Parametric Analysis and Optimization of Rotary Ultrasonic Machining of Zirconia (ZrO$_2$) Ceramics

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Abstract. Micro-channels are considered as the essential part of several medical applications such as microfluidics devices, lab on a chip, microbiology, etc. In most applications, fluid flow is required to pass through certain microchannels. The fluid flow characteristics such as flow rate and fluid dynamics are mainly accomplished based on the surface quality and dimensional accuracy of the microchannels. In this study, the microchannels are fabricated on zirconium oxide (ZrO$_2$) using rotary ultrasonic machining (RUM). A full factorial design of experiments is employed in order to detect the influences of key input parameters of RUM including cutting speed (S), feed rate (FR), depth of cut (DOC), frequency (F) and amplitude (A) on surface roughness (Ra), edge chipping (EC), depth error (DE) and width error (WE) of the milled microchannels. Multi-objective genetic algorithm (MOGA) was employed to determine the optimal parametric conditions for minimizing the values of Ra, EC, DE, and WE of the fabricated microchannels. Results revealed that the minimum value of Ra = 0.26 µm, EC = 10.1 µm, DE = 4.2% and WE = 7.2% can be accomplished through the multi-objective optimization at higher levels of frequency and amplitude and lower levels of feed rate, depth of cut and cutting speed.

1. Introduction

Advanced ceramics such as alumina, zirconia, aluminum nitride, silicon nitride, and boron carbide are extensively being used in various medical and engineering applications. This is due to their superior properties, which include very high hardness, excellent wear resistance, and chemical inertness. However, because of their high hardness and brittleness, the advanced ceramics are difficult to be machined efficiently with traditional machining technologies such as turning, milling, and drilling [1]. Among the advanced ceramics, zirconium dioxide (ZrO$_2$), commonly known as zirconia, is one of the most widely used ceramic material because of its ability to guarantee excellent properties such as, high hardness, high thermal resistance, and fracture toughness, high flexural strength even at high temperatures and is chemically inert [2]. Due to its high biocompatibility, ZrO$_2$ is widely used for load-bearing functional structures in medicine and dentistry bio-implantable applications, including joints and dental implants [3]. Micro-channels are considered as the essential part of ZrO$_2$ for several medical applications such as microfluidics devices, lab on chip, microbiology, etc. In most applications, fluid flow is required to pass through certain microchannels. However, microchannels, micro holes, and other similar micro-features are almost impossible to generate in advanced ceramics through conventional machining processes. Therefore, there is a need to develop a cost-effective non-
traditional process to machine advanced ceramic material efficiently.

Several machining processes have been applied for machining zirconia ceramic materials. For example, Guarino et al. [4] used a fiber laser process for milling pockets on yttria-stabilized zirconia. The effect of laser parameters was investigated on surface roughness and material removal rate (MRR). Results showed that the smooth surface along with higher MRR can be achieved at high scan speed, a high number of repetitions and low hatch distance. Nanosecond laser was applied by Jian Li et al. [5] for machining micro-sized steps and a blind hole in yttria-tetragonal zirconia polycrystal ceramic. Results revealed that a high removal rate of 1.35 mm$^3$/min and smooth surface roughness of $Ra = 2.824 \, \mu m$ can be obtained at a scan speed of 150 mm/s and laser fluence of 8.9 J/cm$^2$.

Micropatterns of 30 μm diameter and 10 μm depth were fabricated on zirconia by using the Femtosecond laser process in [6]. Laser-assisted grinding was also applied for machining zirconia [7]. Results showed that grinding force the tool damage can be reduced with the help of the laser assistance. The micro electric discharge machining process was applied for precision micromachining of zirconia ceramic. Microchannels with different sizes were fabricated on ZrO$_2$ by using the laser beam process [8]. The authors investigated the significance of laser beam parameters on the surface roughness and the channels’ geometrical accuracy. Results reveal that the surface roughness and the geometrical accuracy can be controlled by adjusting the input parameters of the laser process. The influence of micro-milling parameters was investigated on microgrooves machined on zirconia ceramic in the study documented in [9]. Authors found that the sintering temperature has a major influence on the machinability of ZrO$_2$. Recently, Rotary Ultrasonic machining (RUM) is applied for machining advanced ceramics. For example, Abdo et al. [10,11] used RUM for machining microchannels on alumina ceramics. Results indicated that RUM can be applied to fabricate very precise microchannels with superior surface finish and high dimensional accuracy under certain optimized RUM input parameters. RUM was also applied for face milling of zirconia ceramic in the study documented in [12]. A mathematical model was developed by Xiao et al. [13] to analyze the cutting force in RUM of dental zirconia ceramics.

From the reported research, it can be concluded that very few research studies are conducted on the micro-machining of zirconia ceramic while no study carried out on the fabrication of microchannels in zirconia by applying RUM. The majority of the reported studies are limited to applying the laser process on the machining of zirconia. The most drawbacks of the laser process are that the process poorly affecting the thermal and the physical the machined surfaces. In this study, a full factorial design is used to analyze the effect of five RUM input parameters on the selected outputs. The selected input parameters include cutting speed (S), feed rate (FR), depth of cut (DOC), amplitude (A), and frequency (F). The outputs including the surface roughness (R$_a$), edge chipping (EC), channel depth error (DE) and width error (WE) are analyzed. Moreover, the multi-objective genetic algorithm (MOGA) tool is used to optimize the R$_a$ and EC while keeping the DE and WE less than 10%.

2. Materials and method

The experiments in this study were conducted using Ultrasonic 20-linear from DMG, Germany (see figure 1a). Zirconium Oxide (ZrO$_2$) has been used as a substrate material for micro-machining from CeramTec Germany. All the ZrO$_2$ samples used in the experiments were of the dimension 50 mm × 50 mm × 10 mm as shown in Figure 1b. Nickel bonded diamond RUM tools with a diameter of 0.5 mm provided by Schott company Germany were utilized in the current investigation as presented in Figure 1c. The cross-sectional dimensions of the fabricated microchannel are 0.5 mm (width) × 0.2 mm (depth) × 6mm (length) (see Figure 2a). The mentioned size of the microchannels was selected based on the micro-fluidics applications [14–16].

2.1 Design of experiments

The full factorial design of experiments (DOE) was used to design the main experiments aiming to detect the influence of RUM input parameters on the selected outputs. Five input parameters with two levels each resulted in 32 experiments (2$^5$). Eight central points were added randomly to the design,
so a total of 40 experiments was performed. The range of the RUM input parameters (see Table 1) used in this study were selected based on the preliminary runs and the studies reported on the micro-machining of glass and ceramic materials using RUM [10,11,17,18].

![Figure 1: (a) DMG Ultrasonic machine, (b) ZrO\textsubscript{2} substrate, (c) micro-RUM tool](image)

| Parameter (unit) / levels | Lower level | Center point | Higher level |
|--------------------------|-------------|--------------|--------------|
| Cutting speed (S), rpm    | 3000        | 5000         | 7000         |
| Feed rate (FR), mm/min   | 0.5         | 1            | 1.5          |
| Depth of cut (DOC), mm    | 0.0125      | 0.025        | 0.0375       |
| Amplitude (A), μm         | 5           | 20           | 35           |
| Frequency (F), kHz        | 22          | 24           | 26           |

2.2 Measurement Procedures
The channel width, channel depth, were measured using an optical microscopic. The depth error is calculated as the difference between the targeted depth and the measured depth of the channel after machining. Similarly, the width error is calculated as the difference between the targeted width and the actual width after machining. The percentage of width error and depth error were used for the analyzes. Figure 2a represents samples of actual microchannels fabricated on ZrO\textsubscript{2} material and Figure 2b shows a schematic of the microchannels. Surface roughness (Ra) was measured along each channel bed at four different locations using portable surface roughness from Mitutoyo, Japan. The average of these four readings was used for analysis. Figure 2c shows the setup of measuring surface roughness.

3. Results and analysis
Table 2 lists the experimental results of 40 microchannels fabricated in ZrO\textsubscript{2} using full factorial design. Figure 3 shows typical scanned 2D profiles of the microchannels machined at different process parameters. It shows clearly that the RUM input parameters have a significant effect on the surface roughness of the fabricated microchannels.

3.1 Effects of RUM parameters on Ra

![Figure 2. (a, b) Actual and schematic of the machined microchannel, (c) Set up of measuring Ra.](image)
Figure 3. Examples of typical scanned Ra profiles of the fabricated microchannels

Table 2. Experimental results

| Exp. # | Inputs | Outputs |
|--------|--------|---------|
|        | S (rpm) | FR (mm/min) | DOC (mm) | F (kHz) | A (µm) | Ra (µm) | EC (µm) | DE (%) | WE (%) |
| 1      | 7000    | 0.5       | 0.0375   | 26      | 35     | 0.42    | 14.2    | 5.5    | 12.1   |
| 2      | 5000    | 1         | 0.025    | 24      | 20     | 0.37    | 15.2    | 4.6    | 11.8   |
| 3      | 7000    | 0.5       | 0.0375   | 22      | 5      | 0.29    | 16.8    | 4      | 12.4   |
| …      | …       | …         | …        | …       | …      | …       | …       | …      | …      |
| 36     | 5000    | 1         | 0.025    | 24      | 20     | 0.23    | 16.2    | 3.8    | 8.7    |
| 37     | 7000    | 1.5       | 0.0375   | 26      | 35     | 0.54    | 14.7    | 8.1    | 12.4   |
| 38     | 3000    | 1.5       | 0.0375   | 26      | 5      | 0.48    | 18.7    | 5.4    | 12.6   |
| 39     | 7000    | 0.5       | 0.0125   | 26      | 35     | 0.26    | 13.1    | 7.2    | 6.3    |
| 40     | 7000    | 0.5       | 0.0125   | 22      | 35     | 0.31    | 9.5     | 6.9    | 8.1    |

The response surface plots for the surface roughness are shown in Figure 4. It is obvious from Figure 4a that the minimum value of Ra can be found at higher levels of cutting speed (S) and lower value of feed rate (FR). This is because the contact time between the machined surface and the RUM tool increases at higher cutting speed, resulting in reducing the cutting force and as a result producing smoother surface [10,19]. On the other hand, the increase in the feed rate causes an increase in Ra. This is because the high feed rate leads to more stress and accordingly produces a rough surface [11,20]. The higher levels of amplitude and moderate to high levels of frequency result in the minimum values of Ra, as depicted in Figure 4b. The surface roughness (Ra) was observed to increase with increasing the depth of cut as shown in Figure 4c.

3.2 Effects of RUM parameters on EC
In RUM, edge chipping (EC) is the main reason for damaging the machined surface [21]. Figure 5 shows the surface plots of the EC. It can be shown in Figure 5a that as the spindle speed increases and the feed rate decreases, the values of EC reduce considerably. This happens because any change in input parameters which leads to an increase in the force means the edge chipping will increase [10,11]. Regarding the effect of ultrasonic parameters, it can be said from Figure 5b that the minimum values of edge chipping are found at high levels of frequencies and amplitudes. Due to an increase in the cutting force, the EC was observed to increase with increasing the depth of cut as shown in Figure 5c.

3.3 Optimization results
A multi-objective genetic algorithm (MOGA) was applied to minimize Ra and EC of the fabricated microchannels. The constraints were to keep the depth error and the width error of less than 10%. A total of 774 generations were modeled using the MOGA. Figure 6 shows the design points obtained using the bubble charts. The real design points represented to the actual experimental runs and the virtual runs are predicted by the response surfaces based on radial basis functions.
Figure 5. Response surfaces plots for edge chipping (EC).

The four outputs at a time can be shown in Figure 6 using a 4D bubble. The colors of the bubbles represent the width error (WE) whereas the diameter represents the depth error (DE). The effect of Ra and EC is clearly recognized in the 4D graph, as the low Ra corresponds to low to med EC. These design points are described by high cutting speed, amplitude and frequency, and low feed rate and depth of cut. On the other side, the above right area of Figure 6 corresponds to design points with high Ra and EC. These are related to high feed rate and depth of cut, low cutting speed, amplitude, and frequency. Regarding the WE and the DE, it can be noticed from the difference in the colors and size of the bubbles in Figure 6 that the variation is not high, and most of the values are located between 5 to 10 µm.

The relationships between all input and output parameters can be seen using a parallel coordinate chart as shown in Figure 7. Most of the unfeasible design points are linked to higher values of feed rate (FR), depth of cut (DOC) and cutting speed which leading to higher width error (WE) and depth error (DE). No significant effect of Frequency (F) and amplitude (A) on WE and DE can be found in Figure 7 as the unfeasible points distribute overall levels of both F and A. Looking to overall responses, the optimal results were found at low levels of feed rate, cutting speed and depth of cut and high levels of amplitude and frequency as listed in Table 3.

Figure 6. A 4D bubble chart showing the design points obtained with outputs of Ra, EC, WE, and DE

Figure 7. A parallel coordinate chart for the analysis of RUM parameters.

Table 3. Optimal points for all outputs

| # | S (rpm) | FR (mm/min) | DOC (mm) | F (kHz) | A (µm) | Ra (µm) | EC (%) | DE (%) | WE (%) |
|---|---------|-------------|----------|---------|--------|---------|--------|--------|--------|
| 1 | 3000    | 0.5         | 0.0125   | 26      | 35     | 0.26    | 10.1   | 4.5    | 7.2    |
| 2 | 3500    | 0.5         | 0.0125   | 26      | 35     | 0.27    | 10.64  | 4.70   | 7.23   |
| 3 | 4000    | 0.6         | 0.0125   | 26      | 35     | 0.27    | 11.28  | 4.67   | 7.33   |
| 4 | 3250    | 0.5         | 0.0125   | 26      | 35     | 0.26    | 10.38  | 4.60   | 7.21   |

4. Conclusions

- RUM can be applied to fabricate precise microchannels in ZrO₂ material. Under the experimental condition, the dimensional accuracy in terms of the depth error and width error is found to be less than 10% and 13% respectively.
- Ra is directly proportional to the depth of cut and feed rate and inversely with cutting speed, frequency (F) and amplitude (A).
- Edge chipping (EC) reduces with increasing cutting speed and decreasing the feed rate and depth of cut.
● Increasing of ultrasonic parameters (F and A) leading to increasing EC.
● The optimal RUM parameters are a feed rate of 0.5 mm/min, a depth of cut of 0.0125 mm, a frequency of 26 kHz, a cutting speed of 3000 rpm, and an amplitude of 35 μm, resulting the outputs as Ra = 0.26 μm, EC = 10.1 μm, DE = 4.2%, and WE = 7.2%.

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