesia stabilized zirconia. Among the five control variables, four of them (vibration amplitude, machining pressure, rotational speed, and abrasive grit size) had significant effects on MRR at primary level.

A mechanistic model to predict MRR for rotary ultrasonic drilling was developed. The model was based on the assumption that the brittle fracture mechanism was the dominant mode of material removal. The model was used to study the influence of different process variables on MRR. The trends predicted by the model were consistent with those reported in experimental investigations.

A new method to extend rotary ultrasonic drilling to face milling of ceramics was proposed. The experimental setup to realize this method had been set up. Preliminary experimental results showed that the experimental setup could achieve the desired results.

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#### REFERENCES

- [1] L. M. Sheppard, "The challenges of Ceramic Machining Continue," American Ceramic Society Bulletin, Vol. 71, No. 11, pp. 1590-1610, 1992.
- [2] S. Jahanmir, L. K. Ives, A. W. Ruff and M. B. Peterson, "Ceramic Machining: Assessment of Current Practice and Research Needs in the United States," NIST Special Publication 834, 1992.
- [3] R. Gilmore, "Ultrasonic Machining," SME Technical Paper, EM89-123, 1989.
- [4] D. Prabhakar, "Machining Advanced Ceramic Materials Using Rotary Ultrasonic Machining Process," M.S. Thesis, University of Illinois at Urbana-Champaign, 1992.
- [5] D. V. Cleave, "Ultrasonics Gets Bigger Jobs in Machining and Welding," Iron Age, September 13, pp. 69-72, 1976.
- [6] K. F. Graff, "Ultrasonic Machining," Ultrasonics, May, pp. 103-109, 1975.
- [7] D. Prabhakar, P. M. Ferreira and M. Haselkorn, "An Experimental Investigation of Material Removal Rates in Rotary Ultrasonic Machining," Transactions of the North American Manufacturing Research Institution of SME, Vol. 20, pp. 118, 1992.
- [8] Anonymous, "Ultrasonic Drilling with a Diamond Impregnated Probe," Ultrasonics, January-March, Vol. 2, pp. 1-4, 1964.
- [9] K. W. Hards, "Ultrasonic Speed Diamond Machining," Ceramic Age, Vol. 82, No. 12, pp. 34-36, 1966.
- [10] P. Legge, "Ultrasonic Drilling of Ceramics," Industrial Diamond Review, Vol. 24, No. 278, pp. 20-23, 1965.
- [11] A. I. Markov, Ultrasonic Machining of Intractable Materials (translated from Russian), Illife Books, London, 1966.
- [12] M. Kubota, Y. Tamura and N. Shimamura, "Ultrasonic Machining with a Diamond Impregnated Tool," Bulletin of Japan Society of Precision Engineering., Vol. 11, No. 3, pp. 127-132, 1977.
- [13] P. Legge, "Machining Without Abrasive Slurry," Ultrasonics, July, pp. 157-162, 1966.
- [14] A. I. Markov and I. D. Ustinov, "A Study of the Ultrasonic Diamond Drilling of Non-metallic Materials," Industrial Diamond Review, March, pp. 97-99, 1972.
- [15] A. I. Markov et al., "Ultrasonic Drilling and Milling of Hard Non-metallic Materials with Diamond Tools," Machine & Tooling, Volume 48, No. 9, pp. 45-47, 1977.
- [16] P. G. Petrukha et al., "Ultrasonic Diamond Drilling of Deep Holes in Brittle Materials," Russian Engineering Journal, Vol. 50, No. 10, pp. 70-74, 1970.
- [17] W. R. Tyrrell, "Rotary Ultrasonic Machining," SME Technical Paper MR 70 - 516, 1970.
- [18] Z. J. Pei, D. Prabhakar, P. M. Ferreira and M. Haselkorn, "A Mechanistic Approach to the Prediction of Material Removal Rates in Rotary Ultrasonic Machining," PED-Vol. 64, ASME, pp. 771-784, 1993, and to appear at Transactions of the ASME, Journal of Engineering for Industry.

Rotary Ultrasonic Drilling (RUD), a hybrid drilling process combining the material removal mechanisms of diamond grinding and ultrasonic machining, has the potential to do so. Achievements of Rotary ultrasonic drilling: Saving processing cost by increasing efficiency and reducing wear Higher surface quality, Improving geometrical precision, Smaller burrs are created, Tool life-circle is increased friction reduction between the tool and cutting chip. Further reduce the cutting force, which is suitable in cutting brittle materials.