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Machinability of ZTA-TiC ceramics by electrical discharge drilling

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Abstract

Electric discharge machining of ceramics becomes principally feasible if the ceramic material has a sufficiently high electric conductivity. This can be achieved by adding transition metal carbides, borides or nitrides such as titanium carbide. In case of electric discharge drilling the small electrode dimensions lead to higher current densities compared to die sinking. In order to avoid bursting of the ceramics by thermal shock machining parameters have to be well adjusted and the material should have a high thermal conductivity. A parameter study was carried out to observe the removal behavior depending on machine parameters such as discharge energy, pulse form and flushing conditions.

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Keywords: ZTA-TiC; electrical discharge drilling, pulse form, flushing conditions, discharge energy

1. Introduction

High performance ceramics are well known for their outstanding wear resistance and are therefore suitable for high wear applications in all kind of industrial fields. Especially moulds and dies that are used for processing of abrasive materials require tools with high hardness to withstand the occurring loads. In order to enable an economical production of ceramic components with low quantities for mould or die inserts with fine structures and sharp inner edges EDM (Electrical Discharge Machining) is the only applicable machining process. According to König et al. for EDM an electrical conductivity of at least 1 Sm^{-1} has to be exceeded. Recent work by the authors [1, 2] has shown that electrically conductive ZTA-TiC ceramics with high wear resistance can be machined by die sinking and Wire-EDM in a stable process with high accuracy. In order to thread the wire electrode through the work piece EDM drilling is mostly used to create the required initial holes. Due to the small electrode dimensions higher current densities occur during EDM drilling compared to die sinking. In order to avoid bursting of the ceramics by thermal shock, machining parameters have to be well adjusted and the material should have a high thermal conductivity. A parameter study was carried out to observe the removal behavior depending on machine parameters such as discharge current, discharge time, pulse form and flushing conditions.

2. Experimental

This study focuses on ZTA-TiC ceramics consisting of an alumina matrix (APA0.5, Ceralox, USA), 24 vol-% titanium carbide (STD120, H.C. Starck, Germany) as electrically conductive phase and 17 vol-% zirconia stabilized with 1.5 mol-% yttria. The yttria content was adjusted by mixing monoclinic zirconia (TZ0, Tosoh, Japan) and tetragonal zirconia particles stabilized with 3 mol-% yttria (TZ-3YS-E, Tosoh, Japan) according to the mixing route by Basu et al. [3]. The starting powders were attrition milled with zirconia milling balls and sieved after drying. Samples with a diameter of 45 mm and height of 10 mm were hot pressed at 1525 °C. Mechanical and electrical characterization is shown at [1]. Material properties are listed in Table 1.

Table 1. Material properties of ZTA-TiC composite [1]

Material properties	Average value	+/-
3-point bending strength σ [MPa]	1050	135

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Hardness HV10 [kp]	1960	69
Rel. density [%]	99,14	0,47
Indentation toughness [$MPam^{0.5}$]	6,06	0,1
Electrical conductivity [Sm^{-1}]	4932	-
Thermal conductivity (RT) [W/mK]	18,5	-

EDM drilling tests were performed on an electrical discharge machine for initial drill holes (SLPR 1200-600, bes Funkenerosion GmbH, Germany) The combination of pump, flow rate sensor, control valve and pressure gauge enables a constant volumetric flow rate of the dielectric flushing medium to maintain stable gap conditions [4]. Copper tube electrodes (Typ-D) with a diameter of 2 mm exhibit two flushing canals separated by a centered bar that prevents the forming of a button at the bottom of the hole [4]. IME 63 (oelheld GmbH, Germany) was used as oil based dielectric fluid with a disruptive discharge voltage of 58 kV at 2.5 mm. In this study rectangular and triangular pulses were investigated. Theoretical feed rates v_{theor} which are referred to in the text are calculated by dividing of the actual feed rate v_{act} by the proportion of effective pulses p_{eff} (equation 1). Surface roughness was analyzed by tactile measurements (Perthometer, Mahr, Germany).

$$v_{theor} = \frac{v_{act}}{p_{eff}} \cdot 100\% \qquad (1)$$

3. Results and Discussion

In order to increase material removal rate and feed rate the discharge energy, and therefore the electrical energy that can be converted into thermal energy, can be increased by increasing discharge current i_e and discharge time t_e. The energy also depends on the pulse form and the voltage according to equation (2). Discharge voltage depends on electrode material, dielectric fluid and gap width but is usually approximately 20 V high [5].

$$W_e = \int_0^t u_e(t) \cdot i_e(t) dt \qquad (2)$$

The following results show the influence of pulse form, discharge current, discharge time and volumetric flow rate of the dielectric fluid on machining results.

3.1. Rectangular pulses

In a first step rectangular pulses were used to machine the ceramic sample (see fig. 1). Machining parameters used for these first investigations are listed in table 2.

Table 2. Machining parameter for tests with rectangular pulses

Material properties	Value	Unit
Starting voltage U_Z	130	V
Dielectric flow rate q	6	l/h
Duty factor τ	74	%
Discharge time t_e	40	µs

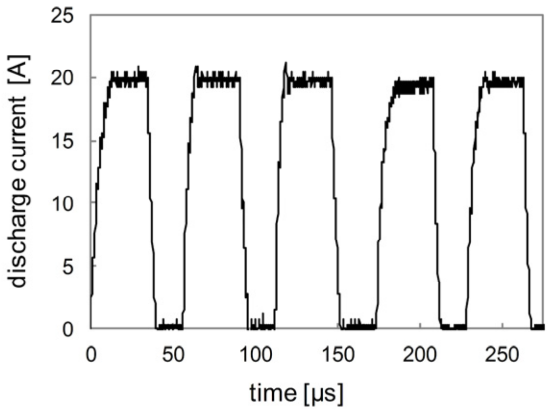

Fig. 1. Rectangular pulse shape of electrical discharges with discharge current of i_e = 20 A

Fig. 2 shows the theoretical feed rates for discharge currents from 5 to 25 A. As expected increasing the discharge current leads to an almost linear increase of the theoretical feed rate. At currents of i_e = 20 A and above spalling of material occurs at the surface. Considering the material removal mechanisms in die sinking of ZTA-TiC [1], which are melting, vaporization and spalling of resolidified molten material, the increasing of discharge energy combined with higher current densities in EDM drilling adds spalling of unmolten material to these removal mechanisms. As already reported by Lauwers [6] high discharge energies lead to creation of micro cracks. In combination with thermal cycling due to the electrical discharges these cracks result in uncontrolled spalling of material at the surface. EDM drilling with higher discharge time (60 µs) at a discharge current of 15 A and therefore also higher discharge energy equally leads to spalling of the sample on its surface, which correlates with the assumption made. The difference in the removal mechanisms between 15 and 20 A leads to an increase in mean roughness index from R_a = 2,05 µm to R_a = 7,16 µm respectively and also can be seen in SEM images of the surface (fig. 3).

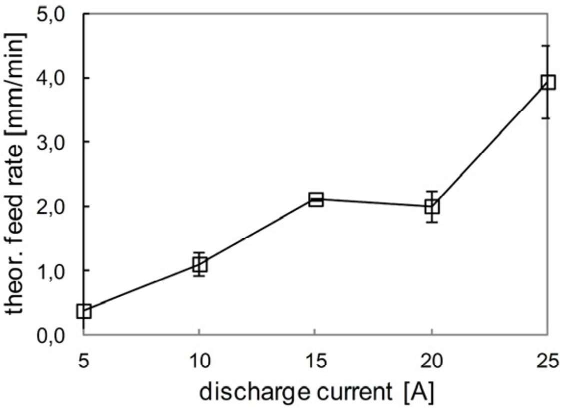

Fig. 2. Theoretical feed rate depending on discharge current for EDM drilling of ZTA-TiC with rectangular pulses

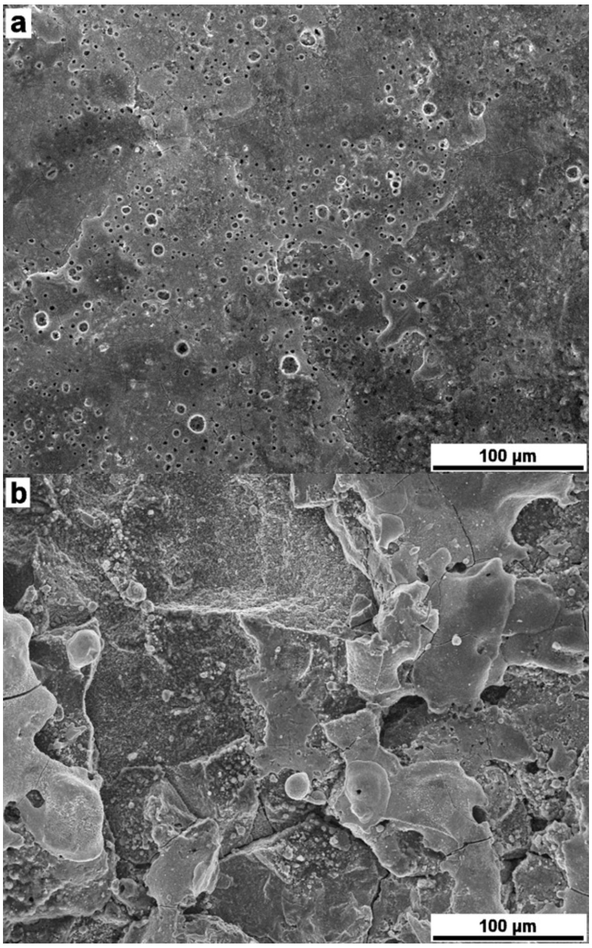

Fig. 3. SEM image of ceramic surface after EDM drilling with rectangular pulses, t_e = 40 µs and (a) i_e = 15 A and (b) i_e = 20 A

3.2. Triangular pulses

Triangular pulses were investigated besides rectangular pulses to reduce the energy of each single discharge, to slow down the heating rate of the work piece material and to delay the current drop. The pulse shapes of these investigations are shown in fig. 4.

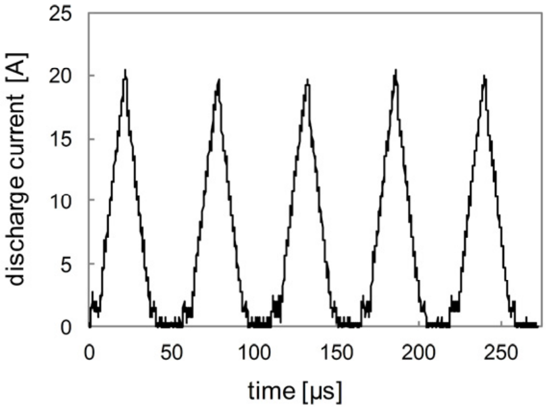

Fig. 4. Triangular pulse shape of electrical discharges with i_e = 20 A, U_Z = 130 V, t_e = 40 µs, τ = 74 % and q = 4 l/h

In initial tests starting voltage and discharge current were kept constant at 130 V and 15 A respectively. Discharge time was varied from 40 µs to 120 µs for the triangular pulses in steps of 20 µs. According to equation (2) the discharge energies were calculated for rectangular and triangular pulses for these altering discharge times. The results exhibited in fig. 5 show that the energy of one rectangular discharge with a discharge time of 60 µs is about as high as the energy of a triangular pulse with a discharge time of 120 µs.

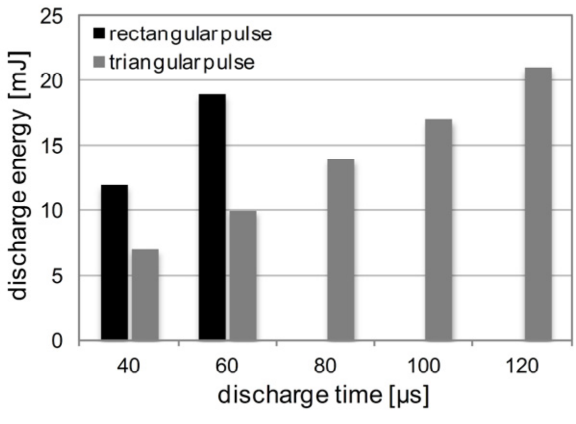

Fig. 5. Discharge energy for different pulse shapes with discharge current i_e = 15 A and starting voltage U_Z = 130

Fig. 6 shows the machining results of these investigations. First of all it has to be mentioned that no spalling of material occurs for any of these parameters. Even the triangular pulses with highest discharge energy (t_e =120 µs) do not cause cracks that lead to spalling of material. Therefore not only the amount of energy that yields into the material by each discharge but also the resulting heating rate of the work piece plays a decisive role. The graphs show that theoretical feed rate rises from 1.1 mm/min at 40 µs to its maximum of 1.9 mm/min at 60 µs. Further increase of discharge time leads to decreasing theoretical feed rate to a nearly constant level of about 1.7 mm/min. The drill oversize due to secondary discharges at the lateral area of the hole decreases between 40 µs and 60 µs discharge time and increases from 60 µs to 120 µs. Due to higher discharge energies at longer discharge times the material removal rate has to increase according to literature [7]. Comparison of feed rate and drill oversize shows that after reaching a maximal feed rate at 60 µs an increase of discharge time also increases the amount of discharges in the lateral gap due to higher amount of debris in the dielectric fluid. These secondary discharges do not contribute to material removal at the frontal gap and therefore limit the theoretical feed rate. The actual feed rate (not shown here) decreases with higher amount of secondary discharges which makes this correlation between drill oversize and feed rate even more clearly.

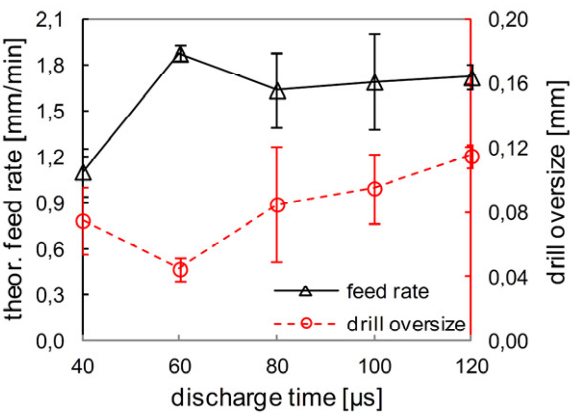

Fig. 6. Theoretical federate and drill oversize for discharge time from 40 µs to 120 µs with discharge current i_e = 15 A and starting voltage U_Z = 130 V

The influence of discharge current on theoretical feed rate and drill oversize is shown in fig. 7a. As expected the theoretical feed rate increases with increasing discharge current due to higher discharge energy. Drill oversize shows approximately the same trend as the feed rate which can be explained by the higher electrical conductivity of the dielectric fluid in the lateral gap due to higher contamination caused by higher material removal rates. The effect that secondary discharges limit the feed rate was not observed although the feed rate and therefore the material removed in the frontal gap is significantly higher for 25A and 40 µs than for 15 A and 120 µs. Considering the roughness of the machined samples (see fig. 7b) there is a clear shift of material removal mechanisms from melting and vaporization of material to spalling for highest discharge current (25A) that can explain the difference in feed rate for these machining parameters. At 20 A spalling was observed during machining on the sample surface, more precisely on the edge of the hole, but a closer look by means of SEM did not confirm this for the machined surface itself that is mainly generated by melting of material. Fig. 8 shows SEM images of the machined surfaces at 20 A and 25A. The difference in material removal mechanisms also can be seen in cross sections of samples machined with 20 A and 25 A in fig. 9. Machining with 20 A mainly leads to melting of the material which partly resolidifies on the surface in a thin layer and no creation of cracks can be observed. The remaining work piece material shows no indications for changes in the material composition and therefore constant material properties can be assumed during EDM process.

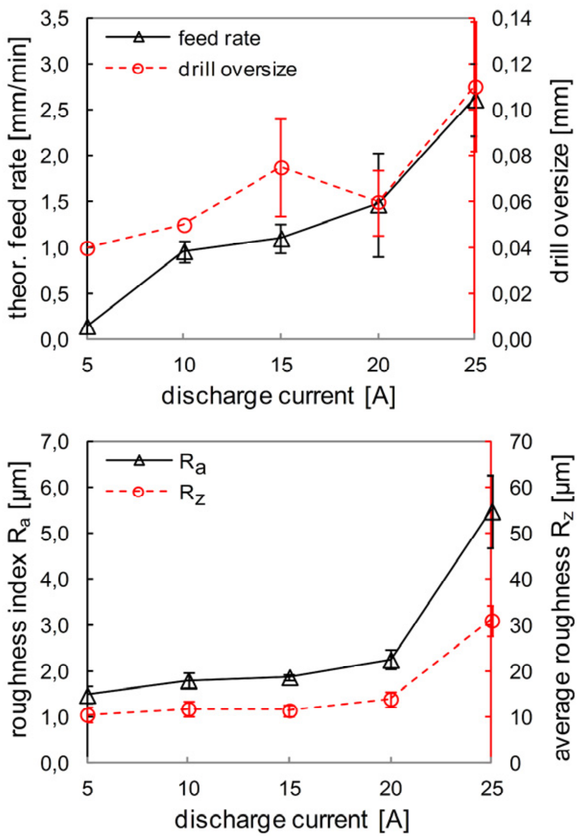

Fig. 7. (a) Theoretical federate and drill oversize; (b) mean roughness index R_a and average roughness R_z; for discharge current from 5 A to 25 A with discharge time t_e = 40 µs and starting voltage U_Z = 130 V

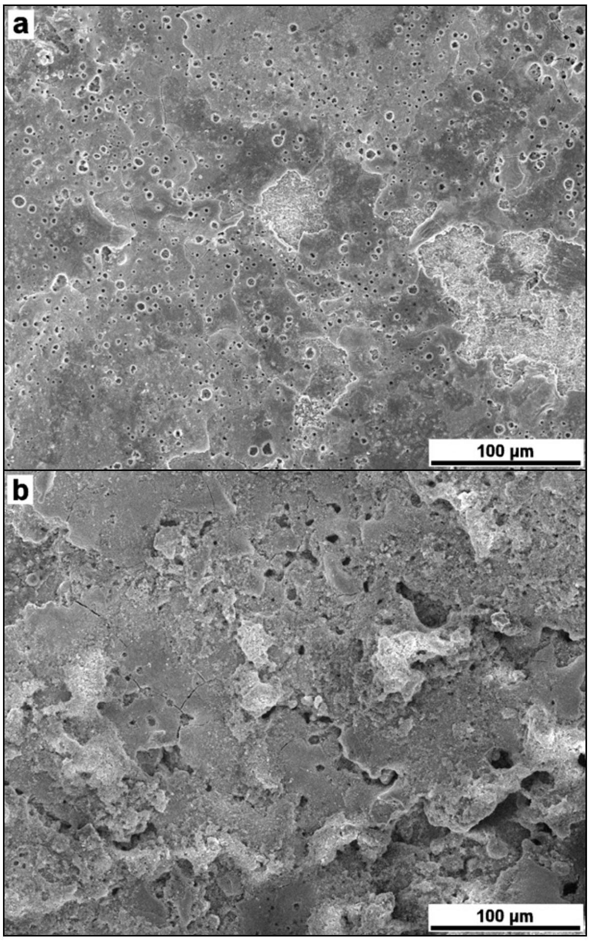

Fig. 8. SEM images of surface structure for samples machined with discharge time t_e = 40 µs and starting voltage U_Z = 130 V at (a) 20 A; (b) 25A

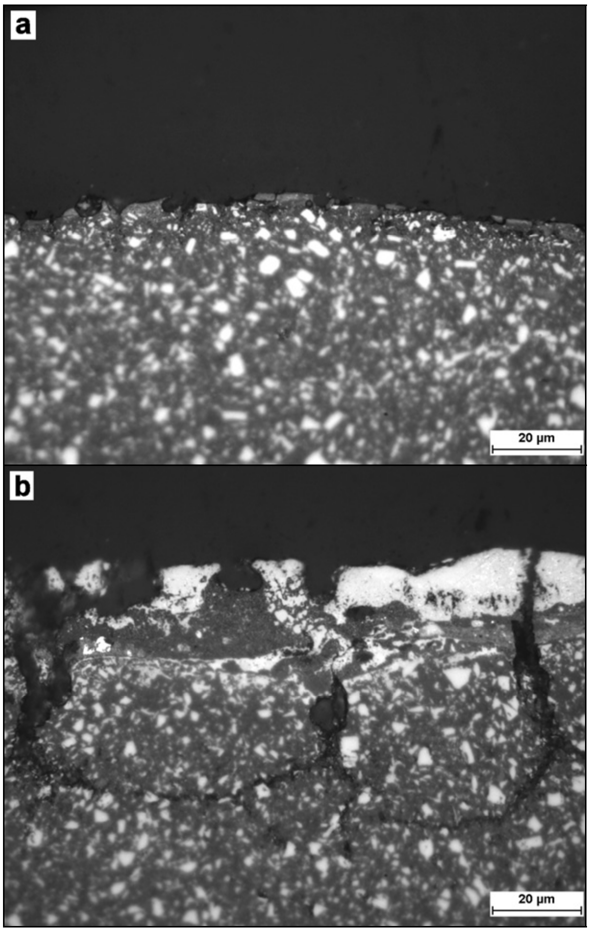

Fig. 9 Optical micrographs of cross sections; machined with discharge time t_e = 40 µs and starting voltage U_Z = 130 V at (a) 20 A; (b) 25A

Increasing the discharge energy by raising the discharge current up to 25 A results in the formation of a thick resolidified layer enriched with molten and resolidified titanium carbide. Deep cracks perpendicular to the surface occur due to high residual stresses induced by quenching of the molten layer during machining. After leaving the heat affected zone and reaching the unmodified zirconia toughened material, the cracks are deflected and continue in a parallel direction to the surface. As result of this effect large fractions of work piece material are chipping off the surface and leave a rough surface with a high amount of defects.

The absence of such a layer for lower discharge energies, one may assume, is due to the higher melting point of titanium carbide (3017°C) compared to alumina (2054°C) and zirconia (2677°C) [8]. Hence, for low discharge energies, the titanium carbide particles are removed by melting and vaporization of the surrounding matrix without changing the aggregate state of titanium carbide.

Besides discharge parameters the flushing conditions, especially for EDM of ceramics, have a significant influence on the EDM process [9]. Therefore the volumetric flow rate of the flushing medium was varied from 1 l/h to 6 l/h while discharge current, discharge time, starting Voltage and duty factor were kept constant at i_e = 15 A, t_e = 60 µs, U_z = 130 V and τ = 74 %. By this procedure the effects of flow rate on feed rate and drill oversize can be studied separately. Fig. 10 shows theoretical feed rate and drill oversize for these tests. Increasing volumetric flow rate leads to higher theoretical feed rates and decreasing drill oversize. By immediate removing of debris from the frontal and lateral gap high volumetric flow rates reduce the contamination of the dielectric fluid faster and thus increase its disruptive strength. Therefore secondary discharges in the lateral gap, which reduce the theoretical feed rate and increase the drill oversize, are inhibited and the discharges in the frontal gap are predominant leading to higher feed rates. Investigations of the surface by SEM images and roughness measurements have shown that the surface structure and therefore the material removal mechanisms are not affected by changing flushing conditions. Consequently the volumetric flow rate of the dielectric fluid has a strong influence on process stability and cost effectiveness of EDM drilling as well as on the accuracy of the machining process.

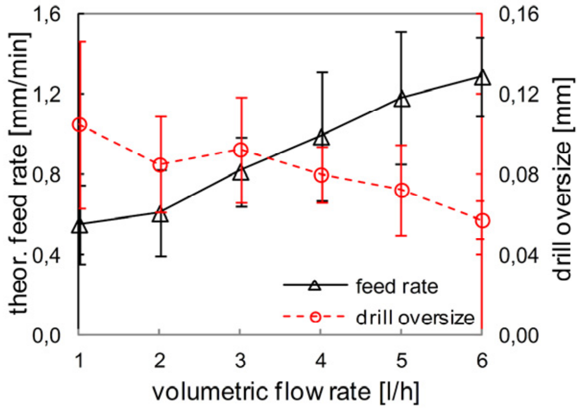

Fig. 10 Theoretical feed rate and drill oversize for volumetric flow rates of the dielectric fluid from 1 l/h to 6 l/h with i_e = 15 A, t_e = 60 µs, U_z = 130 V and τ = 74 %

4. Summary

In this study electrically conductive ceramic ZTA-TiC composites were machined by EDM drilling with variation of pulse shape, discharge current, discharge time and flushing conditions. The results show the strong influence of machining parameters on the machining quality, the economical performance and the accuracy of the EDM process. While high discharge energies driven into the ceramic material in a short amount of time may lead to spalling of material, an adequate adaption of the machining parameters results in a rather smooth surface structure without any cracks going into the work piece. Therefore triangular pulses with a discharge current of 20 A or lower are more suitable for EDM drilling of ZTA-TiC than rectangular pulses, since rectangular pulses do not allow a broad variation of parameters to adjust the parameters fine enough. The drill oversize and the feed rate during machining mainly depend on the correct flushing conditions controlled by the volumetric flow rate. It was shown that the volumetric flow rate has to be high enough to remove the debris in the dielectric fluid from the gap fast enough in order to increase the feed rate and decrease the drill oversize.

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