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Zirconium dioxide-reinforced aluminium oxide ceramic for micro-milling of graphite

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Abstract
Tool and mould making is one of the most important sectors for production of complex parts with highest economic efficiency. Particularly the milling process is a key technology for the manufacturing of tool electrodes for electrical discharge machining (EDM). Beside copper, graphite is the most industrial relevant tool electrode material for sinking-EDM. According to the state of the art the machining of graphite results in high tool wear in consequence of strong chemical and abrasive effects. Currently, uncoated and cost intensive diamond coated cemented carbide tools are used for industrial applications. High tool costs and short tool life have a negative impact on the economic efficiency of the manufacturing process and increase the overall production costs. To reduce the production costs, the needs for innovative cutting materials and dedicated manufacturing processes are high. The zirconium dioxide-reinforced aluminium oxide ceramic used in this investigation shows a great potential because of the high hardness H, the missing binder phase and the covalent bond. The aim of this investigation is the examination of the application behaviour of ceramic cutting tools during the machining process of graphite. Therefore, dedicated milling tests in partial and full cut were carried out. For evaluation of the application behaviour of the ceramic tools, the surface quality of the machined graphite depending on the wear of the tools was considered. The results show that a minimum surface roughness of Ra = 0.80 µm and average surface roughness of Rz = 6.55 µm could be achieved in first milling tests. Due to a strong sharpening effect of the cutting edge during the machining, the possibility was provided to produce complex components with highest precision and without chipping behaviour. The machining of graphite using ceramic milling tools shows extensive advantages compared to conventional milling tools, which may positively affect the economic efficiency of machining graphite in the future.

Keywords: ceramic, cutting tools, milling, graphite

1. Introduction

For the production of complex parts with highest economic efficiency the tool and mould making belongs to one of the most important industrial sectors. For the manufacturing of tool electrodes for electrical discharge machining (EDM) copper and graphite represent the most common materials [1, 2]. According to the state of the art uncoated and diamond coated cemented carbide tools are applied for the machining of graphite. However, the use of these tools leads to high tool wear and reduced tool life times T_{St} in consequence of strong chemical and abrasive effects. This results in an early elution of the binder phase and a fast chipping of the coating, which leads to high tool and process costs as well as reduces the economic efficiency of the manufacturing process [3].

A promising approach to overcome the present challenges is the usage of a zirconium dioxide-reinforced aluminium oxide ceramic type AZ25PPr. The ceramic shows a great potential due to the high hardness H, the missing binder phase and the covalent bond. A previous scientific study demonstrates the high potential of this ceramic as cutting material [4]. To gain comprehensive knowledge about this ceramic and its characteristic, the application behaviour of the ceramic type AZ25PPr during the machining of graphite was investigated with milling tests in partial and full cut to determine the applicability of the tools in terms of surface quality and tool wear.

2. Experimental setup

2.1. Cutting material and geometry

Within this work, the application behaviour of ceramic cutting materials was investigated using cutting tools made of a zirconium dioxide-reinforced aluminium oxide ceramic type AZ25PPr, which is a chemical composition of aluminium oxide of $m_{C,Al}$ = 75 % and zirconium dioxide of $m_{C,ZrO2}$ = 25 %. The used ceramic tools were grinded by the company Hoppe Präzisionstechnik GmbH, Hoyerswerda, Germany, according to the state of the art and were provided with a parabolic radius transition, that positively influences the process characteristics and allows increased cutting parameters.

2.2. Testing methods and devices

For the experimental investigations of the application behaviour, the milling process was carried out on the 3-Axis-HP-machine Gamma 303 High Performance of the Wissner Gesellschaftfür Maschinenbau mbH, Göttingen, Germany. The measurement of the surface roughness Ra and Rz were realised by the surface metrology device MicroProf 100 of the FRT GmbH, Bergisch Gladbach, Germany. A non-contact measuring procedure with the profile method was performed on five different spots on each investigated surfaces [5]. To enable a suitable visualisation of the experimental results, the scanning electron microscope (SEM) JCM-5000 of the company Joel Neoscope, Akishima, prefecture Tokyo, Japan, was used. The maximum width of flank wear land VB_{max} was also measured with the SEM by computerised comparative analysis.

3. Experimental investigations

Within the investigations of the ceramic cutting materials, dedicated milling tests were carried out to evaluate the application behaviour of the tools and to define appropriate process parameter ranges. As workpiece material the graphite material type EDM-AF5, which is considered as a finishing graphite with an average grain size d_G < 1 µm as well as ceramic milling tools type AZ25PPr were applied. The tools have a diameter D = 4 mm, four cutting edges and a cutting edge length of l_{ce} = 7 mm. To evaluate the behaviour of the tools during the machining of graphite statistical Design of Experiments (DoE) was used. Included factors were the spindle speed n, the depth of cut a_p and the feed per tooth f_t. Each test series was repeated three times for statistical validation. Figure 1a) to Figure 1c) show the influence of the process parameters on the surface roughness Ra.

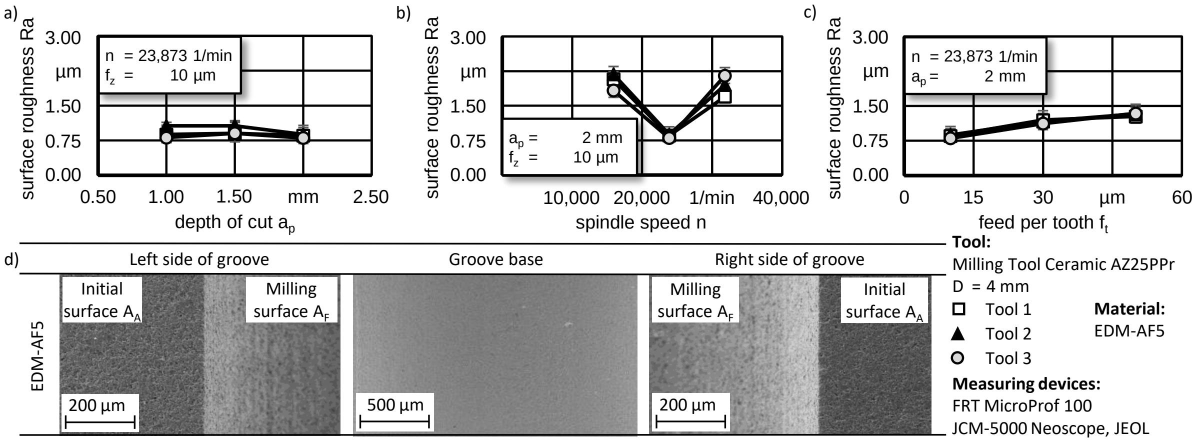

Figure 1. Results of dedicated milling tests a – c) surface roughness Ra depending on different parameters and d) SEM images of milled groove

Fundamentally, there is no influence of the depth of cut a_p on the surface roughness during the machining. The parameters feed per tooth f_t and spindle speed n show a significance.

As the feed per tooth f_t increases, the process force F_{Pr} also rises from F_{Pr} = 16.5 N to F_{Pr} = 25.7 N, which leads to an increased breakout behaviour of the workpiece and a reduced surface quality. The process forces F_{Pr} were recorded in all experiments with the 3-component-dynamometer type 9256B1 of the Kistler Instrumente AG, Winterthur, Germany. The surface roughness Ra is also affected by the spindle speed n. Highest surface quality of Ra = 0.80 µm and Rz = 6.55 µm could be achieved using a spindle speed of n = 23,873 1/min, a depth of cut of a_p = 2 mm and a feed per tooth of f_t = 10 µm. To visualise the results of the milled grooves, Figure 1 d) illustrates SEM images of the grooves. The shown surfaces indicate that a transcrystalline separation process was achieved during the machining of graphite. According to the results, the machining parameters which generated the highest surface quality will be used for further investigations. More experiments were carried out to identify the wear at the micro-geometries of the tools.

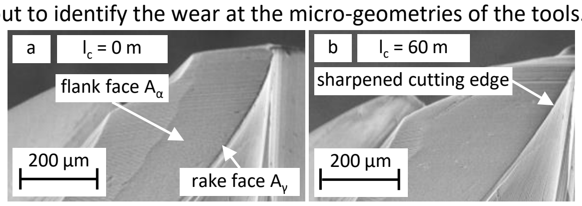

Figure 2. Sharpened cutting edge after machining of graphite

Therefore, dedicated milling experiments with ceramic milling tools of the type AZ25PPr in partial cut with a defined path length of l_c = 60 m were conducted. On all investigated ceramic tools, a significant increase in the wedge angle β_0 was observed over the path length l_c, which converges to a maximum from β_0 = 70.7° to β_0 = 83.2°. Furthermore, a strong increase of the cutting edge offset SV and the maximum width of flank wear land VB_{max} was found. With a path length of l_c = 60 m, a cutting edge offset of SV = 58.6 µm and a maximum width of flank wear land of VB_{max} = 510.2 µm could be identified. The findings also show a significant change at the tool micro-geometries after a path length of l_c = 60 m. During the machining of graphite, a reduction of the maximum chipping of the cutting edge starting from $R_{S,max}$ = 2.5 µm to a minimum value of $R_{S,max}$ = 1.3 µm could be observed. Further, a decrease of the rounded cutting edge radius of 50 % from r_β = 7.2 µm to r_β = 3.6 µm was found. In summary, it could be shown that a homogenisation of the cutting edges occurs which leads to a sharpening of the cutting edges during the machining process, see figure 2.

4. Conclusion and further investigations

The major objective was the evaluation of the application behaviour using an oxide ceramic type AZ25PPr for the machining of graphite. Based on the investigations, a suitable set of process parameters in the examined process area could be identified and shows a great applicability. Furthermore, it could be demonstrated for the machining of graphite that a positive effect on the wear behavior is achieved compared to CVD-coated tools used in the state of the art. Due to the significant improvement of the cutting edge micro-geometries, a sharpening effect occurs, which significantly enhances the surface quality. It was found that a transcrystalline separation process could be realised as a result of the sharpening effect with an increased surface quality of Ra = 0.64 µm and Rz = 5.22 µm. Figure 3 shows that the sharpening of the cutting edges allows components to be manufactured with highest precision, sharp edges and without chipping behaviour.

The findings show an excellent transferability to industrial applications. Based on the evaluated process parameters, complex and highly challenging structures could be produced.

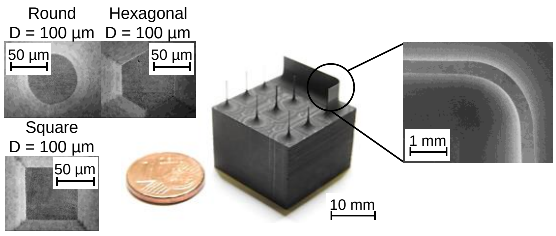

Figure 3. Graphite electrodes manufactured with ceramic milling tools type AZ25PPr with different shaped microstructures

With these conclusions, a recommendation may be given to apply the ceramic tools as roughing tools and to use CVD-coated tools in the finishing operation for the machining of graphite. This allows an extension of the application range and an increase in economic efficiency. In further investigations, the machining process will be examined in more detail and material-specific studies will be carried out. This work is supported by the funding program Zentrales Innovationsprogramm Mittelstand (ZIM) by the Federal Ministry for Economic Affairs and Energy (BMWI).

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