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Temperature Characterization of Ion-Implanted Boron-Doped Diamond Tools in Ultra-Precision Turning of Metallic and Plastic Materials

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Abstract
Ultra-precision turning is a crucial technology for the production of optical components used in industries such as medical technology, aerospace and automotive industry. Dedicated single crystal diamond tools enable the production of advanced optical surfaces and components with high dimensional accuracies and low surface roughness values. Despite the superior mechanical hardness of single crystal diamonds, temperature induced tool wear occurs during the machining. Therefore, the characterisation and interpretation of the cutting temperatures are of utmost importance for improving ultra-precision turning. According to the state-of-the-art, a dedicated cutting edge temperature measurement system based on ion-implanted boron-doped single crystal diamonds as a highly sensitive temperature sensor for ultra-precision turning was developed. Using this cutting edge temperature measurement system enables a holistic view of the temperature development during ultra-precision turning. Based on this, the temperature behaviour during the finishing process of ultra-precision specific materials such as copper, aluminium, brass, PSU, PC and PMMA was identified and the temperature-related differences evaluated. For this purpose, the real cutting power was recorded for each investigated material, allowing the cutting edge temperatures to be determined using an additional developed simulation model. Based on this, fundamentally different material-dependent cutting edge temperatures could be identified for the investigated materials. According to the results, significantly higher cutting temperatures could be shown for metallic materials compared to plastics. The highest cutting edge temperature of ϑ_{Ce} = 187.35 °C was determined for brass as a metallic material and the highest cutting edge temperature of ϑ_{Ce} = 69.83 °C for PSU as a plastic material. This provides the fundamentals for further research works to identify the complex temperature-induced wear behaviour of single crystal diamonds in ultra-precision turning.

Keywords: Temperature sensor, ion-implantation, boron-doped diamonds, ultra-precision turning

1. Introduction

The optic and photonic industry drives innovation and growth by providing key technologies for the manufacturing of optical components. This includes the production of high-performance and precision optics made of metallic and plastic materials for the manufacturing of optical lenses in a wide range of applications in the field of medical technology, consumer applications such as virtual and augmented reality as well as projection-based image processing methods, which are considered highly relevant for industry. Increasing demands for reduced process times t_P, cost efficiency and improved quality in terms of shape accuracy a_S and surface roughness are driving the continuous development of tools and moulds, alongside a focus on sustainability and climate neutrality. Ultra-precision turning with single crystal diamond (SCD) tools is essential for the production of high-precision optics and complex optical systems. These diamond tools are characterised by a low rounded cutting edge radius in a range of 20 nm ≤ r_β ≤ 50 nm, a radius waviness of r_w ≤ 250 nm as well as an exceptional hardness of H_V = 10,000 HV [1]. However, despite their significant mechanical hardness H_V, temperature-induced wear of the diamond tools occurs during the cutting process.

According to the state of the art, SCD tools suffer from this specific tool wear even during the machining of non-ferrous materials such as aluminium (Al), copper (Cu), brass (CuZn), and various plastics [2, 3, 4]. The initiation and development of tool wear is significantly influenced by the cutting temperatures ϑ_C occurring in the cutting zone [5, 6]. Improving process knowledge in ultra-precision machining, particularly regarding tool life, wear behaviour and complex interactions of process parameters to enhance efficiency and stability, requires a precise understanding of cutting edge temperatures ϑ_{Ce}. However, there are no precise methods available in the current state-of-the-art to monitor the cutting edge temperatures ϑ_{Ce} online during the process with sufficient sensor accuracies a_{Se}.

For this purpose, an innovative cutting edge temperature measurement system based on ion-implanted boron-doped diamonds could be developed to analyse the temperature behaviour in ultra-precision turning. To enable high sensitive temperature measurements, ion-implantation was used for partial and specific boron-doping close to the cutting edge of the SCD, whereby the electrosensory properties of the boron-doping enable a direct temperature measurement in the cutting zone related to the changing electrical resistances R_{el}. Within this research work, investigations were carried out to identify the cutting edge temperatures ϑ_{Ce} in relation to the real cutting power P_C during finishing of metallic and plastic-based materials.

2. Experimental Setup

2.1. Ion-implanted boron-doped diamond

To determine the cutting edge temperatures ϑ_{Ce} during ultra-precision turning, partial ion-implanted boron-doped diamonds were used for the experimental application. The boron-doped diamonds were manufactured using specific ion-implantation, whereby the targeted introduction of boron-ions changed the material behaviour of the SCD from an isolator to an electrically conductive material. Ion-implantation was used by applying a 100keV ion-implanter with an ion-source based on a source of negative ions by cesium sputtering. The diamonds were manufactured by the FELIX BLOCH INSTITUTE FOR SOLID STATE PHYSICS at the UNIVERSITY OF LEIPZIG, Leipzig, Germany.

To use a boron-doped diamond as a semi-conductor for electronic applications, suitable geometric dimensions are required due to the doping, which influence the electrosensory properties of the doped diamonds. In the following, the selected doping structures, shown in Figure 1, are described, whereby the influence of the doping characteristics with regard to doping lengths d_{len} and doping-level d_{lev} are already described in detail in UHLMANN ET AL. [7].

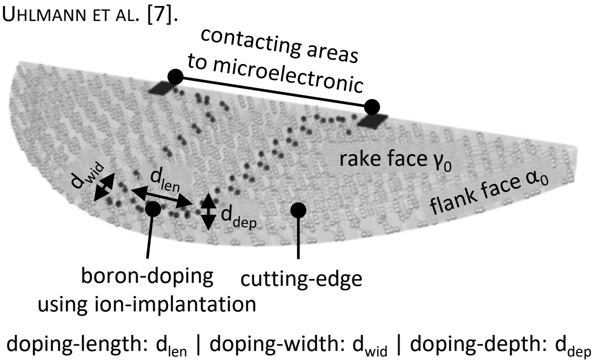

Figure 1. Doping structures of the ion-implanted boron-doped diamond using as a temperature sensor in ultra-precision turning

The boron structures incorporated into the doped diamond are defined by a doping length of d_{len} = 420 µm, a doping width of d_{wid} = 44 µm, and a doping depth of d_{dep} = 150 nm, with a distance of d_C = 90 µm from the cutting edge. Notably, the doping depth of d_{dep} = 150 nm complete isolation of the boron structures within the diamond lattice from external environmental influences. To achieve the desired current flow, a doping level of d_{lev} = 4E^{15} - ions/cm^2 was employed. To establish electrical contact between the ion-implanted boron-doped diamond and the integrated microelectronic system, two additional boron structures were implemented. These structures were designed with a doping width of d_{wid} = 200 µm, a doping length of d_{len} = 2.16 mm, and a doping level of d_{lev} = 4E^{15} - ions/cm. Furthermore, two dedicated contact surfaces A_C with dimensions of 90 µm × 90 µm were integrated to enable effective interfacing with the microelectronic system. These contacting surfaces A_C were implanted up to the graphitization limit with a higher doping-level of d_{lev} = 2E^{16} - ions/cm^2 to achieve a suitable electrical conductivity κ to the boron-structures within the diamond lattice. A necessary distance between the contacting structures of d_C = 1 mm was further selected to avoid short circuits.

2.2. Cutting edge temperature measurement system

A dedicated cutting edge temperature measurement system was developed to carry out the experimental temperature measurements, which is already fully described in detail in previous research works [8]. The cutting edge temperature measurement system consists of a monolithic ceramic tool holder made of MACOR®, which was provided by the company SCHRÖDER SPEZIALGLAS GMBH, Ellerau, Germany. Using this type of ceramic enables a complete isolation of the electronic components from the machine environment. A microcontroller of the type ARDUINO DUE A000062 from the company ARDUINO, Somerville, USA, with an integrated analog-digital converter type ADS1115 from the company TEXAS INSTRUMENTS, Dallas, USA, was used for the evaluation electronic. The integration of the ion-implanted boron-doped diamonds and the metrological connection to the microcontroller was carried out using the single-component adhesive type ELECOLIT 3655 of the company PANACOL-ELOSOL GMBH, Steinbach, Germany. To generate the process data, a graphical user interface was further developed for the transformation, visualisation and storage of the temperature data. According to [9], a resolution accuracy in a range of 0.29 °C ≤ a_R ≤ 0.39 °C, a reaction time of t_R = 440 ms and an overall sensor accuracy a_{Se} with a total measurement uncertainty of U_M = 0.098 °C could be determined for the developed cutting edge temperature measurement system in previous research works [9].

2.3. Calibration of the ion-implanted boron-doped diamond

Prior to carrying out the experimental investigations to identify the cutting edge temperatures ϑ_{Ce}, the cutting edge temperature measurement system based on an ion-implanted boron-doped diamond needed to be calibrated. This enabled the identification of the relationship between changes in electrical resistance R_{el} at varying temperature levels and the corresponding resistance-temperature curve. As a result, the temperature-dependent electrical resistances R_{el} are measurable during the machining process and thus the cutting temperatures ϑ_C can be obtained. For this purpose, a highly sensitive measurement system for calibrating type PA 200 from the company SUESS MICROTEC SE, Garching, Germany, was applied. This measurement device is characterised by a high-precision temperature-controlled wafertherm-chuck-system type SP 74 A from the company ERS ELEKTRONIK GMBH, Hagen, Germany, to expose the boron-doped diamonds to specific temperatures ϑ with a temperature accuracy of a_θ ≤ 0.1 °C. For the calibration, a temperature measurement range of 20 °C ≤ ϑ ≤ 140 °C with a specific temperature change of $\Delta\vartheta$ = 1 °C and a boron-doped diamond with a corner radius of r_ε = 1.5 mm as well as a doping-level of d_{lev} = 4E^{15} - ions/cm^2 was selected. The result of the calibration process concerning the resistance-temperature curve is shown in Figure 2.

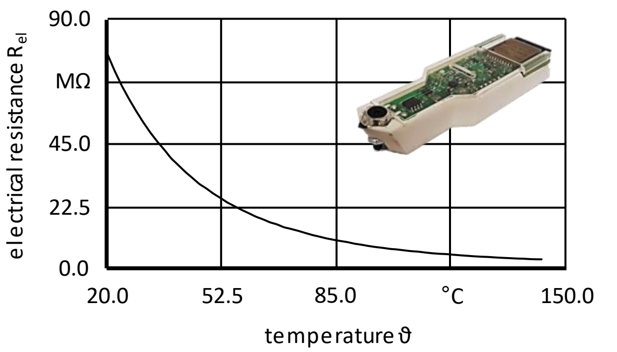

Figure 2. Calibration of the ion-implanted boron-doped diamond

3. Experimental Results

Due to the high sensitivity of the ultra-precision process to fluctuations in the contact zone between tool and workpiece, a highly sensitive monitoring of the cutting edge temperatures ϑ_{Ce} and temperature developments is of increased relevance.

In order to expand the process knowledge in ultra-precision turning with regard to the temperature characteristics of relevant materials and the influence of different material properties on the temperature behaviour during finishing, experimental investigations were carried out to identify the cutting edge temperatures ϑ_{Ce} during the machining of CuZn, Al, Cu, PSU, PMMA and PC. Within the experimental investigations, the 5-axis ultra-precision machine tool Nanotech 350 FG from the company MOORE NANOTECHNOLOGY SYSTEMS, Swanzey, USA, as well as an ion-implanted boron-doped diamond with a corner radius of r_ε = 1.5 mm were applied. A cutting speed of v_c = 350 m/min, a depth of cut of a_p = 5 µm, a feed of f = 5 µm and a rake angle of $\gamma_0 = 0\,°$ were selected as the process parameters for finishing. Prior to the experimental investigations, a validated simulation model was initially developed based on the difference in distance between the cutting edge and the boron-doping, which is fully described in [9]. The used ion-implanted SCD is characterised by a specific and partial boron-doping with a distance to the cutting edge of d_C = 90 µm. This distance d_C between the real implanted boron-doping and the cutting edge results in a defined difference, which limits the knowledge of the cutting edge temperatures ϑ_{Ce} occurring in the ultra-precision turning. For this reason, specific simulations were carried out, whereby the simulated temperatures ϑ_S represent the cutting edge temperatures ϑ_{Ce} obtained during the machining process, which are subsequently used in the experimental investigations. Figure 3 shows the simulation environment and the resulting temperature field during finishing.

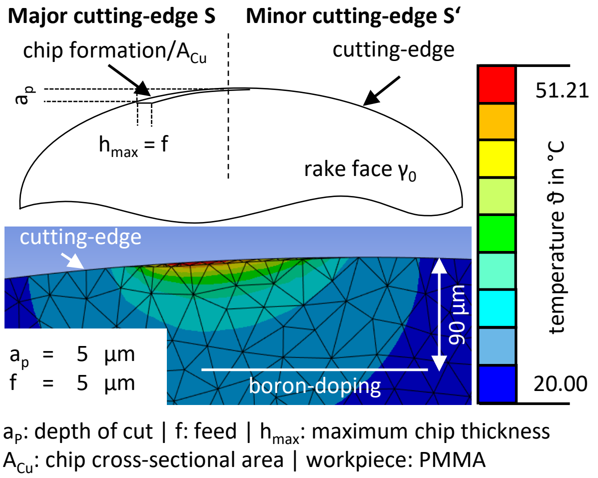

Figure 3. Simulation model for simulating the cutting edge temperatures ϑ_{Ce} during finishing in ultra-precision turning for PMMA

To carry out the simulations according to the real environmental conditions, the cutting power P_C of the cutting process, which serves as a heat source Q for the simulation model, is of decisive importance. The cutting power P_C is characterised by the cutting force F_C as well as the cutting speed v_c and is defined as $P_C = F_C \times v_C$. The cutting force F_C required to calculate the cutting power P_C and simulate the cutting edge temperatures ϑ_{Ce} of the boron-doped diamonds were measured using a MINIDYN 9256C2 three-component dynamometer from Kistler Instrumente AG, Winterthur, Switzerland. The cutting speed v_c represents a relevant process variable and can be selected as required.

Using the simulated temperature field related to the cutting power P_C enables the determination of the temperature development and the temperature distribution between the cutting edge and the boron-doping. Based on the comparison of the cutting edge temperatures ϑ_{Ce} with the measured cutting temperatures $\vartheta_{C,M}$ in the boron-doping area, a validation could be successfully realised and the cutting edge temperatures ϑ_{Ce} were determined as a function of the used process conditions in terms of cutting power P_C, cutting speed v_c, depth of cut a_p, feed f, chip cross-sectional area A_{CU} as well as the used material. To validate the simulation model, the cutting edge temperatures ϑ_{Ce} were simulated as a function of the cutting power P_C, the area of the energy input A_E and the applied process parameters. As a validation basis, the simulated temperatures ϑ_S in the boron-doping area were compared with the measured cutting temperatures $\vartheta_{C,M}$, whereby the cutting edge temperatures ϑ_{Ce} could be identified using the simulated heat field. Figure 4 shows the cutting power P_C as a function of the cutting force F_C for the analysed materials during finishing.

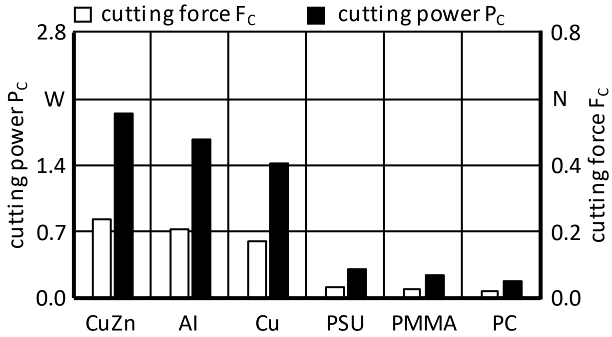

Figure 4. Cutting power P_C and cutting forces F_C for each investigated workpiece material during finishing in ultra-precision turning

For the applied parameter configuration within the finishing process, cutting forces in a range of $0.031\text{ N} \leq F_C \leq 0.334\text{ N}$ and cutting power in a range of $0.181\text{ W} \leq P_C \leq 1.948\text{ W}$ could be measured. The highest cutting force of $F_C = 0.334$ N and the highest cutting power of $P_C = 1.948$ W were determined for brass, whereas the lowest cutting force of $F_C = 0.031$ N and lowest cutting power of $P_C = 0.181$ W were achieved for PC. In general, the cutting power P_C, which correlates directly with the cutting forces F_C, was higher for the metallic materials compared to plastics. For this reason, the reduction in cutting forces F_C results in a reduction in cutting power P_C. The differences between the metallic and plastic-based materials are due to the respective material properties, which are described in detail below when analysing the cutting edge temperatures ϑ_{Ce}.

Based on the real cutting power P_C, it was possible to identify the cutting edge temperatures ϑ_{Ce} for each investigated material and to derive material-specific influences. Figure 5 shows the measured cutting temperatures $\vartheta_{C,M}$ and the cutting edge temperatures ϑ_{Ce} for each analysed material, taking into account the recorded cutting power P_C during finishing.

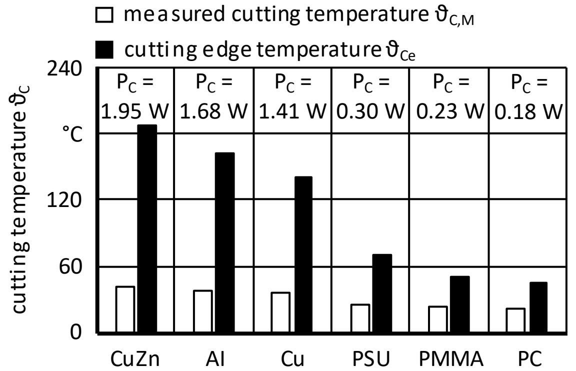

Figure 5. Temperature development in terms of measured cutting temperatures $\vartheta_{C,M}$ and cutting edge temperatures ϑ_{Ce}

As Figure 5 shows, the developed cutting edge temperature measurement system with an ion-implanted boron-doped diamond as a temperature sensor was able to reliably measure the cutting temperatures $\vartheta_{C,M}$ for all investigated materials. Within the experimental investigations, cutting edge temperatures between $45.64\text{ °C} \leq \vartheta_{Ce} \leq 187.35\text{ °C}$ related to the measured cutting temperatures in a range of $22.01\text{ °C} \leq \vartheta_{C,M} \leq 42.28\text{ °C}$ were determined, whereby the highest measured cutting temperature of $\vartheta_{C,M} = 42.28$ °C and the highest cutting edge temperature of $\vartheta_{Ce} = 187.35$ °C were achieved for the brass material at a cutting power of $P_C = 1.948$ W. For the machining of aluminium, a measured cutting temperature of $\vartheta_{C,M} = 38.64$ °C and a cutting edge temperature of $\vartheta_{Ce} = 162.49$ °C at a cutting power of $P_C = 1.680$ W were recorded, while for the machining of copper, a measured cutting temperature of $\vartheta_{C,M} = 36.87$ °C and a cutting edge temperature of $\vartheta_{Ce} = 141.24$ °C at a cutting power of $P_C = 1.412$ W could be obtained. The lowest measured cutting temperature of $\vartheta_{C,M}$ = 22.01 °C and cutting edge temperature of ϑ_{Ce} = 45.64 °C was measured when cutting PC at a cutting power of P_C = 0.181 W. In comparison, a higher measured cutting temperature of $\vartheta_{C,M}$ = 23.50 °C and a higher cutting edge temperature of ϑ_{Ce} = 51.21 °C with a cutting power of P_C = 0.233 W were determined for PMMA. The results for machining the plastic materials showed that the machining of PSU resulted in the highest measured cutting temperatures of $\vartheta_{C,M}$ = 25.34 °C and cutting edge temperatures of ϑ_{Ce} = 69.83 °C using a cutting power of P_C = 0.298 W.

Based on the results, different cutting edge temperatures ϑ_{Ce} could be shown for each investigated material. This can be attributed to the different material properties, which result in different cutting forces F_C and thus cutting power P_C. When machining brass, a higher cutting edge temperature ϑ_{Ce} with a temperature gradient of $\Delta\vartheta_{Ce}$ = 46.11 °C was observed compared to copper and of $\Delta\vartheta_{Ce}$ = 24.86 °C compared to aluminium. Brass and aluminium are characterised by higher cutting forces F_C, cutting power P_C and thus by higher cutting edge temperatures ϑ_{Ce} due to their alloy composition and higher tensile strengths of $\sigma_{T,brass}$ = 540 N/mm^2 and of $\sigma_{T,aluminium}$ = 320 N/mm^2 compared to copper with $\sigma_{T,copper}$ = 260 N/mm^2. The higher tensile strength of brass $\sigma_{T,brass}$ and the presence of additional elements like zinc, nickel, iron and plumb contribute to the highest cutting edge temperature ϑ_{Ce}. Brass shares structural similarities with copper with a content of c_c = 58 %, resulting in a comparable machining behaviour but slightly in higher cutting edge temperatures ϑ_{Ce} due to the higher chemical element content c_e as well as higher *mechanical strengths* R_m with different lattice distortions.

When machining PSU, a higher cutting edge temperature ϑ_{Ce} with a temperature gradient of $\Delta\vartheta_{Ce}$ = 18.62 °C was measured compared to PMMA and of $\Delta\vartheta_{Ce}$ = 24.19 °C compared to PC. Despite their similar thermal conductivities of PSU with λ_{PSU} = 0.26 W/(mK), PMMA with λ_{PMMA} = 0.19 W/(mK) and PC with λ_{PC} = 0.21 W/(mK), the investigated plastic materials showed different cutting edge temperatures ϑ_{Ce}. This can be fundamentally justified by different polymer chains, which influence the material behaviour in terms of the tensile strengths σ_T. PSU is characterised by the highest tensile strength of $\sigma_{T,PSU}$ = 80 MPa, followed by PMMA with $\sigma_{T,PMMA}$ = 75 MPa and PC with $\sigma_{T,PC}$ = 65 MPa. These tensile strengths σ_T also influenced the cutting forces F_C, whereby a cutting force of F_C = 0.051 N was determined for PSU, F_C = 0.040 N for PMMA and F_C = 0.031 N for PC. Based on this, the use of the same process conditions led to different cutting power P_C and thus to different temperature levels. In addition, the mechanical properties of the polymers are also influenced by the cutting temperatures ϑ_C resulting during the machining process, which can also occur below the glass transition temperature ϑ_G. However, this could not be identified within the parameter areas under consideration.

In general, plastic materials showed significantly lower cutting edge temperatures ϑ_{Ce} compared to metallic materials, which is due to fundamental differences in bonding and material behaviour. Plastic materials consist of specific polymer chains with primary bonds (covalent) and secondary bonds (Van-der-Waals forces F_V, hydrogen bonds, dipole-dipole interactions). In contrast, metallic materials are characterised by metallic bonds with much higher bonding energies E_B, which require more energy E for separation during the cutting process. The higher mechanical strength R_m of metal materials compared to plastic materials results in increased cutting forces F_C and cutting power P_C in the cutting process, which leads to higher cutting edge temperatures ϑ_{Ce}.

4. Conclusion

In this scientific study, the temperature behaviour of different metallic and plastic-based materials such as brass, aluminium, copper, PSU, PMMA and PC was investigated within the finishing process during ultra-precision turning. According to the results, individual cutting edge temperatures ϑ_{Ce} between the investigated materials and the influence of the material-specific properties on the temperature behaviour could be identified. Within the investigations, a direct correlation of the real cutting power P_C with the recorded cutting edge temperatures ϑ_{Ce} could be determined, taking into account the developed simulation model and the measured cutting temperatures $\vartheta_{C,M}$ using the dedicated cutting edge temperature measurement system. The highest cutting edge temperature for the metallic material was achieved for brass with ϑ_{Ce} = 187.35 °C at a cutting power of P_C = 1.948 W and the highest cutting edge temperature for the plastic material was obtained for PSU with ϑ_{Ce} = 69.83 °C at a cutting power of P_C = 0.298 W. Due to the higher tensile strengths σ_T and *bonding energies* E_B, fundamentally higher cutting power P_C as well as cutting edge temperatures ϑ_{Ce} were documented for the metallic materials compared to the plastics.

Based on the results, the complex relationships between the temperature behaviour of electrical conductive metallic materials compared to electrical isolating plastic materials and their specific temperature development could be identified during finishing in ultra-precision turning.

In summary, the use of the developed state-of-the-art cutting edge temperature measurement system with ion-implanted boron-doped diamonds as a temperature sensor provides fundamental insights for the detailed and comprehensive characterisation of temperature development related to the real cutting power P_C and cutting edge temperatures ϑ_{Ce}. Future research works will address the improvement for the understanding of the specific temperature development in different materials, focusing on the relationships to the wear behaviour of SCD in ultra-precision turning. This work was funded by the German Research Foundation (DFG).

References

[1] Uhlmann, E.: 5th Meeting of the Collaborative Working Group on Micro Production Engineering. CIRP Winter Meeting, Paris, 22.01.2014.

[2] Gubbels, G. P. H.; Van der Beek, G. J. F. T.; Hoep, A.L.; Delbressine, F. L. M.; Van Halewijn, H.: Diamond Tool Wear when Cutting Amorphous Polymers. Annals of the CIRP - Manufacturing Technology 53 (2004), p. 447 – 450.

[3] Gubbels, G. P. H.: Diamond Turning of Glassy Polymers. Eindhoven, Niederlande, Dissertation, 2006.

[4] Sharma, A.; Joshi, S. S.; Datta, D.; Balasubramaniam, R.: Modeling and analysis of tool wear mechanisms in diamond turning of copper beryllium alloy. Journal of Manufacturing Processes 56 (2020), p. 439 – 450.

[5] Evans, C.: Cryogenic Diamond Turning of Stainless Steel. Annals of the CIRP - Manufacturing Technology 40 (1991), p. 571 – 575.

[6] Paul, E.; Evans, C. J.; Mangamelli, A.; McGlauflin, M. L.; Polvanit, R. S.: Chemical aspects of tool wear in single point diamond turning. Precision Engineering 14 (1996), p. 4 – 19.

[7] Uhlmann, E.; Polte, M.; Hocke, T.; Thißen, K.: Characterisation and investigation of ion-implanted boron-doped single crystal diamonds as temperature sensor for ultra-precision machining. euspen´s 23nd International Conference & Exhibition, Copenhagen, DK, 2023, S. 63 – 64.

[8] Uhlmann, E.; Polte, J.; Polte, M.; Hocke, T.: Boron-doped mono-crystalline diamond as cutting tool for temperature measurement in the cutting zone. Procedia CIRP 101 (2021), p. 258 – 261.

[9] Polte, J.; Hocke, T.; Uhlmann, E.; Thißen, K.: Fundamental Investigations on Temperature Development in Ultra-Precision Turning. The International Journal of Advanced Manufacturing Technology, 2025.