

Electrical Discharge Machining (EDM) of High-Performance Ceramics

Materials and Process Development for Wear Resistant Precision Tools with High Geometrical Complexity

Rainer Gadow, Richard Landfried and Frank Kern

Abstract Important and high value adding applications of modern structural ceramics are in the field of tools and dies in manufacturing engineering. That is, processing of highly abrasive materials in powder injection molding or extrusion requires mold materials with high wear resistance to increase the durability of the tools and to sustain a high quality of the manufactured products. High-performance ceramics, which exhibit high hardness, bending strength, and toughness, features the perfect combination of properties for these applications. Their drawback is that they cannot be economically customized in complex shapes and small lot sizes, as they are required in tool and mold design. Recent development of electrically conductive oxide ceramics enabled the use of EDM, the most used process for machining of hard materials, as an alternative to conventional ceramic manufacturing technologies. By combining the shaping and final machining of ceramics by EDM in one process step, complex shaped assemblies with fine structures, small tolerances, and the benefits of ceramic material properties can be produced. The focus is on ZTA-based ceramics with the addition of titanium carbide that can be machined by wire-EDM and die sinking. Mechanical and electrical properties of the materials as well as the characteristics of the machining process and its influence on the workpiece material are analyzed. Additionally, the feasibility of the ceramic material for tool inserts is shown by real wear tests in extrusion dies.

Keywords Ceramics · EDM · ZTA

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1 Introduction

Structural ceramics with high hardness, strength, and wear resistance are presently extensively used in the field of mechanical engineering, e.g., for cutting tools or wear resistant insert, besides which “classical” applications and biomedical applications are becoming increasingly interesting. Alumina-based ceramics due to their high hardness and moderate cost are the most important oxide materials, however the limited strength and fracture resistance of the materials restrict their use in applications requiring high damage tolerance. Improved fracture resistance of alumina can, among others, be achieved by the addition of a zirconia dispersion, this leads to the group of ZTA materials (zirconia toughened alumina) [1, 2]. A dispersion of tetragonal grains zirconia can, by stress induced phase associated by dilatation and shear, distinctly retard crack growth and thus increase the strength and fracture resistance while retaining the high hardness. Mechanical properties of ZTA materials can be tailored by variation of the zirconia content and its stabilization and by microstructural features resulting from changes in recipe and heat treatment conditions [3, 4].

EDM (electric discharge machining) is a machining technology which is today one of the state of the art machining processes for metals. The voltage in the gap between a tool electrode and workpiece is increased until the voltage exceeds the electric strength of the dielectric (either water or oil) in the gap. The high temperature in the resulting plasma channel and the cavitation associated with the breakdown of the plasma channel after shut down of the voltage leads to melting, evaporation, and spallation of workpiece material, which is subsequently flushed out of the gap by the flow of dielectric fluid. These discharges, having a scale of tens of micrometers, take place in the range of milliseconds and the total machining result is the superposition of the individual discharges [5, 6]. The most widespread EDM technologies are die sinking, where the tool electrode, typically made of copper or graphite, represents the mirror image of the structure to be machined and wire cutting, where the tool electrode is a thin metal wire describing a relative motion to the workpiece. Evidently, EDM processes require electrically conductive electrode materials, therefore, the ZTA materials for EDM processes are blended with a electrically conductive refractory carbide nitride or boride; in the present case, TiC which forms a percolating network and thus provides the electrical conductivity necessary for machining. The ZTA–TiC material, recently developed by the authors, features high strength and hardness combined with moderate fracture resistance and most importantly, a good ED-machinability [7, 8]. It has been shown by the authors that the machined surfaces have no glassy or foamy layer and show no damage to the bulk material by machining in contrary to most other ED-machinable engineering ceramics such as Si_3N_4 -TiN or Y-TZP-TiN [9, 10]. Thus, workpieces can be machined with high accuracy and without a drop in mechanical strength. In the present paper, structural and mechanical features of the ZTA–TiC materials and the machined surfaces are described and some examples given relating to the application of this ED-machinable material.

2 Materials and Methods

2.1 Ceramics Manufacturing and Characterization

The starting powders for the manufacturing of ZTA–TiC are submicron-size alumina (APA 0.5, $S_{\text{BET}} = 8 \text{ m}^2/\text{g}$; Ceralox, Tuscon, AZ) and 17 vol % 1.5Y-TZP. The yttria content of 1.5 mol % was adjusted according to the “mixing route” by using partially stabilized TZ-3YS-E ($S_{\text{BET}} = 7 \text{ m}^2/\text{g}$; Tosoh, Tokyo, and Japan) and monoclinic TZ-0 ($S_{\text{BET}} = 15 \text{ m}^2/\text{g}$; Tosoh). The electrically conducting TiC dispersion was a microsize TiC (HC Starck, STD120, and $d_{50} = 2.3 \text{ }\mu\text{m}$). The feedstocks were produced by mixing and milling of the starting powders in 2-propanol for 2 h in an attrition mill using Y-TZP milling balls. After milling, the solvent was evaporated and the feedstocks dried and screened through a 100 μm mesh [7]. Samples for characterization and blanks for ED-machining were produced by hot pressing in graphite dies of 40–50 mm diameter at 40 MPa axial pressure for 2 h in vacuum (FCT Anlagenbau, Germany). For mechanical characterization, disks of 2.5 mm thickness were lapped and polished on both sides to a mirror-like finish and cut into bending bars of 4 mm width. Bending strength was determined in a 3-pt setup with 15 mm outer span (Zwick, Germany). Fracture resistance was measured by direct crack length measurement of HV10 indents using the Niihara model [7,11]. Moreover, Vickers hardness HV10 (Bareiss, Germany) and elastic modulus (IMCE, Belgium) were measured. The microstructure of the materials and machined surfaces was investigated by SEM (Zeiss Gemini, Germany) and optical microscopy (Leitz, Germany); the surface roughness of machined materials was determined by tactile method (Mahr Perthometer, Germany). Electrical resistivity was measured on at least three $2 \times 4 \text{ mm}$ bars in 4-pt measurement (Keithley, Multimeter 2750, USA).

2.2 ED-Machining

Machining testes were carried out with different machines. Basic EDM tests to validate the machinability were performed by die sinking (Elbomat, AEG, Germany) with fixed parameters: a starting voltage of $u = 150 \text{ V}$, a discharge duration of $t_e = 5 \text{ }\mu\text{s}$, and a discharge current of $i_{e.} = 10 \text{ A}$ in IonoPlus (Oelheld, Germany). Further, die sinking experiments were carried out on Form 1000 (Agie Charmilles, Switzerland) using a discharge duration of $t_e = 10 \text{ }\mu\text{s}$ and a discharge current of $i_{e.} = 10 \text{ A}$, $t_0 = 24 \text{ }\mu\text{s}$. Wire-EDM with a brass wire coated with zinc ($\varnothing = 0.1 \text{ mm}$) was performed by Agie Charmilles SA (Losone, Switzerland) using a CUT1000 OilTech (Agie Charmilles, Switzerland). The parameters were set for highest feed rate.

2.3 Wear Test

In order to investigate the wear resistance, a field test comparable to real conditions in a injection molding or extrusion die was done using a split die of $4 \times 4 \text{ mm}^2$ diameter mounted on a twin screw extruder (ThermoElectron, Germany). One half of the die was made of ED-machined ZTA–TiC and the other half was made of hardened steel. For 20 h, a thermoplastic paste for LPS–SiC consisting of 66 m-% sub-micrometer size SiC powder, 7 m-% Y_2O_3 , 5 m-% Al_2O_3 , and 22 m% binder (Icomont 583G, EMBE, Germany) was extruded through the die, the wear of the ZTA–TiC, and its metallic counterpart was measured every 5 h.

3 Results and Discussion

3.1 Mechanical Properties

The mechanical and electrical properties determined for the hot pressed ZTA–TiC are listed in Table 1 [7]:

The material feature hardness and Young’s modulus value were comparable to ultrafine alumina. Moreover, a high strength and moderate fracture resistance. The electric conductivity is several orders of magnitude higher than the minimum value for EDM defined by Koenig [5].

The microstructure of the polished surface of ZTA–TiC is shown in Fig. 1. Dark gray grains are alumina light gray grains TiC and white grains are zirconia. Sub- μm size zirconia grains and 1–2 μm size TiC grains are embedded in the alumina matrix which has an average grain size of $\sim 1 \mu\text{m}$. The structure is fully dense, which is in good accord with measured theoretical density of $> 99 \%$.

3.2 Properties of ED-Machined Surfaces

An optical micrograph of a polished cross section through an ED-machined surface (die sinking) is shown in Fig. 2.

Table 1 Mechanical and electrical properties of ZTA–TiC

Property	Value	Unit
Vickers hardness HV10	1950	–
Young’s modulus E	400	GPa
Bending strength σ_{3pt}	1050	MPa
Fracture resistance [11] K_{IND}	6.06	$\text{MPa}\sqrt{\text{m}}$
Electric conductivity	4900	S/m

Fig. 1 Microstructure of ZTA–TiC and SEM image

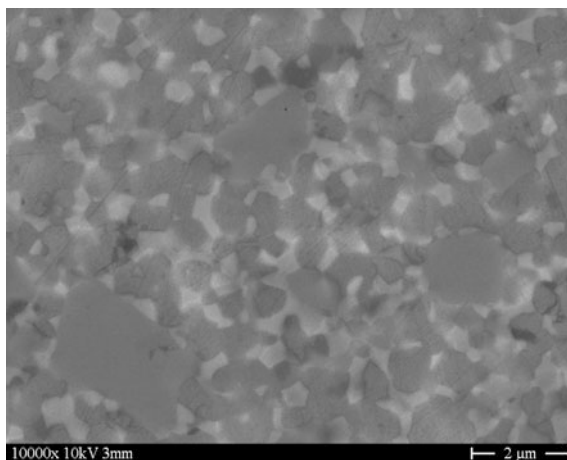
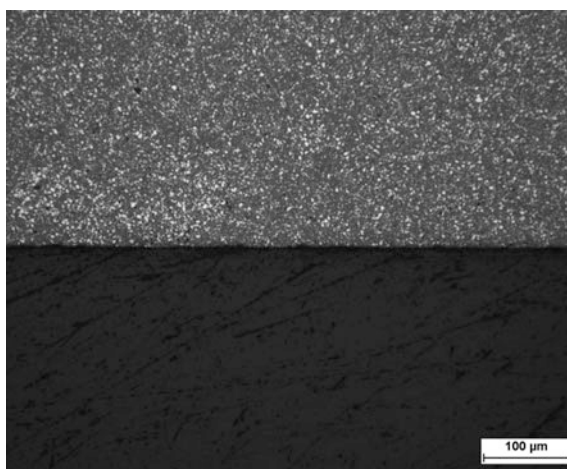


Fig. 2 Optical micrograph Cross section through a ZTA–TiC surface after die sinking



It can be clearly seen that the die sinking process does not leave any glassy layer on the top of the machined surface, the material removal leaves a clean surface which shows no difference to bulk material.

During the first machining step (roughing), best mean surface roughness values R_a of 0.4–2.5 μm can be obtained in die sinking depending on TiC grain size [12] and $R_a = 2.6 \mu\text{m}$ can be obtained in wire cutting [8]. The roughness obtained is strongly machine and parameter-dependent. By subsequent dressing steps, the roughness can be further reduced to values below 1 μm . Material removal rates depending on machine parameters and material composition can be as high as 2.5 mm/min [7, 12].

3.3 Wear Resistance Test

The validation of wear resistance was demonstrated by extruding a thermoplastic SiC paste simultaneously over a ZTA–TiC and hardened steel die. While the hardened steel, which was initially perfectly smooth ($R_a < 0.1 \mu\text{m}$), shows progressive deterioration over time and reaches a surface roughness of $R_a 0.3 \mu\text{m}$ after 5 h and $1 \mu\text{m}$ after 10 h the ZTA–TiC insert despite initially higher roughness of $R_a = 0.3 \mu\text{m}$ did not show any wear even after 20 h. The roughness stayed at this moderate level. The surface of the steel showed severe groves in the flow direction and some SiC grains embedded into the surface. The ceramic did not show changes in surface properties except for a slight polishing effect only visible in SEM.

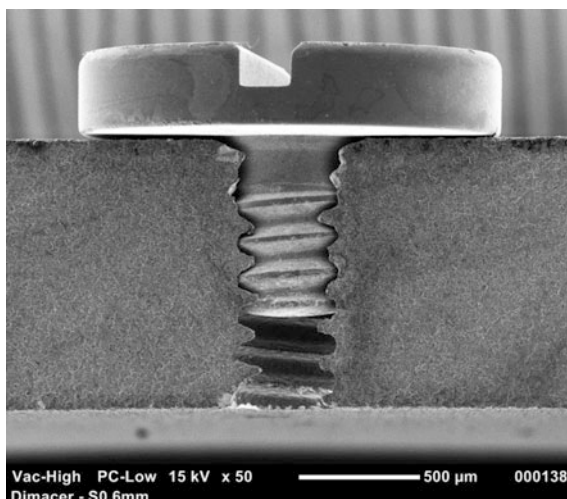
3.4 Application Examples

A complex shaped ED-machined mold insert for a inductively heated injection molding die is shown in Fig. 3. The outer diameter, if the component was manufactured by wire cutting, forms a blank with 50 mm diameter and 25 mm height. The structures in the front and back side of the component were manufactured by die sinking. The function of the component was to heat up a metallic inlay in situ by an inductor integrated in the rear part of the component and subsequently bond the heated metal part to polymer during the mold filling process in injection molding with the aim to improve the adhesion strength of metals and polymer [13]. The component was integrated into a steel mold. Due to the relatively high CTE of the ZTA–TiC material ($> 8 \times 10^{-6} \text{ K}^{-1}$), it has a good thermal match in combination with steel. Another example for a geometry which is impossible to produce by conventional hard machining is given in Fig. 4. It shows a $200 \mu\text{m}$ fine pitch thread cut into a ZTA–TiC plate of $600 \mu\text{m}$ thickness by ED-milling. Some other

Fig. 3 ED-machined ZTA–TiC mold insert for injection molding, diameter 40 mm [13]



Fig. 4 200 μm fine pitch thread manufactured by ED-milling in ZTA–TiC [14]



components not shown here were wear resistant mold inserts for injection molding of glass-fiber filled polymers, to improve the durability of the molds and ensure the dimensional accuracy of the molded components in mass production processes.

4 Summary

ZTA–TiC ceramics produced by hot pressing offers attractive mechanical properties such as high strength and hardness together with a sufficient fracture resistance to be applied as wear resistant mold inserts. The relatively low amount of electrically conductive phase is sufficient to ensure machinability with feed rates similar to metals. The material removal proceeds down to the bulk of the material without leaving a glassy layer on top of the machined surface. Due to the absence of cracks, perpendicular to the surface the machined parts retain their high strength. The feasibility of the concept was proven in different applications. ED-machining of ceramics enables manufacturing of complex customized ceramic parts at high accuracy and surface quality which are either impossible to manufacture by conventional technologies or only at high cost due to their geometrical features. From the viewpoint of ceramics manufacturing, near net shape forming processes are only economical for high number of items. In case of purpose built items such as mold inserts or machinery components which are produced in small numbers, EDM enables economical manufacturing.

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