Microsecond measurement resolution for process cycle diagnostics of micro-EDM milling

ARTICLE INFO

ABSTRACT

Ceramics are non-conductive materials, consequently, they cannot be machined directly by any electrical means. If these ceramics contain some small fractions of conductive components, e.g., as pollutant or as glue materials, they perform a certain, really low level, local and accidental flash of some conductivity. The reported research was performed on this border of science, with ceramics that are below the practical and also below the state-of-the-art conductivity level for electrical machining. Even so, micro-Electric Discharge Machining (micro-EDM) for cermaics was developed with varying and many times uncertain success. The paper describes the required, extended measuring system of a micro discharge milling machine equipped with a linear encoder, voltage, and current sensors. With the help of the installed measuring system, the ceramic discharge milling of the Al_2O_3–TiC mixture was tested, in particular, the process stability, the geometric transient zones and the edges of the machined grooves.

1. Introduction

Process parameters are of paramount importance in the micro electrical discharge range. The process has significantly more uncertainty than the macro-sized machining, especially when machining special materials, such as ceramics. Metal-optimized controls are challenging to deal with handling a series of discharges during such ceramic machinings. It is very difficult to examine the relationship between the quality, quantity, and surface area of discharge due to a large number of parameters and unstable dependencies [1].

In the reported research, the specifics for micro-EDM machining of Al_2O_3 -TiC mixture ceramics are explored [2] and improved. In the field of EDM, the micro range starts when the tool/machining area is below or equal to the 1mm threshold. The material's conductivity moves below the percolation boundary, which means that its conductivity varies widely depending e.g. on the location and on the local machining conditions, etc. Macroscopic conductivity in the micro range is much lower, and the material acts mainly as an insulator. This variability makes the process even less stable, which requires an analysis of the relationship between process success and machining conditions. As important part of the research, ceramic micro spark cutting milling experiments and measurements had to be carried out. The relationship between cutting parameters and process stability had to be found, especially in transient sections. Correlations were explored by measuring the machining site and the spark discharge process during the micro milling process. *A novel, extended measuring and diagnostics system was designed to meet this border conditions.* An appropriate, complex machined path was designed for comprehensive testing and monitoring the EDM process as shown in Fig. 1.

By using this V-shape, e.g. the toolpaths overlap each other resulting a continuously changing machining width, so, it was designed for representing starting process, continuous/stable maching and complex interrelationships of the geometries as well. During the measurement, electrical discharge milling was used, which means material removal per many layers.

2. Literature review

The idea of cutting ceramic sparks is not new, but it has not yet spread widely due to the difficulties of technology, moreover, the examined range of conductivity is not yet explored in the literature, neither in practice. Recently, several scientific articles on this technology were published and its difficulties come to light.

The lesson of Ming et al.'s [3] review article is that the spark cutting of ceramics requires intelligent processes, including adaptive regulation. Pachaury and Tandon [4] also found that the development of EDM control could pave the way for broader distribution.

The primary deficiency of control in the micro discharge machining range is that material near its percolation boundary may have non-conducting islands, that in this typical absence of discharges they are incorrectly detected and regulated by control solutions based on current and voltage measurement.

Actually, the conductivity of the material is out of the scope according to the state-of-the-art EDM literature as presented in Fig. 2.

According to the measurements of Cai et al. [5], the percolation limit for Al_2O_3–TiC mixtures is about 20%., above this level, the material has acceptable conductivity for the EDM process.

By Lin et al. [6], 70/30% ceramic spark cutting was tested for optimization purposes, but the studies were carried out in the macro range. Chang et al. [7] attempted to chip ceramics with lower conducting phase content also in the macroscopic range. Elmenshawy et al. [8] analyzed the machining of ceramics already with a very high Al_2O_3 content. According to their results, an acceptable material removal rate can be obtained by the optimization of the process. However, the diversity of
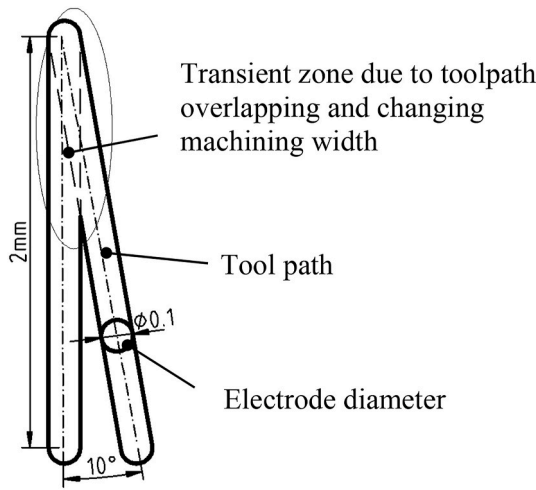
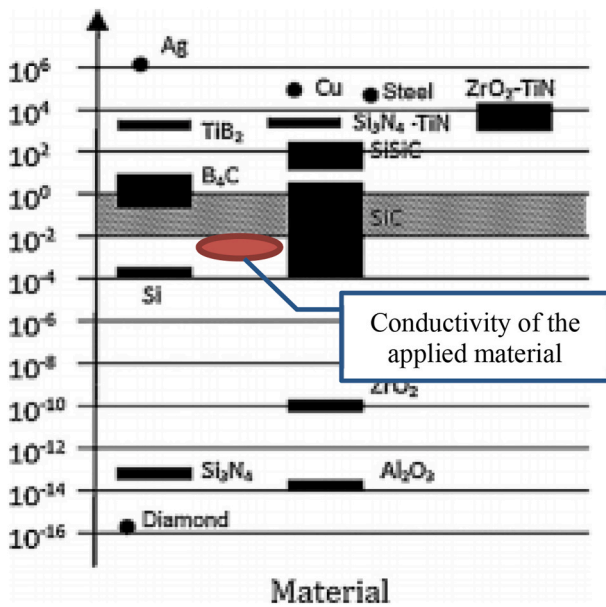**Fig. 1.** Machined groove shape and tool path.

Fig. 2. The conductivity of different ceramics including the alumina-oxide mixture used in this research [12]. The grey are shows the state-of-the-art limit of EDM machining, above it the materials can be machined by EDM, below it not. Consequently, *the machined material of the reported research is below the actual state-of-the-art limit.*

conductivity in micro ranges can still lead to control problems. Studies [9–11] can be found in the literature regarding micro-EDM on ceramics, but these materials are mainly ZrO2 and Si_3N_4 based, so, they are on the appropriate level of conductivity.

The results of Ferraris et al. [12] can be mentioned in the micro range, who used Al_2O_3–TiCN mixture (70/30%) in micro discharge machining. However, materials with higher ratio were not investigated yet.

As part of the research, electric discharge machining of Al_2O_3–TiC ceramics were examined. Based on EDS measurement, the material's content is ca. 75% Al_2O_3 and 25% TiC, which beyond the limit of the percolation.

The applied material is less than slightly conductive, but the conduction net's topology is unknown. The actual conductivity may strongly depend on the place of local measurement, especially in the micro ranges, consequently, this machining in highly uncertain if at all
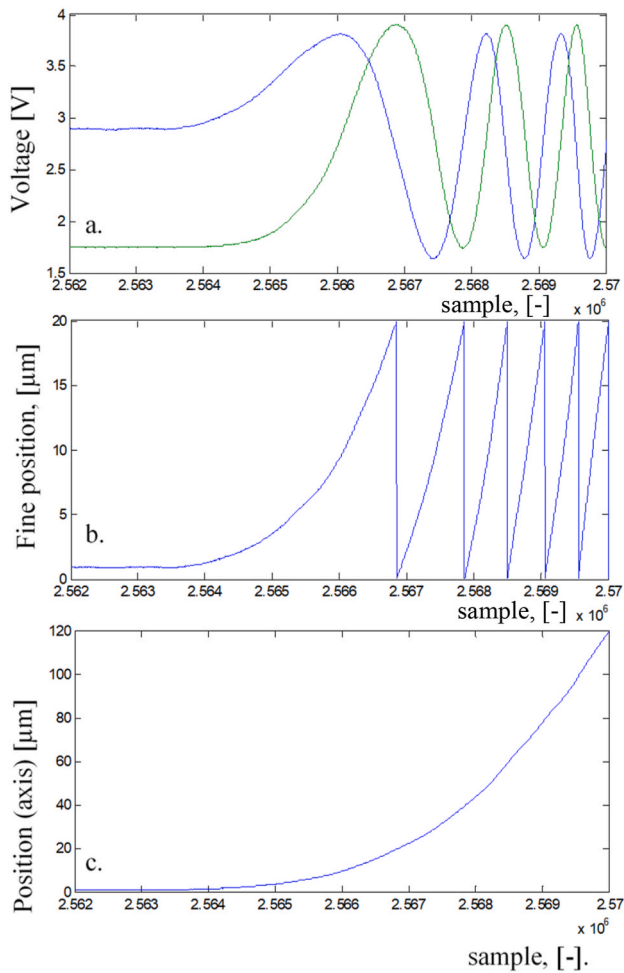

Fig. 3. Linear scale and its setup on the micro EDM machine.

possible.

3. Measurement extensions

To measure the milling process of the discharge machine, a linear encoder, a differential voltage measuring device, and a shunt resistance was used to extend the classical measuring solutions. The purpose of the experimental setup is to investigate the discharge properties and the machined surface statistically.

3.1. Machining environment

The experiments were carried out on a Sarix SX-100 high-precision micro EDM machine. A Tungsten-carbide electrode with a diameter of 0.1mm was used for the machining applying kerosene as dielectric.

3.2. Voltage measurement

Minimal energy discharges are applied during the micro-EDM machining. These charge values sometimes are in the range of the capacitance of the measuring instruments. This means that the measuring system affects the process itself. To reduce this effect, a HAMEG HZ100 type differential probe was used, which has an input capacity of only 1.2pF and 8MΩ resistivity.

3.3. Current measurement

The occurrence of discharge can be seen from the surge in current values. During the current measurement, it has to be ensured that the measurement did not increase the inductance of the system and only bring minimal parasitic capacity into the system. Consequently, a shunt resistor had been applied. The shunt resistance was 65 mV/25A. This resistance is 0.0024 Ohm, which has only minimal effect on discharge. The poles of the shunt resistor were connected to a HAMEG HZ105 differential probe. The noise of this measurement is relatively high, but in this case, the detection of the discharges was the primary purpose (not the description of the concrete signal curve).

3.4. Movement/position measurement

The movement of the machine was measured only on one axis (Y).

Fig. 4. a) Voltage-time signals of the two phases; b) Calculated fine position; c) Calculated position on the axis.

The movement in the X direction can be calculated due to the geometry restraints of the tool path. A Mitutoyo AT115 type linear encoder was used (Fig. 3), which has a pitch of 20 μm. This type is a sinusoidal one which gives the possibility to measure the displacement below the pitch size.

Based on the actual Y position, the X position can be calculated based on formula 1.

$$Y = X * \tan(10°) \tag{1}$$

The voltage of the two phases, the fine position and the calculated tool position can be seen in Fig. 4.

The fine position of the table can be calculated by the formula (2).

$$FPOS = DIV * \arctan\left(\frac{U_1}{U_2}\right) \tag{2}$$

Where *DIV* is the pitch of the encoder and U_1, U_2 are the voltages of the two phases.

The position of the tool on the tool path is calculated by equation (3).

$$POS = N * DIV + FPOS \tag{3}$$

N is the number of the pitches moved.

3.5. Data acquisition

The signals converted to voltage were acquired by a high-speed and high-resolution digitizer. The applied National Instruments USB-4431 instrument has 4 simultaneous channels, and each has a 24bit
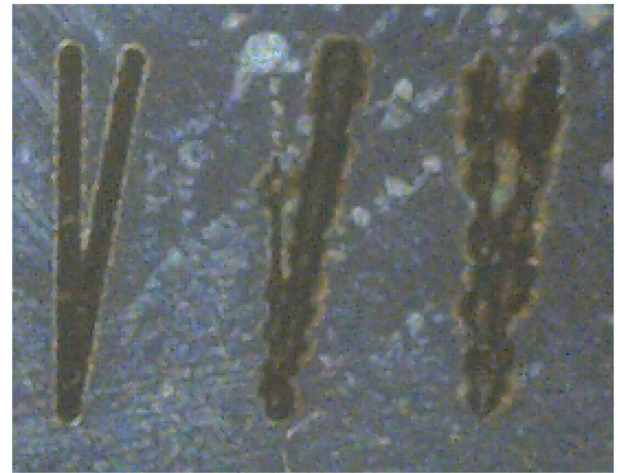

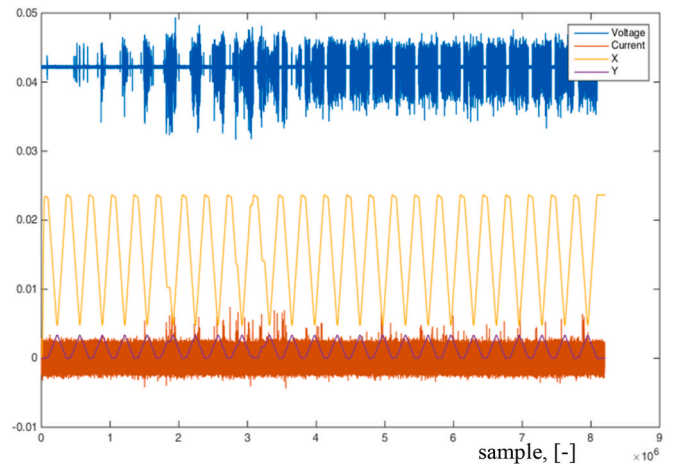**Fig. 5.** Prepared grooves on alumina oxide cermics with different EDM machining parameters.

Fig. 6. Position, voltage and current values for the machining of *many multilayers*.

digitizing resolution. *The measurements were carried out at 102.4 kHz.* The measurement was continuous, which generated a large amount of data. Real-time processing was unnecessary, therefore, the acquisition control PC just collected the data for further offline processing. The acquired data were processed by developed LabView and Matlab algorithms.

4. Experimental results

After completion of the really exciting experiments, *visible differences can be observed on the machined grooves.* Fig. 5 shows some of the resulted V-shapes. The shape on the left had a stable discharge process, as confirmed by microscopic recording as well. In the second case in the middle, the process became unstable, it only rarely discharged on the vertical stem. In the third case, the process takes place, but several break-ups (resulting many burning-in stages) can be observed on the edges of the grooves. *It clearly represents that the machining is on the border of feasibility and here the selection of the appropriate machining parameters and the related diagnostics requires especial attention. The paper reported on the established measurement basis for enabling this requirement.*

Fig. 6 shows the position, voltage, and current values, where it can be seen that, on the first layers, fewer discharges occurred, and later, more sudden current jumps can be observed. *An important and promising result is that the signal values are synchonised* on this high frequency enabling
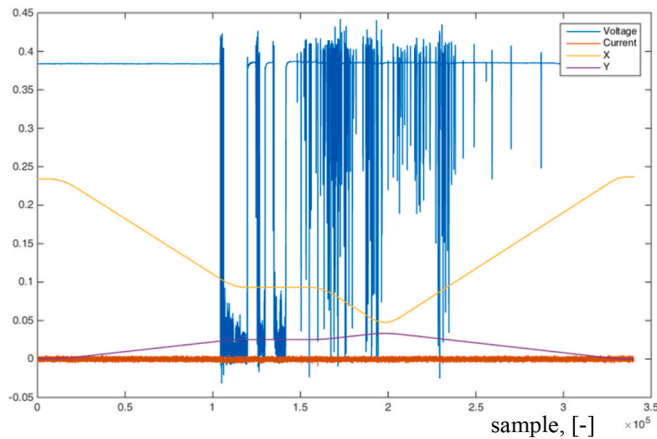
Fig. 7. Position, voltage and current for the machining of *one layer*.

the later established, more sophicticated analysis, diagnostics and control that is an extremely difficult assignment in this border field of micro-EDM machining of cermics.

In Fig. 7., machining of one layer is represented. *The introduced measurement solution mirrored well the instablities and uncertainties during the progress of the supervised micro-EDM process, consequently, it enables the realisation of appropriate diagnostics and later, the control as well.*

5. Conclusions

The paper introduced an extended measuring system of a micro discharge milling machine equipped with a linear encoder, voltage, and current sensors. With the help of the installed measuring system, the ceramic discharge milling of the Al_2O_3–TiC mixture was tested, in particular, the process stability, the geometric transient zones and the edges of the machined grooves. Analyses have shown that even having individual discharge events between 100 and 200kHz during micro electrical discharge milling, a measurement sampling frequency of 102kHz is sufficient. As a result, a system for subsequent process measurement and processing has been established. The proposed measuring system can assign the individual discharge events to the concrete place on the workpiece. The data obtained from the prepared system was used to develop optimization algorithms, too.

Acknowledgments

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