Micro Electro Discharge Machining of Electrically Nonconductive Ceramics

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Abstract. EDM is a known process for machining of hard and brittle materials. Due to its noncontact and nearly forceless behaviour, it has been introduced into micro manufacturing and through constant development it is now an important means for producing high-precision micro geometries. One restriction of EDM is its limitation to electrically conducting materials.

Today many applications, especially in the biomedical field, make use of the benefits of ceramic materials, such as high strength, very low wear and biocompatibility. Common ceramic materials such as Zirconium dioxide are, due to their hardness in the sintered state, difficult to machine with conventional cutting techniques. A demand for the introduction of EDM to these materials could so far not be satisfied because of their nonconductive nature.

At the Chemnitz University of Technology and the Fraunhofer IWU, investigations in the applicability of micro-EDM for the machining of nonconductive ceramics are being conducted. Tests are undertaken using micro–EDM drilling with Tungsten carbide tool electrodes and ZrO_2 ceramic workpieces. A starting layer, in literature often referred to as 'assisting electrode' is used to set up a closed electric circuit to start the EDM process. Combining carbon hydride based dielectric and a specially designed low-frequency vibration setup to excite the workpiece, the process environment can be held within parameters to allow for a constant EDM process even after the starting layer is machined. In the experiments a cylindrical 120 μm diameter Tungsten carbide tool electrode and Y_2O_3- and MgO- stabilized ZrO_2 worpieces are used. The current and voltage signals of the discharges within the different stages of the process (machining of the starting layer, machining of the base material, transition stage) are recorded and their characteristics compared to discharges in metallic material. Additionally, the electrode feed is monitored. The influences of the process parameters are analysed with regard to the discharge type, electrode wear and process speed.

Using the found parameters, micro geometries can be successfully machined into nonconductive Y_2O_3- and MgO- stabilized ZrO_2 ceramic by means of micro–EDM.

Keywords: micro electro discharge machining, ceramic, zirconium dioxide, assisting electrode, vibration
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INTRODUCTION

Electro Discharge Machining

The Electro Discharge Machining process is based on ablation of material through melting and evaporation. The electrical discharges occur between tool electrode and workpiece in a dielectric medium that separates the two. A voltage is attached to both electrodes and, when the breakdown voltage of the medium is reached, a plasma channel allowing for a current flow is established and a discharge takes place. On the base of the plasma channel the temperature can reach $T \geq 10000\,K$, melting and evaporating electrode material. When the energy input is stopped the discharge ends, leading to an implosion of the plasma channel followed by a collapse of the surrounding gas bubble. The reflow of the dielectric medium flushes particles away and cools the electrode surface. Repeating the process, a voltage is attached to the electrodes again and the setup is prepared for the next discharge. Naturally, it will take place where the breakdown barrier is lowest, hence the distance between the electrode is the smallest – in an ideal dielectric – or, in a real dielectric liquid, the conductivity of the gap between the electrodes is the highest, e. g. when particles or gas bubbles reduce the breakdown voltage of the medium. By constant repetition of the process, the tool electrode surface is resembled in the workpiece and, by feeding the tool, a transfer of the geometry takes place. Because of the process nature, the surface is an assembly of single discharges and shows a crater–like topology. The geometrical accuracy and the surface roughness depend on the size and shape of these craters and therefore on the volume that is ablated with each discharge. A minimisation of discharge energy is the key to accuracy and optimal surface characteristics. Consequently, the discharge gap must also be minimised.

In micro–EDM, the discharges have a typical duration of $t_e \approx 100\,ns$ and transfer energy of $W_e \approx 10\,\mu J$. The resulting crater width depends on the workpiece material properties, but a diameter of $d_c \approx 5\,\mu m$ and depth of $\leq 1\,\mu m$ can be obtained. The resulting surface roughness can be as low as $R_z \leq 1\,\mu m$.

A major benefit of the Electro Discharge Machining Process, due to its electro–thermal nature of ablation, is independency of material hardness and brittleness. The noncontact nature of the process results in a nearly force–free machining, allowing the usage of soft, easy to machine electrode materials even when shaping very hard workpieces. This also enables the machining of fragile or thin workpieces. Furthermore, fine micro tools can be used in small angles to the workpiece surface without deviation or breaking. For all those reasons, EDM has been widely used in the generation of micro parts [1].

Ceramics

Ceramic materials are, due to their extraordinary properties such as high hardness and biocompatibility, increasingly used in micro parts. Its machining, however, is difficult, and mostly slow and expensive grinding processes are used [2]. Electro discharge machining with its nearly forceless behaviour and independence of hardness and material brittleness seems to be an appropriate process, but is mainly limited to conductive materials. In research, several approaches have been taken to machine nonconductive ceramic by means of EDM, with the 'assisting electrode' method, developed by Mohri and Fukuzawa [3, 4], leading to successful machining of Zirconium dioxide materials.

State of the art

In conventional micro–EDM, an important focal point in research has been the superposition of vibration onto the tool or workpiece to improve flushing conditions and thus stabilizing the process. The usage of ultrasonic as well as low-frequency vibration has been investigated and has lead to great improvements in achievable aspect ratios for micro bores [5].

In previous studies, the assisting electrode approach has been adapted to a vibration–assisted micro–EDM setup to examine the effects of different frequencies and amplitudes on process speed and achievable geometries [6, 7].

As the micromachining of these materials is often targeted at medical applications, a commonly used biocompatible Zirconium dioxide compound is selected. The process is analyzed and adapted in order to find suitable parameters to allow for the generation of micro bores in solid ZrO_2 material.

EXPERIMENT

Experimental setup

Machine tool

A standard micro–EDM machine tool is used for the experiments (*Sarix T1-T4*) and modified to comply with the special requirements of micro–EDM of nonconductive ceramics. The modifications developed within previous studies consist of a basin, filled with dielectric oil and equipped with a peristaltic pump for flushing and filtering of the medium independent from the main dielectric circuit and an active workpiece clamping unit that can be exited with low–frequency vibration of up to $f = 1000\,Hz$ and $\hat{a} = 20\,\mu m$ *peak–peak*. Additionally, an electrode guidance system is applied to enable electrode rotation without excessive runout error (Figure 1).

Electrode and workpiece material

Centerless ground Tungsten carbide rods (6% Cobalt binder) of $d = 120\,\mu m$ are used as tool electrode.

The workpiece material for the experiments is ZrO_2 with Y_2O_3 stabilization. For a second test, a MgO–stabilized ZrO_2 ceramic is used. Material charcteristics are stated in table 1.

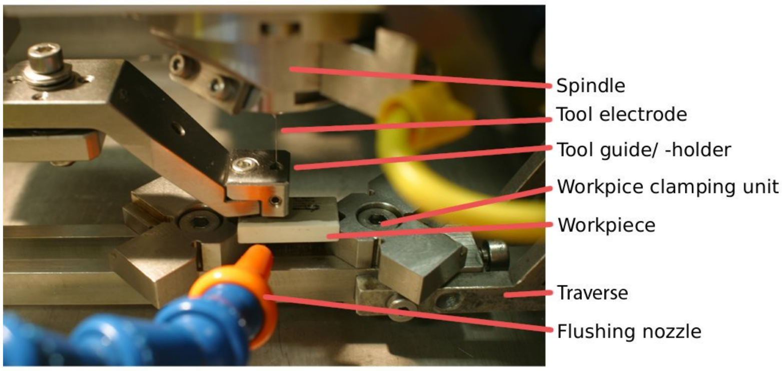

FIGURE 1. Experimental setup

TABLE 1. Workpiece material characteristics

	Symbol [**unit**]	$Y_2O_3 - ZrO_2$	$MgO - ZrO_2$
Density	ρ $[g \cdot cm^{-3}]$	6.0	5.5
Bending strength	σ $[MPa]$	1000	500
Hardness	HV $[10^3 N \cdot mm^{-2}]$	$12 - 20$	$12 - 20$
Thermal conductivity (at $30 - 100°C$)	λ $[W \cdot mK^{-1}]$	$2 - 3$	$2 - 3$
Specific electric conductivity (at $20°C$)	κ $[S \cdot m^{-1}]$	$10^{-3} - 10^{-8}$	$10^{-3} - 10^{-8}$
Max. operation temperature	$T [°C]$	1200	900

Starting layer

A common silver varnish with 45.9 % silver content is used to create the starting layer. It is applied with a paintbrush. After drying, the uniformity of the layer formation is tested by measuring the resistance using a *Fluke* multimeter. The thickness of the layer is approximately $20\,\mu m$.

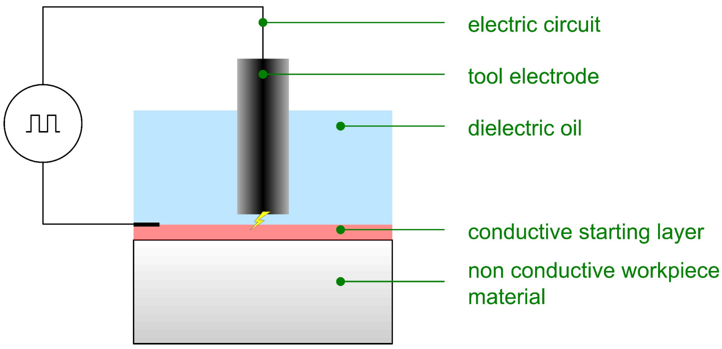

FIGURE 2. Assisting electrode setup

Measurement setup

Current and voltage signals. Current and voltage signals are recorded using a *Tektronix TCP312* current probe, *PMK PKT 9512A* 50 : 1 voltage probe and *Spectrum M2i 2031* A/D measurement cards with up to $200 \cdot 10^6$ samples per second. The card's large on–board memory allows for recording periods of up to $1.2\,s$ for synchronized measurement of both u and i.

Electrode feed monitoring. To get a detailed insight into the state of the process, the electrode feed is monitored. To do so, a *LabView* program is written that analyses the communication between the machine tool control and the stepper motor for the electrode feed and calculates and records the current z–axis position.

EDM parameters

For the experiments, the ED machining parameters are set to identical values to those of the metal EDM. The values are shown in table 2. In previous tests it was found that machining of nonconducting ceramic ZrO_2 material only takes place with cathodic polarity. Using an electrode guidance system, the influence of electrode rotation is examined comparing similar setups with or without rotating electrode.

TABLE 2. Machining parameters of Sarix T1–T4 micro–EDM machine tool

U0	**GP**	**CF**	**GN**	**FR**	**WH**	**IP**	v_{rot}	**feed** s	**vibration freq.**
$130V$	$64V$	0	9	$100kHz$	$5\mu s$	$45A$	$610min^{-1}$	$1000\mu m$	$400Hz$

RESULTS AND DISCUSSION

General machinability

Using the proposed setup, a successful machining of ZrO_2 ceramics is performed, even after the starting layer is completely removed. By using electrode rotation, a significant increase in both process speed ($\Delta t_p \approx 40\,\%$) and resulting bore depth ($\Delta s_b \approx 25\,\%$) is observed (Figure 3). The electrode wear is noticeably reduced, however, with values of $\approx 75\,\%$ relative wear there is still a high reduction potential.

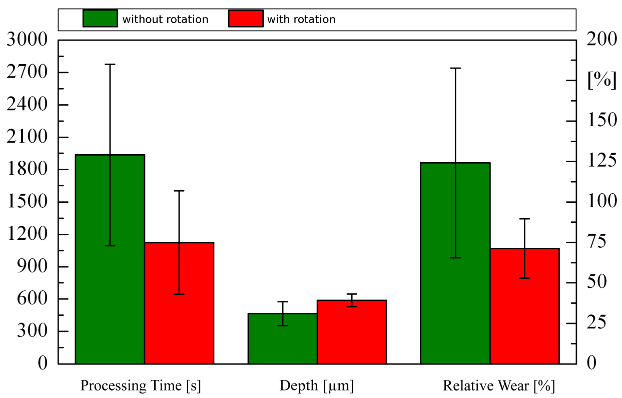

FIGURE 3. Machining results with and without electrode rotation: processing time [s], bore depth [μm], wear [%] (Y_2O_3–ZrO_2)

Stages of the process and discharge types

EDM of metals

The micro–EDM of metals with the used discharge duration of $t_e \approx 100ns$ is normally conducted using negative polarity of the tool electrode. To compare it to the ceramic material, a standard $18CrNi8$ steel is machined with micro–EDM. The discharges show a current peak of $i_e \approx 4A$ throughout the machining process (Figure 4a). The machining depth and therefore the flushing conditions influence the number of discharges per unit of time, but not the current and voltage waveform shapes.

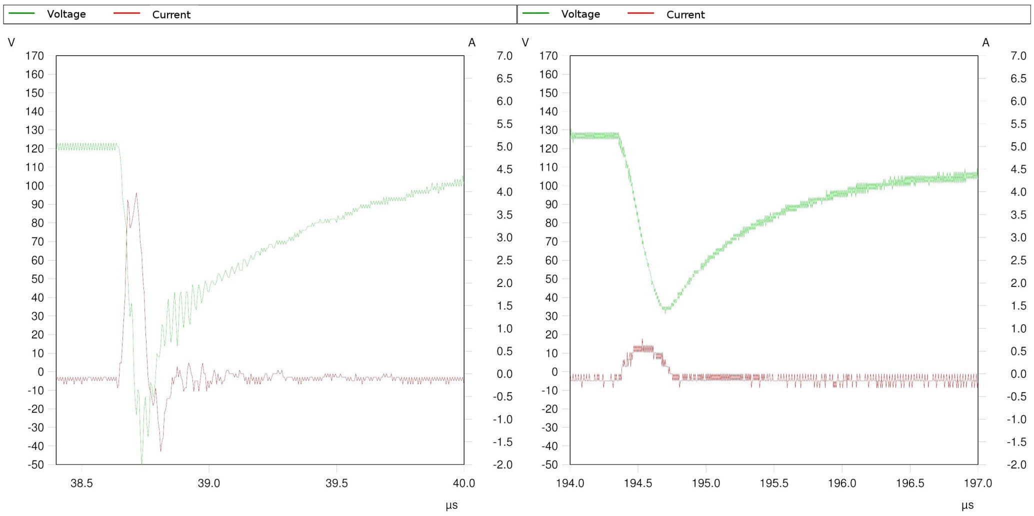

FIGURE 4. Discharge signal a) metal micro–EDM b) micro–EDM of starting layer in ceramic

EDM of nonconductive ceramics

Machining of starting layer. Since the starting layer consists of a silver material, similar discharge shapes to those in metal–EDM are expected. These expectations are confirmed. The current is lower than in metal–EDM of the steel workpiece, but otherwise no large changes in current and voltage signals occur (Figure 4b).

Transition stage. During the machining of the starting layer, a change in the shape of the discharges is observed. The shape of the current signals changes from those of metal–EDM to a short–peak–long–hold type of signal with a hold period of up to $8\,\mu s$ (in previous experiments durations of up to $3\,\mu s$ were observed [7]) at $i_e \approx 0.3A$ (Figure 5). It is assumed that the decomposition of the carbon hydroxide dielectric oil takes place, generating the visible carbon–rich black layer on the ceramic surface [6]. However, it is so far not certain whether it is a (Zirconium–) carbide or carbon structure that is formed. From the beginning towards the end of the starting layer machining, the ratio of the so–called *ceramic* discharges increases.

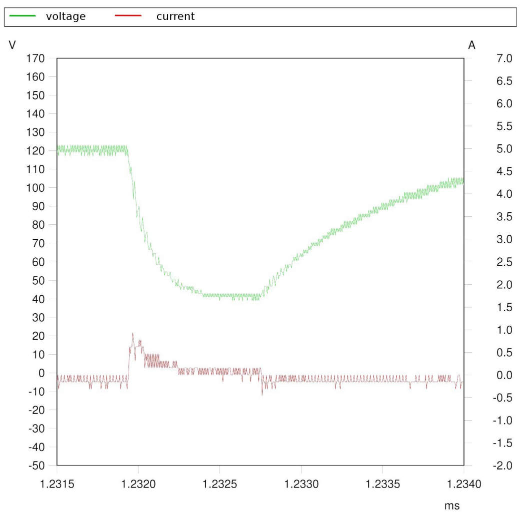

FIGURE 5. current and voltage signal of *ceramic* discharge in micro–EDM (base material stage)

Machining of base material. After the starting layer is completely removed, the machining continues. Now nearly all discharges are in the shape of the ceramic discharges. Another observed phenomenon is the decrease in peak current with an increase of machining depth. Between depths of $150\,\mu m$ and $1500\,\mu m$ (electrode feed) the current decreases up to $50\,\%$. Additionally, the amount of short circuiting rises with increasing depth, in occurance as well as in its durations.

Micro–EDM of MgO–ZrO_2 ceramics. Using identical machining parameters, experiments are carried out to test the machinability of MgO–stabilized ZrO_2 ceramics. A micro bore can be successfully machined into MgO–ZrO_2 as well. In this case, electrode feed recording shows that the process speed is lower than when machining Y_2O_3–ZrO_2 (Figure 6), but further investigations have to be undertaken to gain statistically more reliable data.

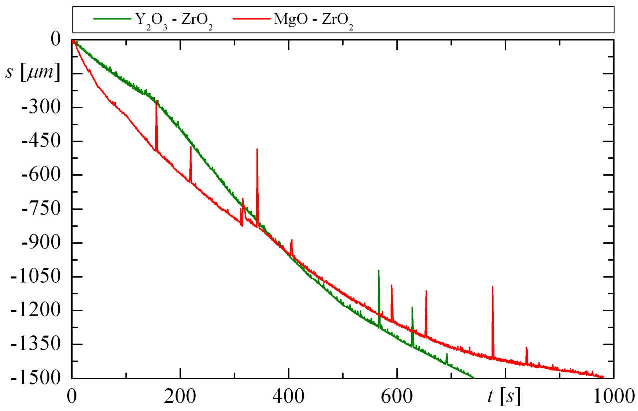

FIGURE 6. Process speed of micro–EDM in Y_2O_3 and MgO stabilized ZrO_2 ceramic. Peaks in the graph represent short retracting movements of the tool electrode.

SUMMARY

Using the assisting electrode method and the proposed experimental setup, micro bores can be successfully machined in MgO– and Y_2O_3–stabilized ZrO_2 ceramic materials. The usage of tool electrode rotation leads to an increase of machining speed and reduces tool wear. While at the beginning of machining the starting layer discharges similar to those in metal–micro–EDM can be observed, a transition into so–called *ceramic* discharges takes place that are characterized by a smaller peak current followed by a long constant low current flow. These make up the majority of discharges when machining the ceramic base material. The process that is used for Y_2O_3–ZrO_2 can be transferred to MgO–ZrO_2.

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