

Article

Explanatory Model of the Material Removal Mechanisms and Grinding Wheel Wear During Grinding of PCD with Water-Based Cooling Lubricants

Peter Breuer ^{1,*} , Eike Reuter ¹, Sebastian Prinz ¹  and Thomas Bergs ^{1,2}¹ Manufacturing Technology Institute—MTI of RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, Germany² Fraunhofer Institute for Production Technology, Steinbachstraße 17, 52074 Aachen, Germany

* Correspondence: p.breuer@mti.rwth-aachen.de

Abstract: Polycrystalline diamond (PCD), which is widely used to manufacture cutting tools due to its extreme hardness, in most cases requires grinding for machining. The cooling lubricant selected for PCD grinding largely affects the frictional conditions and the thermo-mechanical load collective between the diamond grinding wheel and the PCD. As a consequence of this, the material removal and grinding wheel wear mechanisms during grinding PCD depend on the cooling lubricant used. In this study, experimental and numerical investigations were taken into account, demonstrating that using a water-based cooling lubricant during PCD grinding predominantly leads to a mechanical load on workpiece and grinding wheel rather than thermal loads. These original findings can be used to complement existing explanatory models of the PCD grinding process valid for grinding with oil as a cooling lubricant. The aim of this work is to contribute a novel extension to the existing material removal and grinding wheel wear models to enable them for the grinding process with a water-based cooling lubricant. The knowledge obtained from this work is intended to serve as a basis for future industrial process design.

Keywords: polycrystalline diamond; grinding; water-based cooling lubricants; material removal mechanisms; grinding wheel wear; transmission electron microscopy (TEM); explanatory model



Academic Editor: Dariusz Dzik

Received: 15 April 2025

Revised: 19 May 2025

Accepted: 24 May 2025

Published: 26 May 2025

Citation: Breuer, P.; Reuter, E.; Prinz, S.; Bergs, T. Explanatory Model of the Material Removal Mechanisms and Grinding Wheel Wear During Grinding of PCD with Water-Based Cooling Lubricants. *Processes* **2025**, *13*, 1671. <https://doi.org/10.3390/pr13061671>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Non-ferrous materials that are frequently used in aerospace applications and various other scenarios, such as titanium alloys, are commonly machined with cutting tools made from polycrystalline diamond (PCD) [1]. Due to its high hardness, the manufacturing of PCD cutting tools may rely on laser processes but also often includes grinding processes [2]. Without research regarding whether oils [3] and water-based cooling lubricants [4,5] can both be used for grinding PCD with vitrified bond grinding wheels, the material removal and grinding wheel wear mechanisms remain unknown.

In general, the material removal during grinding brittle-hard materials can be traced back to the initiation of cracks in the axial, lateral, and radial directions [6]. PCD, however, is subject to a more complex manifestation of these mechanisms, which can be attributed to its multiphase structure. An earlier research work on grinding PCD with oil as a cooling lubricant by Schindler concluded that both mechanical and tribo-chemical loads in the contact zone are relevant to the material removal. Up to a certain mechanical load limit, the tribo-chemical mechanisms are prevalent. Above the load limit, the mechanical share of the

load becomes dominant, which also leads to a rougher workpiece surface after grinding [7]. Vits continued the work of Schindler and analyzed the tribological phenomena when grinding PCD, also referring to processes with oil as a cooling lubricant. He assumed force peaks resulting from the contact between a PCD diamond grain and an abrasive grain to be the cause for crack initiations in the workpiece, the vitrified bond of the grinding wheel, and the abrasive grain–bond interface. Elevated temperatures in the grinding process in combination with different thermal expansion coefficients of the contact partners were identified as further possible reasons for crack initiations and therefore brittle–hard chip formation [8].

Water-based cooling lubricants may increase the friction between workpiece and abrasive grain [9]. Thus, they may lead to a more efficient chip formation [10]. It can also be presumed that the process cooling in grinding PCD with a water-based cooling lubricant is more efficient compared to a grinding process with oil as a cooling lubricant. This, nevertheless, has only been investigated to a limited extent in the past, for example, by Kenter [11]. Therefore, it is unknown in which way the use of a water-based cooling lubricant influences the material removal mechanisms and the grinding wheel wear mechanisms.

Besides PCD, polycrystalline cubic boron nitride (PCBN) is an important superhard multiphase cutting tool material. The manufacturing of PCBN cutting tools, analogously to the PCD tool manufacturing, includes grinding processes. Scientific research on these PCBN grinding processes exists but in many cases refers to oils as cooling lubricants, for example, in multiple studies of Denkena et al. [12,13]. Water-based cooling lubricants, meanwhile, have not been systematically considered.

Recently, several studies were conducted by the authors of this work to analyze the effect of water-based cooling lubricants on the grinding process of superhard cutting materials on the example of PCD. They carried out tribological investigations [14] and grinding experiments [15] as well as numerical simulations [16]. The present work aims to combine the conclusions from the aforementioned publications with results from transmission electron microscopy (TEM) imaging in order to develop an explanatory model for the material removal mechanisms in grinding PCD with a water-based cooling lubricant. Additionally, an explanatory model for the grinding wheel wear during the grinding of PCD with a water-based cooling lubricant was developed. Both models contribute novel findings to the state of the art in order to mitigate the research deficit described above.

2. Materials and Methods

The investigated PCD samples were analogous workpieces from the manufacturer Element Six, London, United Kingdom. They were rectangular with the following dimensions: width $b_w = 4$ mm and height $h_w = 15$ mm. The thickness was $t_w = 1.6$ mm, and samples were composed of a share of $t_{WC-Co} = 1$ mm, which was accounted for by the WC-Co cemented carbide substrate, and a share of $t_{PCD} = 0.6$ mm, which was accounted for by the PCD layer. This geometry was adapted to the cutting edge of a standard indexable insert. A hole of the diameter $d_f = 0.8$ mm was introduced to the cemented carbide substrate by electrical discharge machining. This was required for the pyrometer fiber used for the temperature measurement. The investigated material was CMX850, a common PCD specification for the manufacturing of milling and rough cutting tools for aluminum alloy machining as well as titanium and composite machining [17]. It had an average diamond grain size of $d_g = 0.5\text{--}1.0$ μm and a cobalt content of $x_{Co} \geq 15$ wt% [18].

The experimental setup, including a sketch of the PCD workpiece, is shown in Figure 1. A five-axis tool grinding machine of the type S22p turbo from ISOG Technology GmbH, Weilheim, Germany (8) was used to machine the workpieces. A vitrified bond cup grinding wheel with a diamond grain diameter of $d_g = 15$ μm and a vitrified bond was chosen (1),

which matches a typical tool selection in corresponding industrial processes. The grinding wheel was sourced from the manufacturer Tyrolit Schleifmittelwerke Swarovski AG & Co K.G., Schwaz, Austria. It was dressed before each grinding test using a corundum dressing wheel of the specification 89A400H5AV83 from the same manufacturer. A three-component dynamometer of the type 9119AA2 from Kistler Instrumente AG, Winterthur, Switzerland was used to measure the normal force F_n and tangential force F_t during grinding (5). The force measurement system relies on an array of piezoelectric crystals. Before the start of the test series, it was calibrated for the expected force range of up to 100 N in normal direction using a static mass element of the same weight force. The solution Aquatec 5001 from Oelheld GmbH, Stuttgart, Germany was used as a cooling lubricant and applied through free-jet nozzles (8). Aquatec 5001 is a mineral oil-free cooling lubricant that is an additive for grinding cemented carbides, among other applications. This ensures that there is no increased cobalt leaching when machining PCD with this coolant [19]. At room temperature and a concentration of $x_{cl} = 3\%$, which is the average concentration investigated in this study, the dynamic viscosity was $\eta = 1.09$ mPas [20].

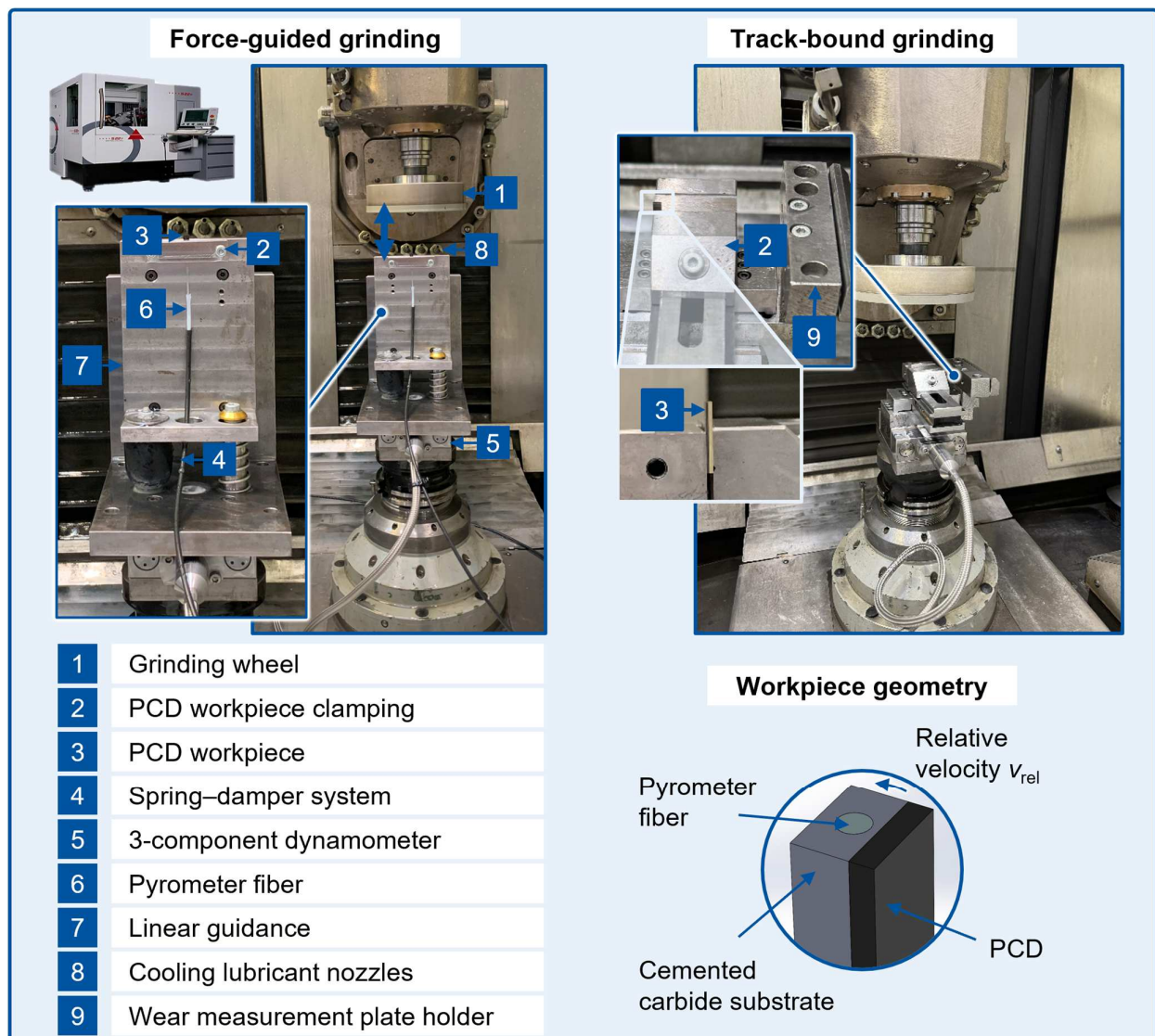


Figure 1. Experimental setup for the grinding tests.

The workpiece (3) was fixed in the workpiece clamping (2). A pyrometer fiber (6) of the diameter $d_f = 0.8$ mm was led through a hole in the cemented carbide substrate for

temperature measurement. It was of the type 3ML and, like the pyrometer of the type 3MH2, from the manufacturer Optris GmbH & Co. KG, Berlin, Germany. The fiber was brought to the contact zone between workpiece and grinding wheel, as described above. For the investigation of the material removal mechanisms, a force-guided process was carried out, which was achieved through the workpiece clamping being placed on a sliding linear guidance (7) suspended on a spring–damper system (4). This enabled the application of a certain normal force F_n to the workpiece by compressing the spring–damper system in an according way in the vertical direction. During this, both process state variables, namely normal force F_n and relative velocity v_{rel} , were controlled directly and kept constant during a single test run. Therefore, the tribological loads to which the PCD was exposed were precisely determined. This enabled the calculation of a mathematical friction model for the multi-grain engagement between PCD and diamond abrasive grains as a function of the physical properties of the water-based cooling lubricant [15]. Furthermore, the determined tribological loads provided a good basis for the TEM image analysis for the same reason. Thus, the explanatory model presented in this work could be derived well from the empirical data collected.

The normal force was varied in the three steps $F_n = 10, 30$, and 50 N. The relative velocity was set to the three values $v_{rel} = 5, 15$, and 25 m/s. Three cooling lubricant concentrations x_{cl} were investigated ($x_{cl} = 1, 3$, and 5%). A full factorial design of experiments with a test repetition for statistical purposes was applied.

A test run consisted of a loading phase, where the grinding wheel rotation was disabled, and the grinding wheel was moved into contact with the workpiece fixed on the spring–damper system. The normal force F_n was increased to the value intended for the test point. After this, the cooling lubricant supply was enabled, and the grinding wheel was set to rotate with the desired relative velocity v_{rel} , while the vertical position of the grinding wheel was kept constant for a process time of $t = 8$ s. This duration was chosen after preliminary tests to ensure relatively stable experimental conditions over a single test run. Longer time periods would have led to significant superposed wear effects, making it difficult to determine the cause–effect relationships occurring.

The grinding wheel wear mechanisms were investigated in a track-bound grinding process with a rigidly positioned workpiece. In this process, the depth of cut a_e was the defining process input variable rather than the normal force F_n . For the analysis of the grinding wheel wear, a track-bound setup is advantageous because the exact material removal V_w is known at all times during the experiment. Aside from the depth of cut a_e , the relative velocity v_{rel} and the cooling lubricant concentration x_{cl} were varied in the track-bound grinding experiments. The depth of cut a_e was varied in the three steps $a_e = 3, 5$, and 7 μm . For the relative velocity, the three steps $v_{rel} = 10, 15$, and 20 m/s were investigated. The cooling lubricant concentration was varied in the three steps $x_{cl} = 1, 3$, and 5% . The macroscopic wear of the grinding wheel was measured through negative contour imprints of the grinding wheel in epoxy wear measurement plates and a MarSurf LD270 contour and surface measuring station by Mahr GmbH, Goettingen, Germany. The microtopography was recorded through direct images of the grinding wheel taken using a 3D laser scanning microscope (LSM) of the type VK-X 150 by the manufacturer Keyence Deutschland GmbH, Neu-Isenburg, Germany.

The methodology for the derivation of the explanatory model for the material removal mechanisms relied on TEM analyses because they have been proven to deliver valuable information about the subsurface impact of the grinding process on PCD and similar workpiece materials, as Vits showed, for example. Following the approach of Vits, a focused ion beam (FIB) was chosen for the sample preparation because it does not significantly influence the workpiece rim zone, according to Vits [8]. Both the FIB preparation and

the TEM analysis were executed at the Central Facility for Electron Microscopy of RWTH Aachen University, Aachen, Germany. The FIB machine used was of the type Crossbeam 350 from the manufacturer Carl Zeiss Microscopy Deutschland GmbH, Jena, Germany. The lamellae were cut from the workpieces in the direction in which the grinding wheel passed during grinding, following the methodology of Vits [8]. First, the lamellae were barred from the surrounding workpiece material, after which they were thinned to a thickness of $t_{\text{lam}} < 1 \mu\text{m}$, cut out, and mounted to a copper web, which was needed to fix the lamellae to the sample holder within the TEM. The width of the lamellae was $b_{\text{lam}} \approx 10 \mu\text{m}$. The FIB preparation is shown in Figure 2.

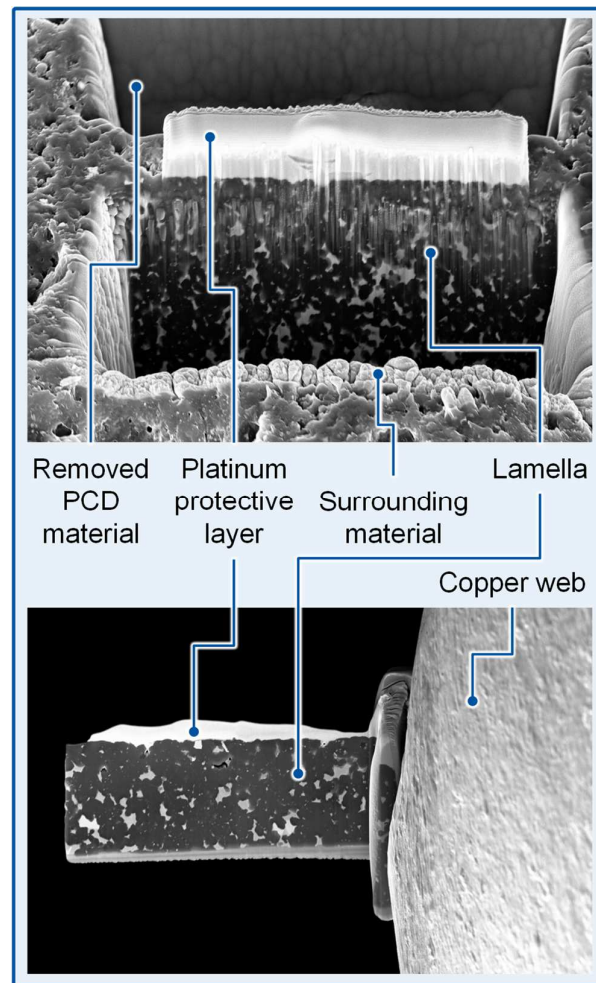


Figure 2. FIB preparation of the PCD lamellae.

The TEM analysis was performed on a microscope of the type Tecnai F20 from the manufacturer FEI, Hillsboro, OR, USA. It was operated in the scanning TEM mode (STEM), which enables a resolution of $d_{\text{TEM}} = 0.24 \text{ nm}$. A bright field (BF), a dark field (DF), and a high-angle annular dark field (HAADF) detector were used. Furthermore, the phase composition of the samples was analyzed through energy dispersive X-ray spectroscopy (EDX).

3. Results and Discussion

3.1. Material Removal Mechanisms

This section first presents the STEM and EDX analysis results. Subsequently, the results of the different samples are compared with each other. The comparison is used to derive findings on the material removal mechanisms when grinding polycrystalline diamond with a water-based cooling lubricant.

Multiple samples ground with varying process parameters were chosen for the TEM analysis on the effects of the PCD grinding process with a water-based cooling lubricant. STEM images from three samples are presented in Section 3. One of them was in the initial state before the grinding process. The other two were subjected to a different thermo-mechanical loads during the grinding process. Both presented samples were ground at a cooling lubricant concentration of $x_{cl} = 3\%$ since the cooling lubricant concentration proved to have a decisively lower impact on the resulting thermo-mechanical load to the workpiece than the normal force F_n and relative velocity v_{rel} , which was confirmed through the tangential force and temperature measurements in the experiments. The first of the ground samples was machined at a normal force of $F_n = 30$ N and a relative velocity of $v_{rel} = 15$ m/s (representing experiments with a lower thermo-mechanical load). The second ground sample was machined at a normal force of $F_n = 50$ N and a relative velocity of $v_{rel} = 25$ m/s (representing experiments with a higher thermo-mechanical load). The experimental results presented in this study, including the EDX analyses, were compiled to representatively illustrate the overall results for the complete research data collected in the context of the work.

Before investigating the samples prepared in the grinding tests, a reference sample of the same PCD specification was analyzed. This was in order to identify any anomalies in the initial state of the samples. The analysis relied on STEM-DF images, as they allowed for a clearer identification of stresses, dislocations, and cracks in the crystal structure. Therefore, in Figure 3, dark areas are to be interpreted as diamond grains, while the cobalt share of the material appears as brighter areas.

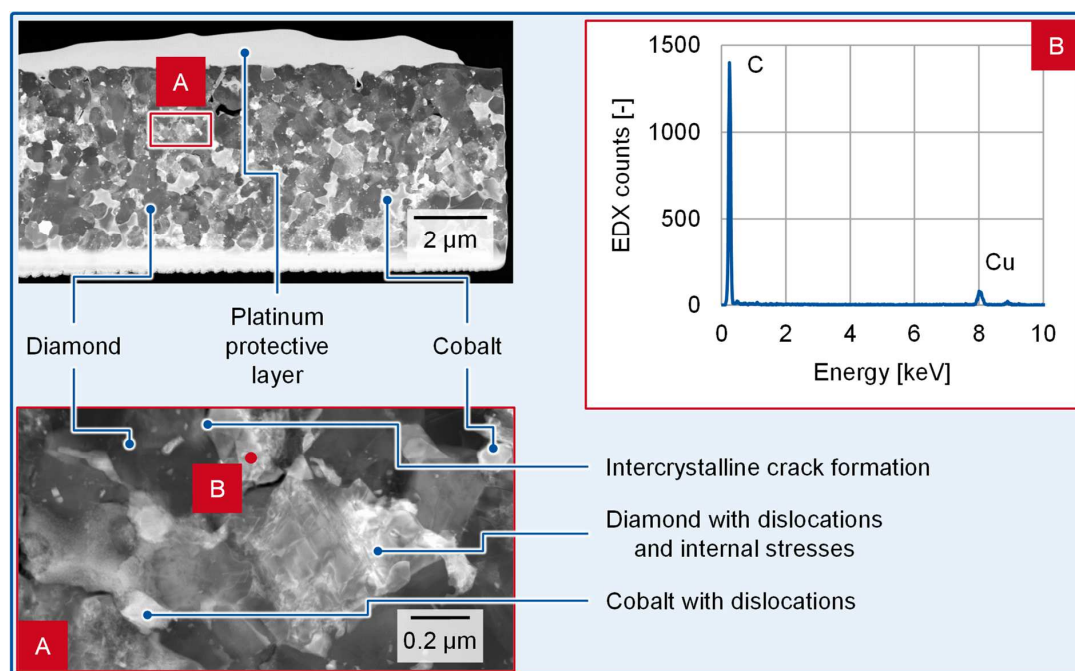


Figure 3. STEM/EDX analysis of the reference sample (unground condition). (A) detail view of the marked area within the lamella; (B) EDX analysis of the marked point within the detail view.

The general sample microstructure consisted of diamond grains of the expected average diamond grain size $d_g \leq 1$ μm, which were in an irregular orientation and interlinked at their contact points. In the spaces in between the diamond grains, residues from the cobalt catalyst were agglomerated. Figure 3A displays a detail of the DF-STEM image as marked in the overview image. It can be seen that intercrystalline crack formation was already present in the material before the grinding process. Furthermore, the diamond as well as

the cobalt crystals already carried dislocations and, partially, signs of internal stresses. In areas where the grayscale in the image did not allow for an unequivocal identification of the present phase, an EDX point analysis was performed, as shown in Figure 3B for the point marked in detail A. In this example, the EDX analysis led to the conclusion that the medium gray area represents a diamond (C) grain with a large amount of dislocations rather than a cobalt inclusion. It can be assumed that more dislocations were present in the lamella than could be identified within a single image because the visibility of dislocations strongly depends on the angle between the crystal planes and the electron beam within the microscope. The detection of copper (Cu) constituents could be traced back to the copper web used as a sample holder (see Figure 2). Traces of copper can be detected in EDX point analyses several micrometers aside the sample holder because of electron backscattering and can thus be neglected for the further evaluation. The findings described above and displayed in Figure 3 prove representative for the entire lamella, which was cut from the reference sample. It can be assumed that the cracks, dislocations, and stresses found in the reference sample were caused by the thermo-mechanical conditions in the sample manufacturing, including a high-pressure, high-temperature sintering process [21].

Figure 4 shows the STEM and EDX analysis of a sample ground with a relatively low thermo-mechanical load, as indicated by the grinding parameters used (normal force $F_n = 30$ N, relative velocity $v_{rel} = 15$ m/s). It is to be noted that the top right-hand corner of the overview image appears slightly darker than the rest of the image. This is due to a thinner area within the lamella, which distorts the imaging fidelity. The contrast between the diamond and cobalt phase in the respective area as well as the part of the image outside the described area remain uncompromised. The microstructure was similar to the reference sample and also showed dislocations in both diamond and cobalt crystals (for example, Figure 4A) as well as intercrystalline cracks. Furthermore, more shattered diamond grains were found within the lamella than within the reference sample. An example is displayed in the marked point B in Figure 4A and verified through the EDX analysis given in Figure 4B. This indicates that an additional mechanical load interfered with the microstructure in the grinding process. The intense and more frequently occurring dislocations in the cobalt phase attribute to the same conclusion. In the example of the marked point C in Figure 4A, the EDX analysis detected traces of copper (Cu) and tungsten (W), as displayed in Figure 4C. While the copper traces were already described for the reference sample (Figure 3), the tungsten traces were not evident in any EDX analysis performed on the reference sample. Nevertheless, it can be argued that they were introduced from the cemented carbide substrate of the samples during the grinding process.

In Figure 5, the test point with a relatively high thermo-mechanical load is focused (grinding parameters: normal force $F_n = 50$ N, relative velocity $v_{rel} = 25$ m/s). Again, an overview STEM image of the lamella and a detailed view with a higher magnification (Figure 5A) are given. It is obvious that below the platinum protective layer, which is shown as a bright strip on top of the PCD microstructure, there is an additional dark layer around point B. An EDX analysis (Figure 5B) was performed, indicating that the layer mainly consists of carbon (C) and oxygen (O). The oxygen-containing layer was exclusively located on top of the sample, and no further EDX analysis throughout the lamella detected any further traces of oxygen. This leads to the assumption that the layer can be considered an impurity caused during the sample preparation or handling. Further peaks in the EDX spectrum can be interpreted as the presence of gallium (Ga) and silicon (Si). This can, on the one hand, be traced back to the FIB used to cut the lamella, which relied on a gallium ion beam. On the other hand, the silicon detections, together with the oxygen detection, lead to the assumption that the impurity layer was a ceramic phase. Additional EDX analyses of the vitrified grinding wheel bond used in the grinding process showed that

the bond contained large amounts of silicon and oxygen as well. Therefore, the impurity is considered a fragment from the grinding wheel bond, introduced during grinding, and its occurrence is neglected for the further analysis and any conclusions made regarding the PCD. The analysis of the STEM-DF image of the lamella led to similar findings compared to the analysis of the sample ground at a low thermo-mechanical load and the analysis of the reference sample. The intensity and recognition density of these findings within the area of the lamella was greater than for the sample ground at the lower thermo-mechanical load. Examples for the identified phenomena are shown in Figure 5A, such as intercrystalline cracks and diamond grains with signs of internal stresses.

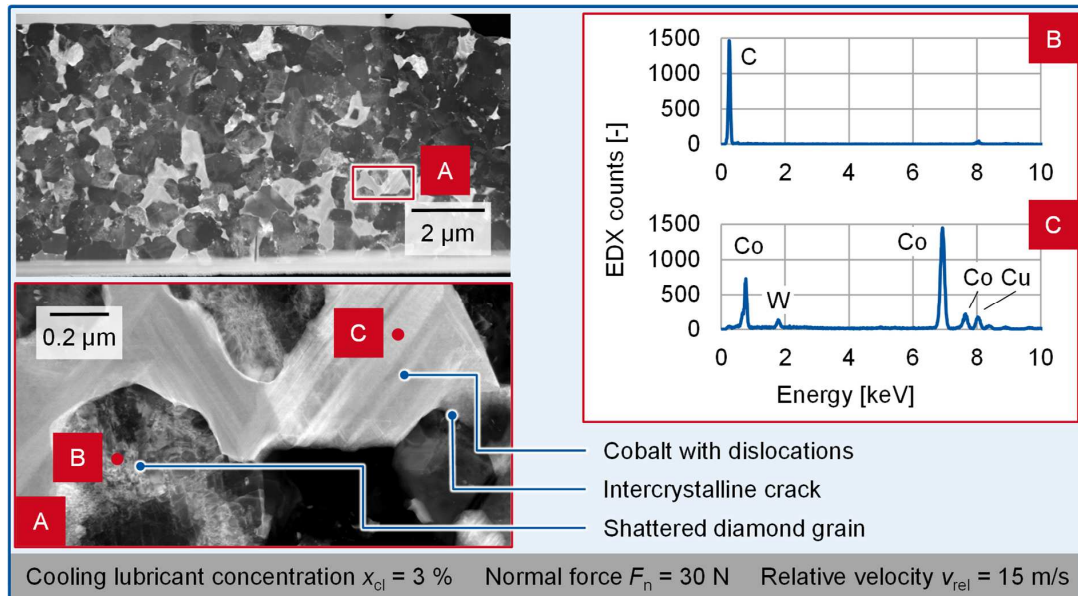


Figure 4. STEM/EDX analysis of the sample ground with a low thermo-mechanical load. (A) detail view of the marked area within the lamella; (B,C) EDX analyses of the marked points within the detail view.

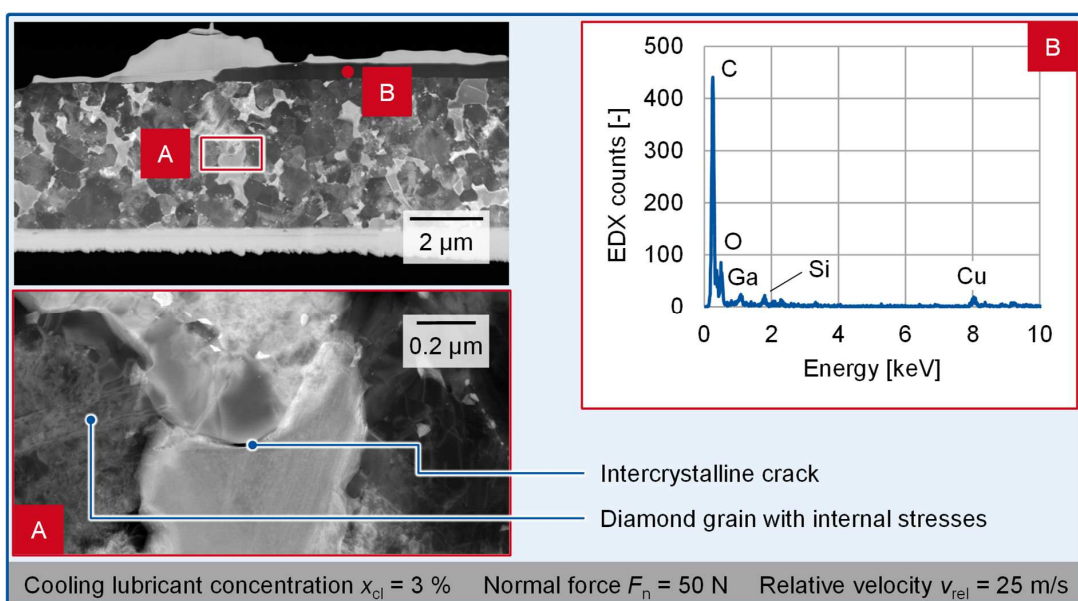


Figure 5. STEM/EDX analysis of the sample ground with a high thermo-mechanical load. (A) detail view of the marked area within the lamella; (B) EDX analysis of the marked point within the lamella.

When comparing the STEM analyses of the reference sample to the sample ground at a low thermo-mechanical load, it becomes obvious that no additional phenomena, especially no signs of additional thermal or mechanical material removal mechanisms, can be seen in the crystallographic structure of the samples. Moreover, the intensity and number of the present defects, such as intercrystalline cracks, dislocations in both phases, and internal stresses in diamond crystals, have increased over the grinding process. As these phenomena can be mainly attributed to mechanical load, and the EDX measurements did not indicate the occurrence of any thermally induced phenomena, the load collective during the grinding process appeared to be mechanically dominated.

An increased process load, introduced through an increase in both normal force F_n and relative velocity v_{rel} by approximately 67% between the samples in Figures 4 and 5, did not lead to the detection of thermal conversions within the EDX analyses either. The only oxidative process whose existence was presumed was not validated by multiple occurrences throughout the sample but was instead deemed a local phenomenon between the PCD microstructure itself and the platinum layer. It can therefore be attributed to the sample preparation or handling rather than the grinding process. The mechanically caused findings increased further in their prevalence. As a consequence, it can be concluded that the sample ground at the higher thermo-mechanical load was subjected to a higher mechanical load, while the thermal share of the load collective remained irrelevant.

The comparison of the samples summarized above implies that the grinding process of PCD with water-based cooling lubricants is strongly mechanically driven rather than thermally. This assumption is highly supported by the previous simulative study of the process conducted in [16]. Together with the findings from the earlier single-grain contact experiments [14], the grinding tests [15], and the TEM analyses in the present study and the findings from the simulation [16], an explanatory model for the grinding process of PCD with a water-based cooling lubricant is developed in the following paragraphs.

Schindler and Vits already presented explanatory models for the material removal mechanisms in the PCD grinding process and discussed the grinding wheel wear during grinding PCD with oil as a cooling lubricant. Both used comparable experimental materials, such as PCD and grinding wheel specifications, indicating that their results are generally comparable to the findings from the present work. Nevertheless, there are crucial differences between the works that lie in the process kinematics and the cooling lubricant type. Schindler's work presented his assumption of partially thermal material removal mechanisms. Furthermore, he stated that the material removal mechanisms change with a certain load limit, even leading to different roughnesses of the ground surface [7]. Vits, to an extent, disagreed with Schindler with regard to the material removal mechanisms relevant for the PCD grinding process, which he attributed to different experimental conditions and parameters in his work [8]. The present work differs from both the studies of Schindler and Vits when the process kinematics and the cooling lubricant are considered. For example, Vits investigated a track-bound grinding process with oil as a cooling lubricant [8], while the present study takes a force-bound grinding process with a water-based cooling lubricant into account. As a consequence of these differences, no previous explanatory model for the material removal mechanisms is directly applicable. Nevertheless, the model by Vits can serve as a structural basis for the explanatory model to be developed in this work.

Vits stated that after the first contact of the grinding wheel and the PCD workpiece, cracks are initiated and grow in both an intercrystalline and transcrystalline manner. After further strokes in the track-bound grinding process, the cracks propagate into the material, causing a weakening of the microstructure and the breakout of several diamond grains [8]. This aligns well with the results of the present study, as intercrystalline cracks were frequently found in the TEM images, especially between a diamond grain and an

underlying cobalt inclusion. The prevalence of this material removal mechanism increased with an increasing mechanical process load. Furthermore, some cracks were detected at diamond–diamond grain boundaries.

Vits attributed the observed intercrystalline cracks to two possible explanations. He assumed that the cobalt phase is exposed to a larger elastic deformation in the areas loaded by a diamond abrasive grain than a PCD diamond grain. Thus, shear stresses are introduced into the grain boundary between diamond and cobalt. In addition, Vits highlighted the thermal expansion coefficients of diamond α_{dia} and cobalt α_{Co} , which differ by a factor of 4.5 to 8 and cause internal stresses when the PCD structure is exposed to elevated temperatures. It should be noted that Vits already assumed that the thermal process loads have a minor influence on the material removal mechanisms than the mechanical process loads when grinding with oil as a cooling lubricant [8]. In the experiments [15] and simulations [16] previous to this study as well as the experiments in the present study, even lower temperatures were found than in the investigations of Vits. Especially, all measured temperatures were far lower than the conversion temperatures of the diamond phase within the PCD, which are generally higher than 575 °C [8]. Additionally, no clear signs of any thermally induced phenomena were identified in the TEM analysis. Hence, it can be assumed that the material removal in the grinding process of PCD with a water-based cooling lubricant is close to exclusively mechanically driven. Therefore, Vits's explanation regarding shear stresses in the diamond–cobalt grain boundaries is considered transferrable to the present explanatory model, while his explanation referring to the thermal expansion coefficients α_i is considered not transferrable.

In the TEM analysis presented above, some diamond grains showed signs of internal stresses and dislocations. Nevertheless, transcrystalline cracks were rarely detected in this study. Although some occurrences of shattered diamond grains are to be noted, for which previous transcrystalline cracks can be considered a possible cause, the transcrystalline cracks appear to be less prevalent than in Vits's investigations. Vits cited thermal alternating loads as a possible cause for the intercrystalline cracks [8]. In light of the same background as described above with regard to the intercrystalline cracks, these loads can be ruled out as a cause for the transcrystalline cracks and the shattered diamond grains in the present study. It can be assumed that the lower prevalence of transcrystalline cracks in this study compared to the experiments by Vits is due to the lack of the share of cracks initiated by thermal causes.

The diamond grain breakouts directly at the surface, as described by Vits [8], were not obvious in any of the TEM images analyzed for the present work. Therefore, it can be concluded that abrasion is a more dominant mechanism for the PCD grinding process with a water-based cooling lubricant. According to Vits, exceeding a certain limit process load is a necessary prerequisite for the increased occurrence of grain breakouts [8]. This finding is congruent to the explanatory model of Schindler, who also investigated the material removal mechanisms in PCD grinding with oil as a cooling lubricant. He came to the conclusion that a critical area-specific normal force F''_n in the grinding process is required to initiate the grain breakouts. Below this critical value, according to Schindler, the material removal is mainly thermally driven. The diamond grains undergo a graphitization and burning process, drastically decreasing their hardness and therefore leaving them in a state in which they are easy to remove for following abrasive grains. The result is a smooth-ground PCD surface with little to any diamond grain breakouts [7]. Although Vits agreed with the observation described by Schindler, he stated that in the parameter range he investigated, thermo-physical phenomena do not seem to be the cause [8]. The present study's conclusion follows this assertion by Vits, as thermally induced phenomena can be

excluded from the explanation, and microscopic abrasion processes are identified as the main cause for the smooth surfaces.

The data acquired through the present work proved insightful with regard to the material removal mechanisms during the grinding of PCD with a water-based cooling lubricant. According to the described comparison between the results of Vits [8] and Schindler [7], along with the results of the present work, an explanatory model for the material removal mechanisms in PCD grinding with water-based cooling lubricants was derived based on the explanatory model of Vits [8]. Figure 6 graphically displays a summary of the identified material removal mechanisms for the grinding process of PCD with a water-based cooling lubricant. Figure 6A shows a depiction of the initial state of a PCD workpiece with protruding diamond grains, diamond grains situated below the surface, and cobalt inclusions around the diamond grain. Figure 6B illustrates the condition of the PCD after the grinding process with a water-based cooling lubricant. Herein, intercrystalline cracks at the diamond–cobalt interface were identified as the most frequent material removal mechanism. Intercrystalline cracks at the diamond–diamond grain boundaries, meanwhile, are classified as a material removal mechanism of average rate of occurrence, alongside dislocations in diamond grains and shattered diamond grains. Voids at the PCD surface and transcrystalline cracks were considered as rarely occurring mechanisms.

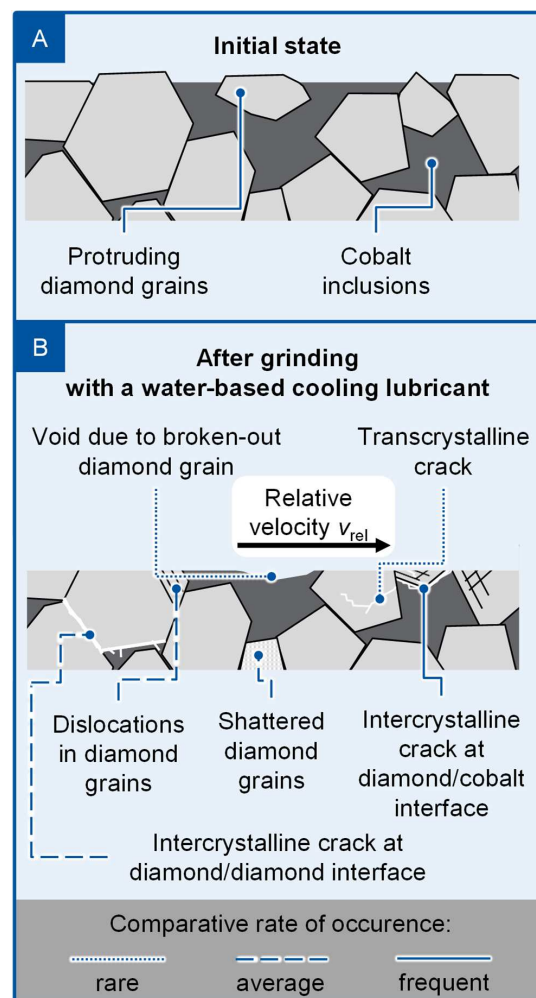


Figure 6. Explanatory model for the PCD grinding process with water-based cooling lubricants based on the explanatory model by Vits for the grinding process with oil as a cooling lubricant [8]. (A) initial state; (B) state after grinding with a water-based cooling lubricant.

3.2. Grinding Wheel Wear

The following paragraphs comprise the main results of the track-bound grinding experiments. Thereafter, an explanatory model for the grinding wheel wear is derived. As a macroscopic wear indicator, the grinding ratio G was calculated. It is defined as the quotient of the material removal V_w and the grinding wheel wear volume V_s . Due to this, a high grinding ratio G attributes to sharp and efficient cutting behavior of the grinding wheel. In Figure 7, a main effect diagram for the grinding ratio G is displayed. At an increased material removal V_w , the grinding ratio G was reduced. It can be assumed that a less sharp grinding wheel topography caused this effect, which will be further assessed in the following microscopic wear analysis. Since an increased depth of cut a_e and a decreased relative velocity v_{rel} both lead to an increased grinding ratio G , it can be assumed that high chip thicknesses h_{cu} are beneficial for an efficient cutting process, as also found by Vits [8], for example. Low chip thicknesses h_{cu} as well as high cooling lubricant concentrations x_{cl} assumably lead to a slippage effect between the grinding wheel and the PCD workpiece, decreased the grinding ratio G and increased abrasive grinding wheel wear.

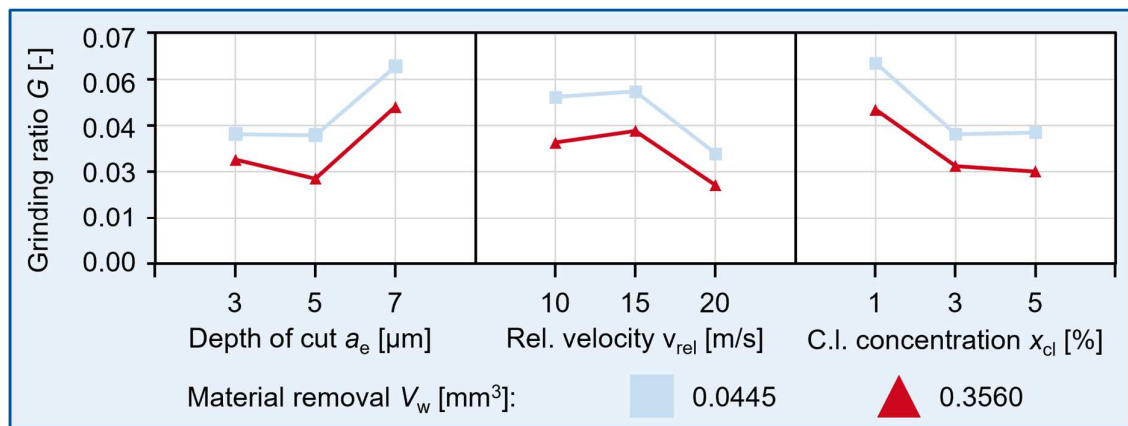


Figure 7. Main effect diagram for the grinding ratio G as a function of the process parameters and the cooling lubricant concentration.

The microscopic evaluation of the grinding wheel wear provided further insight into the present wear mechanisms, which enabled the confirmation and extension of the above-mentioned explanatory approaches to the grinding wheel wear. A representative example for an LSM image series is shown in Figure 8. The same section of the grinding layer is displayed after the dressing process and at the material removal stages also used in Figure 7. The grinding wheel wear mechanisms identified are marked within the images.

The key findings from the analysis of all produced images together with the macro wear analysis include the reduction in grain breakouts, grain flattening, and grain breakage with an increased depth of cut a_e and thus increased grinding ratio G . Furthermore, the clogging of pores intensified with an increased relative velocity v_{rel} , presumably with the cobalt phase of the PCD workpieces, leading to a decreased grinding ratio G . The abrasive wear was identified as a dominant wear mechanism, which resembles the results of Vits for the grinding of PCD with oil as a cooling lubricant [8]. No signs of thermally induced grinding wheel wear were found within the images.

Static topography parameters were deduced from the three-dimensional LSM images, as shown in Figure 9. The mean arithmetic height Sa dropped quickly within the initial wear of the grinding wheel, followed by a slow and continuous wear behavior towards higher material removal V_w . The reduced valley height Svk and reduced peak height Spk decreased initially and increased again at later wear states, leading to the assumption that the wear mechanism of grain breakout did not entirely end after the initial wear phase, but

was rather reduced to a smaller extent. Therefore, new and sharp cutting edges came into contact with the workpiece. This self-sharpening effect was similarly observed by Vits [8]. The peak material volume V_{mp} decreased continuously. This can be explained through abrasive wear of the grinding wheel throughout the grinding process.

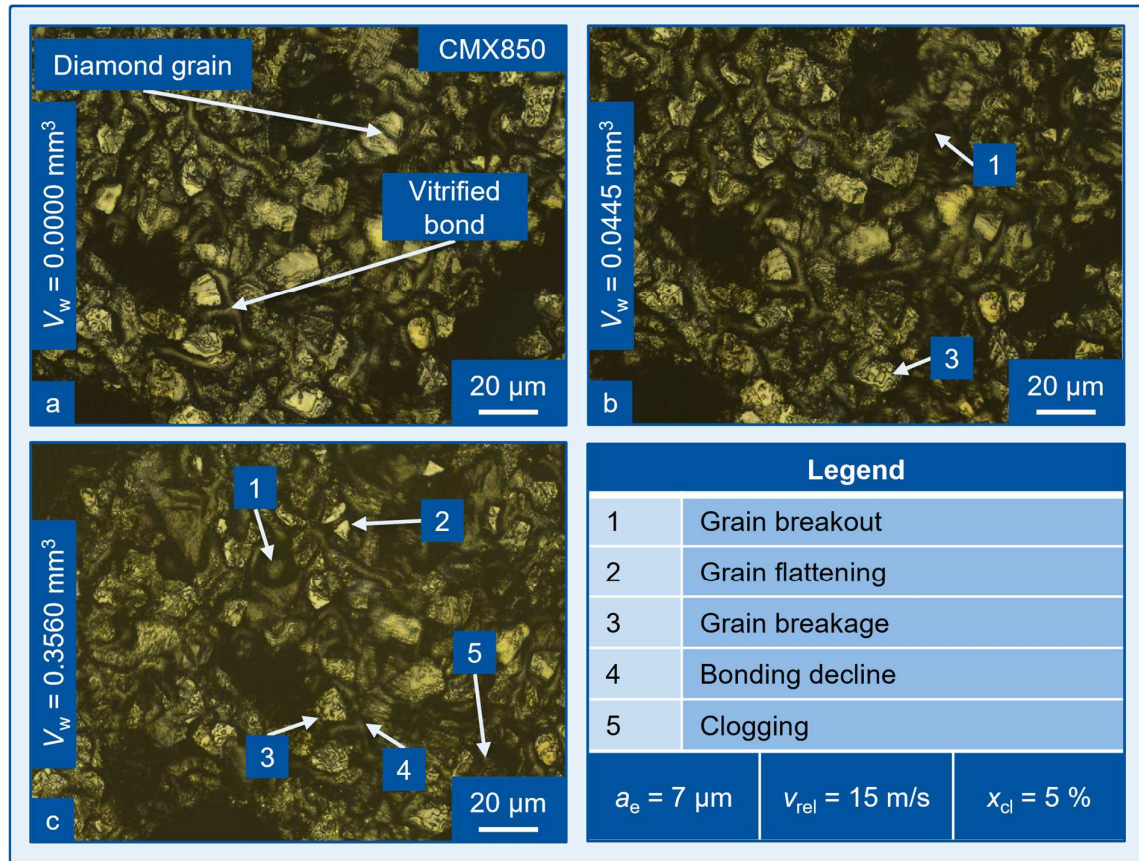


Figure 8. Qualitative grinding wheel micro wear analysis.

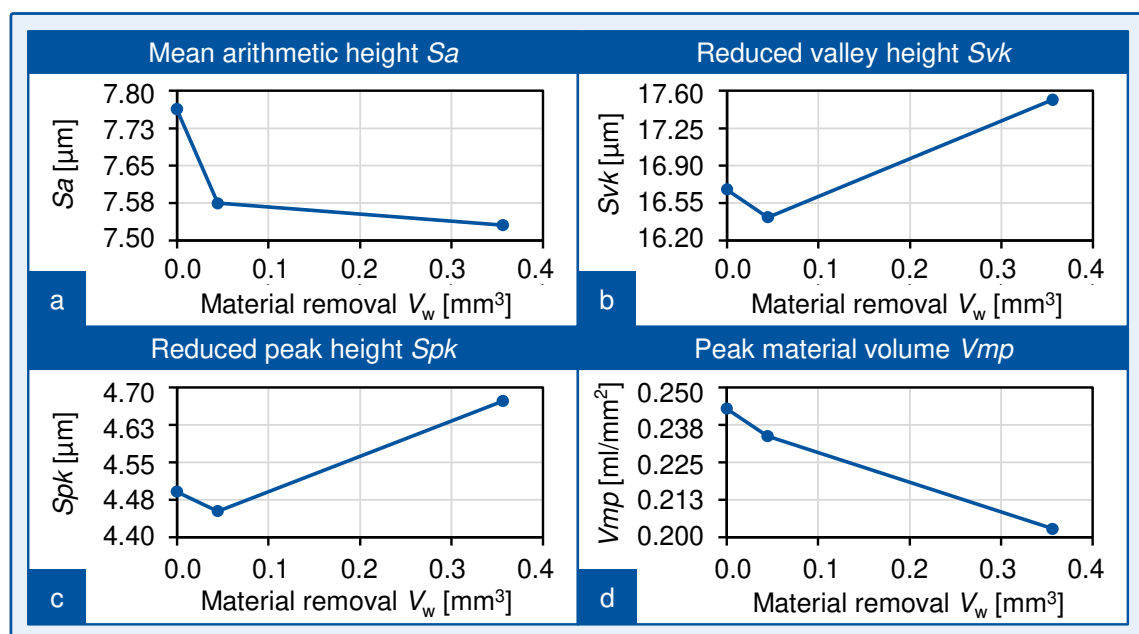


Figure 9. Quantitative grinding wheel micro wear analysis. (a) Mean arithmetic height S_a ; (b) Reduced valley height S_{vk} ; (c) Reduced peak height S_{pk} ; (d) Peak material volume V_{mp} .

The results of the macro and micro wear analysis presented above have subsequently been used to deduce an explanatory model for the grinding wheel wear mechanisms while grinding PCD with a water-based cooling lubricant. During the initial wear of the grinding wheel after the dressing process, the wear mechanisms of bonding declined, and grain breakage and grain breakout were found to be dominant. This led to the changes in the static topography parameters displayed in Figure 9 and thus to the early decrease in the effective roughness depth of the grinding wheel. Within the following continuous wear segment, the effective roughness depth decreased further but at a lower rate than before because the dominant wear mechanisms were abrasive wear and clogging of the grinding wheel. These findings are summarized in Figure 10.

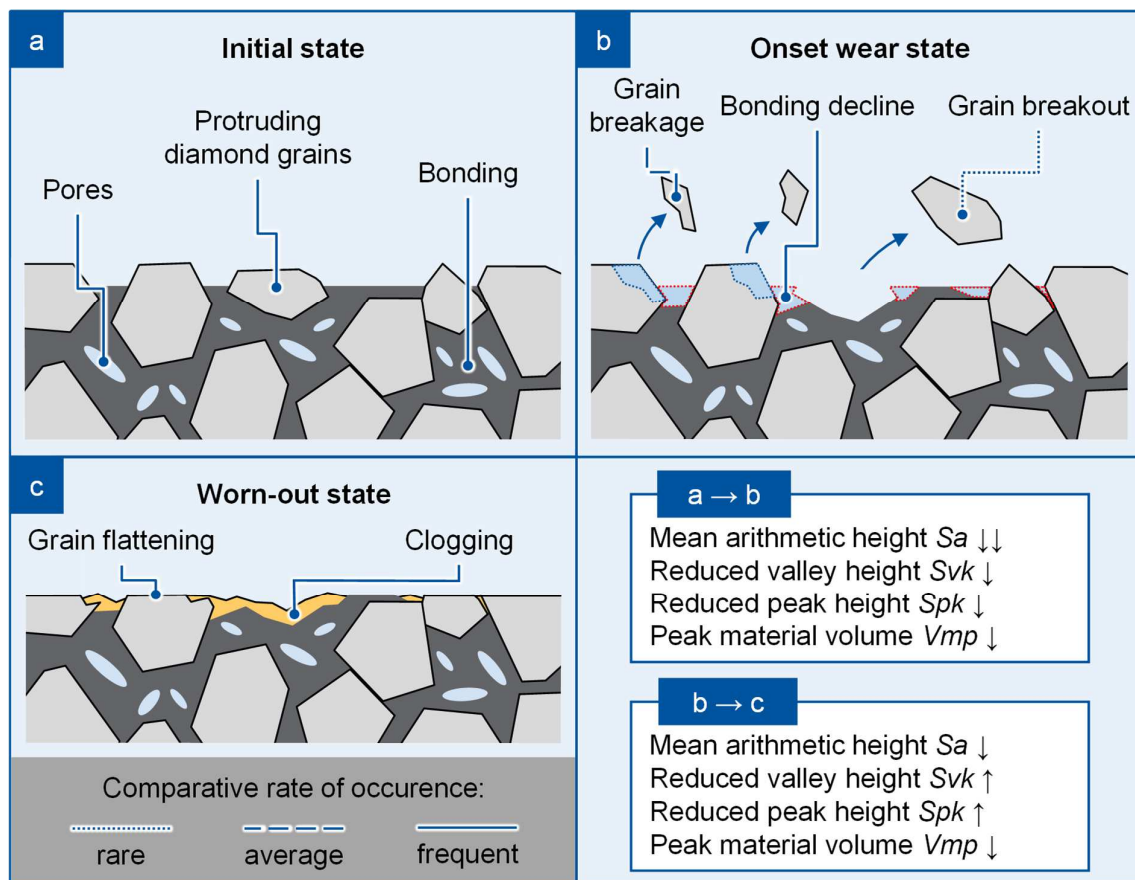


Figure 10. Explanatory model for the PCD grinding process with water-based cooling lubricants. (a) initial state; (b) onset wear state; (c) worn-out state.

4. Conclusions

The present work aimed to develop explanatory models for the PCD grinding process and the related grinding wheel wear with water-based cooling lubricants. Therefore, existing explanatory models of the PCD grinding process valid for grinding with oil as a cooling lubricant were considered as well as novel experimental and numerical investigations. The TEM analysis of ground workpieces presented in this study underlined the conclusion that no thermal material removal mechanisms need to be taken into account for the explanatory model. Consequently, a model was constructed that explained the grinding process of PCD with a water-based cooling lubricant through mechanical material removal mechanisms. The model was based on the explanatory model by Vits for the grinding of PCD with oil as a cooling lubricant. Vits's model, similarly to the model resulting from the present study, is built upon the finding that mechanical material removal mechanisms dominate

the grinding process. Nevertheless, Vits did not fully exclude the possibility of thermally induced material removal mechanisms in grinding PCD with oil as a cooling lubricant [8]. This assumption can be made for grinding PCD with a water-based cooling lubricant, following the results of this work. The explanatory model according to Schindler [7] proved not applicable within the parameter range and under consideration of the experimental materials used. For the grinding process of PCD with water-based cooling lubricants, it can be summarized that the primary material removal mechanisms are intercrystalline cracks at the diamond–cobalt interface as well as, to a lesser extent, at the diamond–diamond grain boundaries. Dislocations in diamond grains and shattered diamond grains were also deemed relevant, while diamond grain breakouts and transcrystalline crack formations were only rarely detected. The further analyses performed to explain the grinding wheel wear mechanisms showed that a division of the wear behavior into initial wear and continuous wear needs to be made. In the initial wear segment, bonding decline as well as grain breakage and grain breakout were dominant. In the continuous wear segment, grain flattening and clogging were found to be the most important mechanisms.

Novel findings within this study include the TEM analysis of PCD samples ground with a water-based cooling lubricant and the subsequent explanation of the material removal as well as the development of an explanatory model for the resulting grinding wheel wear. While research deficits concerning these aspects were closed, further potential for advanced studies on grinding PCD with a water-based cooling lubricant were identified. They can take different water-based cooling lubricants into account. This will further contribute to the understanding of the process, as structural differences in the application behavior of solutions and emulsions or different solutions among each other can be analyzed. Residual stress-mapping techniques can be adapted to suit PCD workpieces and thus used to gain further insight into the application behavior of different cooling lubricants. In the future, the explanatory models from this work as well as the referenced previous and above-mentioned advanced studies will serve as a basis to enable a knowledge-based process design for the industrial application.

Author Contributions: Conceptualization, all authors; methodology, P.B. and S.P.; validation, P.B. and E.R.; formal analysis, P.B.; data curation, P.B.; writing—original draft preparation, P.B.; writing—review and editing, all authors; visualization, P.B.; supervision, S.P. and T.B.; project administration, P.B. and S.P.; funding acquisition, T.B. All authors have read and agreed to the published version of the manuscript.

Funding: The authors greatly appreciate the financial support by the German Research Foundation (DFG) under grant BE 2542/56-3 “Analyse der Verschleißmechanismen beim PKD-Schleifen mit keramisch gebundenen Diamantschleifscheiben auf Basis eines Reibungsmodells” (project number 391043282).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. M’Saoubi, R.; Anxite, D.; Nobel, C.; Attia, H.; Kappmeyer, G.; Engin, S.; Sim, W.-M. High performance cutting of advanced aerospace alloys and composite materials. *CIRP Ann.* **2015**, *64*, 557–580. [[CrossRef](#)]
2. Du, Y.; Liang, Z.; Su, Z.; Ma, Y.; Zhao, X.; Liu, Z.; Xiao, Y.; Huang, H.; Yuan, H.; Zhou, T.; et al. Machine damage in the fabrication of polycrystalline diamond micro end mill with laser and grinding combined processing method. *Diam. Relat. Mater.* **2024**, *148*, 111454. [[CrossRef](#)]
3. Michels, C. Nur mit optimalem System: Schleifen von CBD-/PKD-Werkzeugen. *VDI-Z Spec. Werkzeuge* **2003**, 59–61.
4. Li, G.; Rahim, M.Z.; Pan, W.; Wen, C.; Ding, S. The manufacturing and the application of polycrystalline diamond tools—A comprehensive review. *J. Manuf. Process.* **2020**, *56*, 400–416. [[CrossRef](#)]

5. Kuppaswamy, R.; Airey, K.-A. Micro-grinding characteristics of polycrystalline diamond tool. *Int. J. Adv. Manuf. Technol.* **2015**, *76*, 161–171. [CrossRef]
6. Marshall, D.B.; Evans, A.G.; Yakub, B.T.K.; Tien, J.W.; Kino, G.S. The Nature of Machining Damage in Brittle Materials. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **1983**, *385*, 461–475.
7. Schindler, F. Zerspanungsmechanismen beim Schleifen von Polykristallinem Diamant. Ph.D. Thesis, RWTH Aachen, Aachen, Germany, 2015.
8. Vits, F.J. Tribologie beim Schleifen von Polykristallinem Diamant. Ph.D. Thesis, RWTH Aachen, Aachen, Germany, 2020.
9. Howes, T. Assessment of the Cooling and Lubricative Properties of Grinding Fluids. *CIRP Ann.* **1990**, *39*, 313–316. [CrossRef]
10. Brinksmeier, E.; Heinzl, C.; Wittmann, M. Friction, Cooling and Lubrication in Grinding. *CIRP Ann.* **1999**, *48*, 581–598. [CrossRef]
11. Kenter, M. Schleifen von Polykristallinem Diamant. Ph.D. Thesis, Universität Bremen, Bremen, Germany, 1990.
12. Denkena, B.; Krödel-Worbes, A.; Müller-Cramm, D. Wear-adaptive optimization of in-process conditioning parameters during face plunge grinding of PcBN. *Sci. Rep.* **2022**, *12*, 1012. [CrossRef] [PubMed]
13. Denkena, B.; Grove, T.; Behrens, L.; Müller-Cramm, D. Wear mechanism model for grinding of PcBN cutting inserts. *J. Mater. Process. Technol.* **2020**, *277*, 116474. [CrossRef]
14. Breuer, P.; Prinz, S.; Bergs, T. Tribologische Untersuchungen zur Schleifbearbeitung von polykristallinem Diamant mit wassergemischten Kühlschmierstoffen. In Proceedings of the Schleiftagung, Fellbach, Germany, 31 January–1 February 2024.
15. Breuer, P.; Prinz, S.; Bergs, T. Analyse der tribologischen Verhältnisse beim Schleifen von polykristallinem Diamant mit einem wassergemischten Kühlschmierstoff. In Proceedings of the Schleiftagung, Stuttgart, Germany, 14–17 May 2024.
16. Breuer, P.; Gilles, M.; Knothe, J.; Prinz, S.; Bergs, T. Thermal analysis of the polycrystalline diamond grinding process with a water-based cooling lubricant by numerical simulation. *Int. J. Adv. Manuf. Technol.* **2025**, *136*, 2325–2337. [CrossRef]
17. Element Six Ltd.: Giving Toolmakers a Competitive Edge. Available online: <https://e6-prd-cdn-01.azureedge.net/mediacontainer/medialibraries/element6/documents/brochures/element-six-metalworking-brochure-en.pdf?ext=.pdf> (accessed on 17 March 2025).
18. Element Six Ltd. PCD Grade: CMX850. Available online: <https://e6-prd-cdn-01.azureedge.net/mediacontainer/medialibraries/element6/documents/datasheet/pcd-cmx850.pdf?ext=.pdf> (accessed on 17 March 2025).
19. Produktinformation AquaTec 5001. In *Company Brochure*; oelheld GmbH: Stuttgart, Germany, 2020.
20. Mattes, M. *Physical Properties of the Cooling Lubricant Oelheld Aquatec 5001*; Interview with Breuer, P., via email; oelheld GmbH: Stuttgart, Germany, 2023.
21. Laurindo, Q.M.G.; Rosa, J.M.B.; Da Silva Guimarães, R.; Lugon, R.D.; Xing, Y.; Lima, L.S.; Filgueira, M. Molybdenum as a new binder for polycrystalline diamond (PCD) prepared by HPHT sintering. *Ceram. Int.* **2023**, *49*, 17313–17322. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.