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Manufacturing of graphite electrodes with high geometrical requirements

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Abstract
Graphite is widely used for the die-sinking electrical discharge machining (EDM) process, especially for the roughing process. For the manufacturing of graphite electrodes the milling process is mainly used. The process enables fast processing times t_P and high geometrical flexibility. In consequence of the cutting behaviour of graphite micro-components with geometrical features can be manufactured. In this contribution the manufacturing of micro-pins and bridges with aspect ratios of A = 1:50 were machined with diamond coated milling tools. By variation of the depth of cut a_p and the width of cut a_e it can be shown that the influence of the depth of cut a_p is quite bigger than the influence of the width of cut a_e. This results in consequence of the higher stability of the geometrical features by improved force distribution.

Keywords: milling, graphite, component accuracy

1. Introduction

The electrical discharge machining is an appropriate process for the manufacturing of micro-geometries with high aspect ratios A and sharp corner geometries inside of pockets and channels. Therefore, electrodes made of materials with high electrical conductivity σ like tungsten copper or graphite are used [1, 2]. For the manufacturing of high-precision electrodes the micro-milling process is established. Especially, the cutting of graphite enables a fast manufacturing process. Nevertheless, the limits of the possible aspect ratios A, the reachable quality, and tolerances for the micro-milling process are not clear and need to be investigated.

In this contribution pins with hexagonal, square, and circle geometry and diameter in the range of $50\ \mu m \leq d \leq 150\ \mu m$ were manufactured. Furthermore, bridges with a width in the range of $50\ \mu m \leq b \leq 150\ \mu m$ were machined. The influence of the depth of cut a_p and the width of cut a_e were analysed and the limits for the size of the geometrical features depending on the process strategy were detected. Thereby, basic knowledge about the micro-manufacturing of graphite electrodes with critical geometrical features could be achieved.

2. Graphite

In comparison to the machining of ductile materials like steel or copper during the machining of brittle materials like graphite or glass no conventional chips occur. Furthermore, particles and grains of the machined materials break out individually or in combination. König [3] analysed the fracture behaviour during the cutting process of graphite with geometrical defined cutting edges. The investigations showed that the material removal is mainly caused by fractural breakage, which results in progressing crack fronts. These crack fronts act initially downwards before their distraction into the surface. Thereby, outbreaks below the cutting edges can be determined. Zhou et al. [4] analysed the crack behaviour during the high speed cutting (HSC) process with inserts. With the investigation of high speed camera pictures they identified chips, which were built of attached fragments of graphite particles. Furthermore, they divided the chip formation by varied depth of cut a_p in three major types: semi continuous chip, crushed particle chip, and fractured chip formation.

During graphite machining the removed graphite fragments lead to high tool wear [5, 6, 7]. Within the material removal the graphite fragments, which were removed by surface fatigue, slide along the rake face A_γ. A graphite shift of the suspended graphite grains is formed on the rake face A_γ and accelerated along the rake face A_γ during the cutting process. In that area increased wear can be determined [3].

3. Milling experiments

The experiments were carried out on a five-axes high precision machine tool MP7/5 from the company Exeron GmbH, Oberndorf, Germany. The machine tool has a spindle with a maximum spindle speed of n_{max} = 42,000 rpm, an acceleration of the linear axes $a \leq 10\ m/s^2$, and a control iTNC 530 HSCI FS of the company DR. JOHANNES HEIDENHAIN GmbH, Traunreut, Germany. Diamond coated milling tools with a tool diameter D = 3 mm of the type 63CWI03-DIP from the company HUFSCHMIED Zerspanungssysteme GmbH, Bobingen, Germany, were used. The ultrafine-grained graphite EDM1 with a grain diameter of $d_G \leq 1\ \mu m$ from the company Poco Graphite Inc., Decatur, Texas, USA, was used as workpiece material. Within each process a bridge with a length l = 10 mm and a height of h = 5 mm, as well as three pins with a height of h = 5 mm were machined. Thereby, the widths of the bridges were varied in the range of $50\ \mu m \leq b \leq 150\ \mu m$ in three steps and the diameters of the pins were varied in the range of $50\ \mu m \leq d \leq 150\ \mu m$. Furthermore, the pins were manufactured with round, square, and hexagonal geometry. Within the experiments a spindle speed of n = 20,000 rpm and a feed velocity of v_f = 600 mm/min were selected. The width of cut a_e and depth of cut a_p were varied with a_e = 0.2 mm and a_e = 1.0 mm as well as a_p = 0.2 mm and a_p = 1.0 mm as shown in table 1.

Table 1. Varied process parameters

Strategy	A	B	C	D
Width of cut a_e	1.0 mm	0.2 mm	0.2 mm	1.0 mm
Depth of cut a_p	0.2 mm	0.2 mm	1.0 mm	1.0 mm

The manufactured geometries were analysed with a scanning electron microscope (SEM) and an optical measurement device InfiniteFocus from the company ALICONA IMAGING GMBH, Raaba, Austria.

4. Results

With the chosen process strategies all bridges could be manufactured. Only for bridges with a width of b = 50 µm outbreaks of the corners were observed. These outbreaks occurred with each process strategy. The width b was measured with the InfiniteFocus and the results are shown in figure 1. It can be shown that the bridges with a width of b = 50 µm were machined with a deviation in the range of 10 % < Δb < 20 %, which can be explained with a decreased crack behaviour in front of the rounded cutting edges and a displacement of the bridges during the cutting process. For all other bridges a minimal deviation Δb in the area of the measurement failure could be observed.

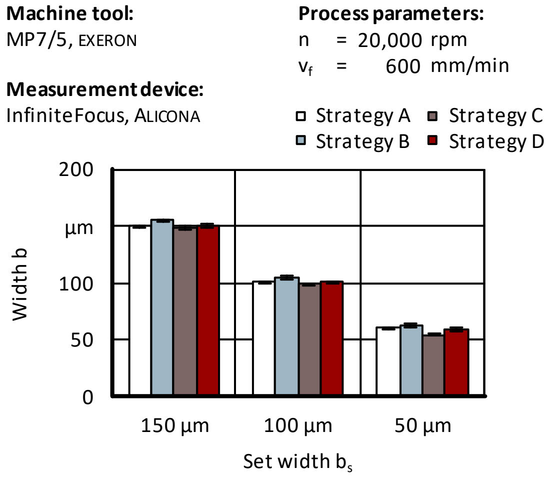

Figure 1. Width b of the bridges manufactured with the process strategies A, B, C and D

An overview of the manufactured pins with the corresponding strategy is given in table 2. The manufacturing of the pins with a diameter of d = 50 µm failed. The pins with a diameter of d = 100 µm could be manufactured with process strategy A and B. All pins with a diameter of d = 150 µm manufactured with strategy D were broken within the milling process.

Table 2. Overview of the manufactured or broken pins

Strategy	A	B	C	D
Pins with diameter d = 150 µm	✓	✓	✓	X
Pins with diameter d = 100 µm	✓	✓	X	X
Pins with diameter d = 50 µm	X	X	X	X
Legend	✓ manufactured		X broken	

Best results were achieved with strategy B with low depth of cut a_p and increased width of cut a_e. By increasing the depth of cut a_p the pressure p in horizontal direction is increased compared to low depth of cut a_p. With increased width of cut a_e the pressure p is conducted in vertical direction. Thereby, pins with high aspect ratio A, vertical walls, and complex geometry can be machined. In figure 2 the pins manufactured with strategy A are shown. It can be seen, that a high form accuracy a was reached and edge radii r < 10 µm could be machined.

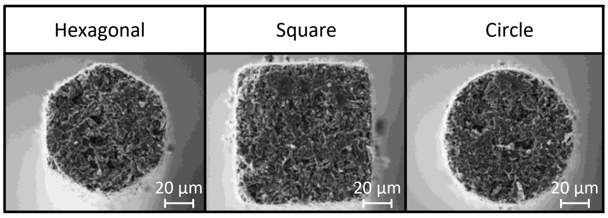

Figure 2. SEM-images of the pins with different geometries manufactured with strategy A

5. Conclusion

The manufacturing of graphite electrodes with high aspect ratio A, vertical walls, and complex geometries is time expensive and requires application-specific process strategies. In this investigation the manufacturing of complex small micro-geometries with high aspect ratio A was reached and pins with hexagonal, square, and circle geometry with vertical walls and a diameter d = 100 µm were manufactured. Furthermore, bridges with a width b = 100 µm, a length l = 10 mm and a height h = 5 mm were produced. The finishing process of a pin was realised in a process time t_P = 44 s with milling tools with a diameter of D = 3 mm.

In further investigations the manufacturing of geometries with an aspect ratio A = 1:100 will be analysed. Furthermore, the size of geometries will be decreased and the complexity will be increased. High potentials are given by the tool geometry, the tool diameter D, the graphite, as well as the process strategy.

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