euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
www.euspen.eu

Ultra-precision cutting of graphite materials for air bearing applications using single crystal diamonds

E. Uhlmann[1,2], M. Polte[1,2], T. Hocke[1,2], F. Felder[1]

[1]*Institute for Machine Tools and Factory Management IWF, Technische Universität Berlin, Germany*
[2]*Fraunhofer Institute for Production Systems and Design Technology IPK, Germany*

fabian.felder@iwf.tu-berlin.de

Abstract

In the field of non-contact bearing motor spindle systems for ultra-precision machining, graphite materials are increasingly focused for the use in complex aerostatic bearing components. The material-specific porosity of graphite enables the consistent distribution of air pressure throughout the bearing surface, which increase the axial and radial load-bearing capacity and stiffness. In order to ensure the functionality of the bearing components, low surface roughness values Ra ≤ 200 nm are essential. Based on the state of the art, uncoated tungsten carbide (WC) tools and polycrystalline Chemical Vapour Deposition (CVD) diamonds are conventional used cutting materials. However, these are characterised by high rounded cutting-edge radii and maximum chipping of the cutting-edges, which lead to increased surface roughnesses. For this purpose, single crystal diamonds (SCD) were used as a solution approach to enable the manufacturing of aerostatic bearing components made of graphite concerning the described requirements. Using SCD with rounded cutting-edge radii $r_\beta \leq 50$ nm leads to tensile stresses in surface-near boundary layers. Induced tensile stresses in brittle materials result in crack formation, which requires extensive investigations using SCD. In this study, the cutting behaviour of SCD for cutting of graphite materials concerning crack formation and breakout behaviour were analysed. Specific turning tests based on statistical DoE using an ultra-precision machine tool were carried out to analyse and quantify the impact of cutting speed, cutting depth, feed rate and rake angle on the surface roughness. First results show the influence of the selected process parameters in dependency to surface roughness as well as the potential of SCD tools for the machining of graphite. In this context, a lower surface roughness could be achieved compared to conventional used cutting materials made of tungsten carbide and CVD diamonds.

Keywords: graphite, single crystal diamond, ultra-precision machining

1. Introduction

Spindle technologies in machine tools based on aerostatic bearing systems show great potential for high- and ultra-precision manufacturing. This non-contact bearing technology is characterised by utilising a thin film of pressurised air in bearing gaps of $s_g < 10$ µm to ensure high rotational speeds s, dynamic stiffness and load capacity c_l. Therefore, components made of porous graphite are increasingly being used to provide a stable air flow through the bearing face and to distribute a constante pressurised air film. According to state of the art, uncoated tungsten carbide (WC) tools and poly-crystalline Chemical Vapour Deposition (CVD) diamonds were applied for machining graphite [1,2]. The use of these tools results in increased tool wear due to the abrasive effect of the graphite agglomerates [2]. In order to overcome the current challenges in the machining of graphite and to meet the requirements in manufacturing of air bearing components, the use of single crystal diamond (SCD) tools represents a promising approach due to its specific geometric and material properties. To gain fundamental knowledge for the machining of graphite using SCD, specific turning tests were carried out to identify suitable parameters and to compare the cutting performance with WC and CVD.

2. Experimental Setup

In order to identify the potential of SCD in graphite machining, experimental turning tests were carried out on the five-axis ultra-precision machine tool Moore Nanotech 350 FG of Moore Nanotechnology Systems, Swanzey, USA. The used materials were isotropic fine-grained graphites EDM-200, EDM-3 and EDM-AF5 of Poco Graphite, INC., Decatur, USA, which are widely used in electrical discharge machining (EDM) but can also be suitable for the use in aerostatic bearing components due to their permeability and specific properties (Table 1).

Table 1. Specific properties of the graphite materials

Parameter	EDM-200	EDM-3	EDM-AF5
Average grain size g_s	10.0 µm	< 5.0 µm	< 1.0 µm
Flexural strength σ_{bB}	55.8 MPa	91.7 MPa	99.9 Mpa
Compressive strength σ_d	96.5 MPa	124.8 Mpa	152.4 MPa
Shore hardness H_s	68.0	73.0	83.0

The used graphite specimen are characterised by a diameter of D = 50 mm and a height of H = 10 mm. For the turning tests, SCD tools with a corner radius $r_\varepsilon = 0.8$ mm, a rounded cutting edge radius $r_\beta \leq 50$ nm and a clearance angle $\alpha_0 = 10°$ of Contour Fine Tooling B.V., Valkenswaard, the Netherlands, were applied. The CVD tools type DCMW11T308 with a corner radius $r_\varepsilon = 0.8$ mm were provided by Mössner GmbH, Pforzheim, Germany. The WC tools type DCGT11T308-FN HU7315-1 with a corner radius of $r_\varepsilon = 0.8$ mm were purchased by Hoffmann SE, Munich, Germany. The surface roughness Ra was measured with a chromatic white light sensor MicroProf100 of Fries Research & Technology GmbH, Bergisch Gladbach, Germany.

3. Experimental investigations and results

In this study, the single-point turning of fine-grained graphite materials EDM-200, EDM-3 as well as EDM-AF5 using SCD were investigated. Subsequently, further tests were carried out to compare the cutting performance of SCD to conventionally used cutting materials such as uncoated WC and CVD diamonds.

3.1. SCD cutting experiments

To gain fundamental knowledge of the potential of SCD, a full factorial design of experiments was used to identify reliable parameters for achieving low surface roughness values Ra. The factor levels (Table 2) were aligned to conventionally used cutting parameters of roughing and finishing processes in ultra-precise SCD machining according to the state of the art [3].

Table 2. Factor levels for specific turning tests on graphite with SCD tools

Parameter	**Factor levels**
Cutting speed v_c	1 m/min $\leq v_c \leq$ 240 m/min
Feed rate f	2 µm $\leq f \leq$ 45 µm
Depth of cut a_p	1 µm $\leq a_p \leq$ 25 µm
Rake angle γ_0	-40° $\leq \gamma_0 \leq$ 8°

The test series were split in pre- and main-tests. The pre-tests were applied to identify the significance of each parameter and a suitable type of the investigated graphite materials. In the main-tests, suitable parameter ranges were achieved for a process-reliable manufacturing of graphite materials in terms of surface roughness Ra. The pre-tests showed that the surface roughness Ra is significantly dependent on the grain sizes g_s of the graphite materials used due to the random orientation of the agglomerates. Therefore, a high variation in mechanical strength could be proven [1,2]. These characteristics lead to an asymmetric breakout behaviour and reduced surface qualities. Based on this, EDM-AF5 with an average grain size of $g_s \leq 1$ µm could be identified as a suitable graphite material for further evaluations. The results of the main-tests show a significance for all analysed cutting parameters, whereby a major impact for feed rate f on the surface roughness Ra was determined (Figure 1). This correlates with previous research works [1,2,5].

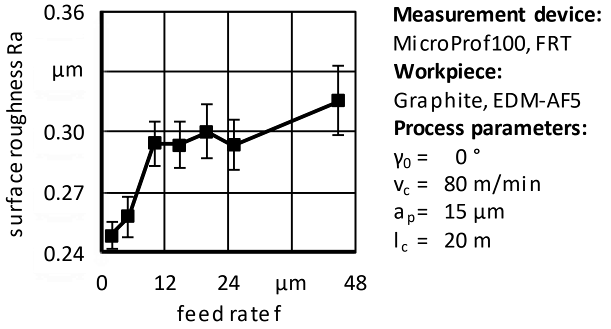

Figure 1. Surface roughness Ra as a function of different feed rates f

The results show that an increased feed rate f results in high surface roughnesses Ra. The lowest value of Ra = 0.249 µm was determined at the minimum investigated feed rate of f = 2 µm, whereby a roughness of Ra = 0.315 µm was identified for a maximum feed rate of f = 45 µm within the analysed process area. In a feed range of 5 µm $\leq f \leq$ 10 µm, the surface roughness increased quite intensely by 12.3 % to a value of Ra = 0.294 µm. For feed rates between 10 µm $\leq f \leq$ 25 µm, the roughness values remain constantly in a range of 0.293 µm $\leq$ Ra $\leq$ 0.300 µm. In comparison to this, the surface roughness Ra within a range of 2 µm $\leq f \leq$ 5 µm shows a sligth incline of 3.5 %. The findings reveal that the surface roughness Ra decreased, as the ratio of chip thickness to cutting edge radius is reduced towards $h(\varphi)/r_\beta \sim 1$. This can be attributed by the characteristic behaviour of brittle materials regarding the occurrence of micro-cracks in surface-near boundary layers due to induced tensile stresses σ [4]. Using SCD with a low cutting edge radius of $r_\beta \leq 50$ nm with decreasing feed rates f lead to reduced tensile stresses σ. Based on this, cracking effects only occur in the area of the cutting depth a_p used. Furthermore, it could be proven that a cutting speed of $v_c = 80$ m/min, a rake angle of $\gamma_0 = 0$ ° as well as a depth of cut of $a_p = 15$ µm lead to the lowest surface roughness Ra in the investigated process area (Figure 1). According to the results of the pre- and main-tests, these parameters in terms of a feed rate of f = 2 µm were used for further evaluation of the cutting performance using SCD.

3.2. Comparison to conventional cutting materials

In further tests, the cutting performance of SCD in turning EDM-AF5 was compared to the cutting materials CVD and uncoated WC in two test series. Firstly, specific parameters for CVD and uncoated WC according to the state of the art were applied [1,2]. In this process a minimum surface roughness of Ra = 0.390 µm for WC and Ra = 0.348 µm for CVD were identified. For the second test series, a direct comparison between the cutting materials was carried out using the same parameters and thus the same theoretical surface roughness depth R_{th} (Figure 2) [4,5].

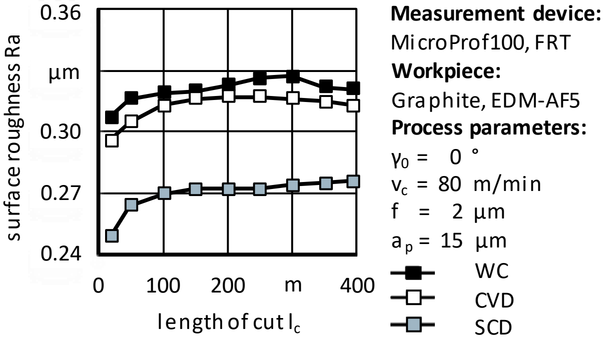

Figure 2 Surface roughness Ra as a function of constant cutting conditions for uncoated WC, CVD and SCD

The used parameters result in surface roughness values of Ra = 0.307 µm for WC and Ra = 0.296 µm for CVD after a cutting length $l_c = 20$ m compared to the parameters chosen according to the state of the art. However, a surface roughness of Ra = 0.249 µm was identified for SCD after $l_c = 20$ m. The findings show the differences in the performance of the used cutting materials regarding the machined surface roughness Ra. Using SCD for the machining of EDM-AF5 leads to a marginal increase of 7.3 % over a total cutting length of $l_c = 400$ m. This correlates to a decrease of 18.4 % in comparison to uncoated WC and of 14.8 % to CVD in terms of surface roughness Ra.

4. Conclusion and further investigations

The findings show that the surface roughness Ra significantly depends on the grain size g_s of the used graphite materials due to material specific properties. In this study, the lowest surface roughness of Ra = 0.249 µm was achieved by using SCD in turning fine-grained graphite type EDM-AF5. Therefore, a cutting speed $v_c = 80$ m/min, a feed rate f = 2 µm, a cutting depth $a_p = 15$ µm and a rake angle $\gamma_0 = 0$ ° were determined by statistical evaluation. The feed rate f was identified with a major effect on the surface roughness Ra, whereby the use of small feed rates f is recommended in turning of fine-grained graphites using SCD. It could be further proven, that the use of SCD in turning of EDM-AF5 allows the manufacturing of surface roughnesses Ra $\leq$ 0.249 µm and is potentially able to substitute conventionally used cutting materials such as WC and CVD. Further investigations address the optimisation of the process limits and the analysis of the wear behaviour of SCD. This work was funded by the GERMAN RESERCH FOUNDATION DFG.

References

[1] König M 1998 Fräsbearbeitung von Graphitelektroden *Diss. RWTH Aachen*.

[2] Almeida F.A, Sacramento J, Oliveira F.J, Silva R.F 2008 Micro- and nano-crystalline CVD diamond coated tools in the turning of EDM graphite *J. Surface & Coatings Technology* **203** 271-276

[3] Uhlmann E, Polte M, Rolon D.A., Kühne S 2019 Ultra-precision-milling of silicon by means of single crystal diamond tools *Euspen 19th international conference and exhibition*

[4] King, R. F, Tabor, D,The strength properties and frictional behavior of brittle solids *Proceed. of the Royal Society of London* **223** 225-238

[5] Brammertz P.H. 1961 Die Entstehung der Oberflächenrauheit beim Feindrehen. *Industrie-Anzeiger* 25-32