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Wear mechanism of single crystal diamonds in ultra-precision cutting of graphite for air bearing applications

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Abstract
In order to meet the continuously increasing function-determining requirements of complex precision components, advances in machine tool components are necessary in addition to technological developments. In this context, motorized spindles in particular show great potential for enabling further increases in accuracy. To achieve high stiffness and damping behaviour of spindle systems, aerostatic bearings made of graphite with bearing gaps $S_g < 10$ µm are gaining more importance in ultra-precision machine tools. To ensure the function of these bearing components, a low surface roughness Ra ≤ 10 nm and shape accuracies $a_S \leq 1$ µm are necessary. Regarding the state of the art, uncoated tungsten carbide tools, diamond coated carbide tools and thick film chemical vapour deposition (CVD) diamonds are used for cutting graphite materials. Cutting with these tools leads to asymmetric breakout behaviour of the graphite grains as well as high tool wear during machining, resulting in insufficient shape accuracies and surface qualities. A promising approach to overcome the current challenges for aerostatic bearing components made of graphite is the use of single crystal diamonds (SCD) with characteristic low rounded cutting edge radii $r_\beta \leq 20$ nm as well as cutting-edge waviness $w_a \leq 200$ nm. Besides the material-specific properties of the SCD, tool wear occurs during the cutting of graphite. For this purpose, the abrasive wear mechanism and surface attrition of SCD were analysed concerning specific blasting tests with defined time intervals of $60\ s \leq t_b \leq 3{,}000\ s$ and different process conditions. Furthermore, two types of graphite granulate with grain sizes in a range of $200\ µm \leq g_s \leq 400\ µm$ were used. First results show a dimensional loss of material on the investigated specimens made of SCD depending on the process conditions, whereby an influence of the surface attrition could be proven.

Keywords: abrasive tool wear, graphite cutting, single crystal diamond

1. Introduction

Ultra-precision (UP) cutting is a suitable technology for the manufacturing of aerostatic bearing components made of porous graphite materials. At state of the art, the machining of graphite components is carried out with uncoated as well as various diamond coated carbide tools. Using these types of tools leads to high tool wear and an asymmetric breakout behaviour of the machined workpieces made of graphite [1]. To meet the high requirements concerning the shape accuracies of $a_S \leq 1$ µm and surface roughnesses of Ra ≤ 10 nm, a transcrystalline cutting process is essential. Within UP-cutting, single crystal diamond (SCD) tools with rounded cutting edge radii of $r_\beta \leq 20$ nm are conventionally used [2]. Based on this, the rounded cutting edge radius r_β shows a major impact on the cutting process and the surface quality, whereby a transcrystalline cutting could be realised. According to the state of the art, the wear mechanisms of SCD tools for the machining of graphite materials is currently unknown. To gain fundamental knowledge about the interrelations between graphite and SCD, the wear mechanisms concerning abrasion and surface attrition were investigated. To obtain an isolated consideration of the wear mechanisms analogy tests with regard to blasting tests were carried out.

2. Experimental Setup

In order to identify the wear mechanisms concerning abrasion and surface attrition, blasting tests with two different types of graphite granulate were carried out. In this study the wear mechanisms were characterised through the analysis of the mass losses m_l and optical measurements of the investigated SCD tools. For blasting experiments, the graphite granulates GSI-OB and R7140H of the company Chemsys GmbH, Castrop Rauxel, Germany, with a grain size in a range of $200\ µm \leq g_s \leq 400\ µm$ were used as abrasive particles. The selection of the grain sizes g_s enables process reliable blasting conditions and leads to an increased tool load due to higher masses m and kinetic energies E_{kin}. GSI-OB is an extruded material with a higher grade of graphitisation g_G than the granulate type R7140H, mainly used as hardgraphite, which is grinded from isostatically pressed graphite parts. Based on this, the ash content c_a of GSI-OB is $c_a = 0{,}2$ %, whereby the ash content c_a of R7140H is $c_a = 2$%. These different material properties are based on different part of the ongoing investigation. For the specific blasting tests, four SCD tools with a corner radius $r_\varepsilon = 1.5$ mm, a rounded cutting edge radius $r_\beta \leq 20$ nm and a clearance angle $\alpha_0 = 10°$ of the company Contour Fine Tooling B.V., Valkenswaard, the Netherlands, were applied. The experiments were performed on the machine tool FSA-1 of the Sablux Technik AG, Bachenbülbach, Switzerland. The experimental setup and the used parameters were chosen according to the blasting tests carried out by Polte [3]. The granulate particles were accelerated through a pressure vessel with an inside diameter of $d_v = 4$ mm, a blasting pressure of $p_b = 0.6$ N/mm² and a volume particle flow of $\dot{V} = 5.5$ cm³/s. For the precise alignment of the granulate beam, a tungsten carbide nozzle with a bore diameter of $d_n = 2.5$ mm was used. The nozzle stand-off distance between the beam exit and the SCD rake face A_γ was $d_{so} = 7$ mm. For abrasion, a blasting incident angle $\alpha_b = 30°$ was choosen, whereby the experiments for surface attrition were carried out with a blasting incident angle $\alpha_b = 90°$.

To enable suitable visualisations of the experimental results as well as to analyse the morphology of the tool wear and graphite grains, the scanning electron microscope (SEM) LEO 1455 VP of LEICA ELECTRON OPTICS, Wetzlar, Germany, was used.

3. Experimental investigations and results

Within this study on wear behaviour of SCD tools concerning abrasive stresses and surface attrition, the graphite granulates GSI-OB and R7140H were applied. Fundamentally, abrasion is characterised by the interaction of several friction pairs with different hardnesses h. The tribological stress results from the penetration of one body into another. The surface attrition results through energetic, force- and stress related interactions that lead to material breakouts of the contacting areas [4]. To quantify the tool wear, the mass losses m_l of the SCD were subsequently measured with a precision scale PLS 1200-3A of KERN & SOHN GMBH, Balingen, Germany. In this context, the results of the mass detection show no significant mass losses m_l for the investigated SCD tools within the investigations. Figure 1 shows the results of the blasting tests concerning abrasive wear.

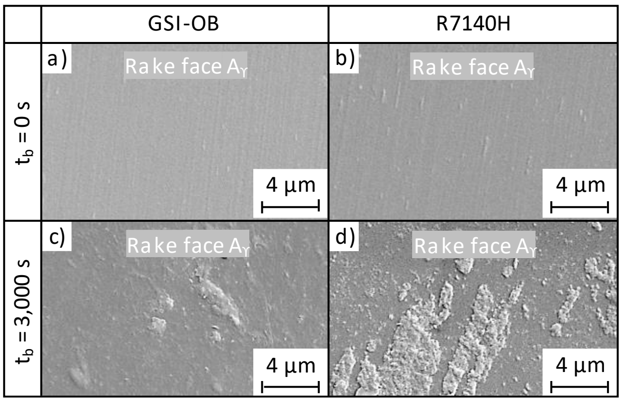

Figure 1. SEM images of a) and b) initial states of the SCD rake faces A_γ, as well as c) and d) machined states after the abrasion blasting tests.

Based on the optical measurements of the machined SCD specimens using different graphite materials, no characteristic indications of an abrasive wear mechanism could be detected in this experimental study regardless of the increasing blasting time t_b. The visible characteristics on the rake faces A_γ could be identified as particle residues of the used graphite granulates. The SEM results show that no abrasive damage occurs in the investigated process area. To investigate surface attrition as a possible wear mechanism, Figure 2 shows the initial states of the SCD cutting-edges (2a, 2b) and their machined states (2c, 2d) after a blasting time of t_b = 3,000 s.

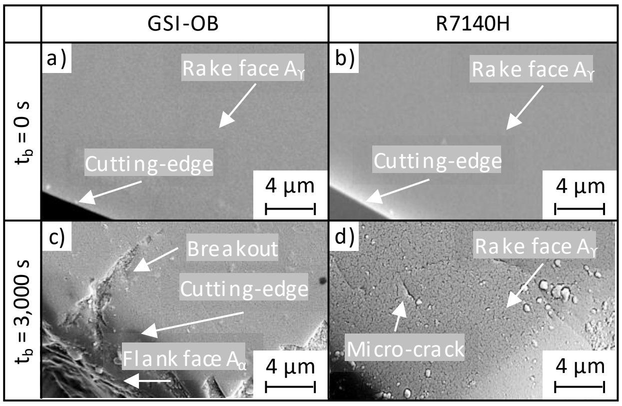

Figure 2. SEM images of a) and b) initial states of the SCD cutting edges and c) and d) machined states after the surface attrition blasting tests

The results on the surface attrition show a significant wear behaviour on the rake face A_γ and the flank face A_α. After a blasting time t_b = 3,000 s, several micro-cracks and material breakouts could be identified on the rake face A_γ as well as close to the cutting edge of the investigated SCD tools. Due to a reduced material thickness t_m, the stability at the cutting edge decreases significantly, which results in an increased breakout behaviour. It can be determined that the individual micro-cracks connect with each other, which allows the formation of larger cracks with an increased blasting time t_b. Furthermore, the extruded graphite granulate GSI-OB leads to an increased breakout behaviour, which shows the influence of the graphite material properties concerning the surface attrition. In addition, rounded cutting edges and cracked edges were observed, which indicate chemical wear due to thermally induced diffusion processes [5]. Regarding to this findings, the grains of both graphite granulates were investigated in the initial states and in the machined states after a blasting process (Figure 3).

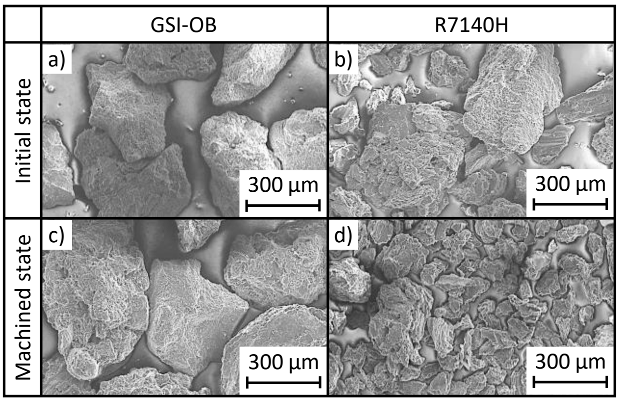

Figure 3. SEM images of a) and b) initial states of the graphite particles as well as c) and d) machined states after a blasting process.

The comparison of the initial states shows similar particle dimensions of both graphite types (3a, 3b). However, the SEM images of the machined hardgraphite R7140H reveal, that the grains break into smaller particles due to the collision with the SCD during the blasting tests (3d). This shows that the selection of graphite materials has a significant impact on the wear behaviour using SCD for the cutting process.

4. Conclusion and further investigations

The findings show that no abrasive wear on the SCD rake faces A_γ could be identified with the used parameters and types of graphite granulates. Based on the investigations, no significant mass losses m_l of the SCD were detected. The results concerning the surface attrition of the SCD show a significant wear behaviour with large micro-cracks und material breakouts in dependency with an increased blasting time t_b. The mass of the SCD could be reduced in an area of 0.012 g ≤ m_l ≤ 0.030 g, which correlates to a reduction of 0.07 % ≤ m_l ≤ 0.17 % using the graphite material type R7140H. Based on the investigations, the surface attrition could be identified as a wear mechanism for SCD using graphite materials. In addition to the mechanical wear, the roundings of the cutting edges and cracked edges indicate the occurrence of thermally induced chemical tool wear. Further investigations address the adhesive and tribo-chemical wear mechanisms on SCD through experimental friction tests. This work was funded by the GERMAN RESEARCH FOUNDATION DFG.

References

[1] König, M.: Fräsbearbeitung von Graphitelektroden. RWTH Aachen, Dissertation, Aachen: Shaker, 1998, S. 32 – 35.

[2] Uhlmann, E.: 5th Meeting of the Collaborative Working Group on Micro Production Engineering. CIRP Winter Meeting, Paris, 2014.

[3] Polte, J.: Kubisch-kristallines Bornitrid ohne Bindephase als Schneidstoff in der Ultrapräzisions-Zerspanung. TU Berlin, Dissertation, Berlin: Fraunhofer Verlag, 2017, S. 39.

[4] Czichos, H.; Habig, K.-H.: Tribologie-Handbuch. Wiesbaden: Vieweg + Teubner, 2020, S. 160 – 168.

[5] Oberschmidt, D.: Mikrofräsen mit zylindrischen Diamant-Schaftfräswerkzeugen. TU Berlin, Dissertation, Berlin: Fraunhofer Verlag, 2009, S. 12.