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Comparison of different approaches towards measuring cutting edge radius and geometry on ultra sharp diamond and cbn tools

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Abstract
To achieve high quality surface finishes, cutting tools with low cutting edge waviness and sharp cutting edges are needed. Commonly, polished monocrystalline diamond tools are used. The size of the optimal cutting edge radius (RE) and micro geometry is highly dependent on the material to be machined. Generally, a smaller RE is suitable for soft materials like copper or aluminium,but brittle materials require a higher value which ensures effective negative rake. Furthermore, the actual RE value is a critical component for setting up process parameters when brittle materials are machined. Currently, the measurement of the RE of ultra sharp tools remains challenging. Ordinarily, the values of RE fall within the range of tens to hundreds of nanometres. Measurement using optical methods is not viable as the diffraction criteria of visible light limits the resolution to effectively larger values than the RE to be measured, while the reflectivity and transparency of polished diamond hinder effective confocal measurements. Consequently, tool manufacturers are generally unable to provide an RE value for a given tool. The current state of the art approach for the measurement is a reversal method. For this, an impression of the cutting edge in a soft material (i.e. copper) is created using a dedicated device and the reverse artefact of the cutting edge is analysed. Currently, the measurements are conducted using atomic force microscopy (AFM). The indentation depth and sidewall angles that can be measured with this approach are limited. In this research, a high precision machining centre is used to generate the reverse artefact, allowing for simple industrial implementation of this technique. Furthermore, additional methods for indentation measurements are explored. These include a combination of focused ion beam (FIB) milling, scanning electron microscopy (SEM) evaluation and direct SEM evaluation of a platinum sputter coated cutting edge. Cutting edge radii with double digit nanometric dimensions have been successfully evaluated using this novel approach.

diamond tool, tool geometry, cutting edge, measurement, scanning electron microscope (SEM), atomic force microscopy (AFM)

1. Introduction

For high quality surface finishes, polished tools with a low cutting edge waviness are needed. Traditionally, these tools are crafted from monocrystalline diamond (MCD); however, alternative materials such as binderless polycrystalline diamond (BL-PCD) or cubic boron nitride (CBN) are increasingly being utilized [1], [2]. Generally, the cutting edge radius (RE) of polished MCD tools falls within the 20-200 nm range and they generally have a 0° rake angle.

To achieve sufficient surface quality when machining hard and brittle materials such as monocrystalline silicon or silicon carbide, it is essential to operate within the ductile cutting regime [3]. This regime is achieved as a combination of hydrostatic pressure, sheer strain and elevated temperature in the cutting zone (primary deformation zone) [4]. The nature of this state is a direct result of tool geometry and mostly the effective rake angle. Which typically has to have a negative value [5], [6].

The effective negative rake can be either generated by an actual rake angle or by selecting an appropriate combination of RE and maximum chip thickness (Hm) value [7]. Therefore, in the context of machining hard and brittle materials in a ductile cutting regime, accurate knowledge of the cutting edge radius of a tool is imperative for the proper configuration of machining parameters, with particular emphasis on the Hm [8], [9], [10]. For these reasons, the evaluation of the cutting edge radius of the cutting tool is a critical factor.

The state-of-the-art approach uses direct and indirect atomic force microscopy (AFM) measurement of the RE. The direct AFM measurement requires a laborious alignment process and the risk of cantilever tip damage is significantly high. Hence, the indirect approach (reversal method) is being explored. The cutting edge of the tool is indented into a soft and ductile workpiece and the resulting indentation is analysed. [11], [12]

Direct optical measuring methods cannot be used due to the optical diffraction limit of light used in the measuring devices. This limits the lateral resolution to 10 nm which is insufficient considering the typical RE values of the evaluated tools [12]. Moreover, the spatial resolution, restricted by the Abbe limit, is also inadequate. The reflectivity and transparency of polished diamonds hinder effective confocal measurements.

This study investigates the feasibility of measuring RE in ultra sharp polished cutting tools using diverse methodologies. The assessment involves SEM techniques and the application of a reversal method. The outcomes obtained from the reversal method are further analysed through AFM and a combination of FIB cutting and SEM analysis.

2. Materials and methods

Two distinct approaches were used to measure the RE in this work. Initially, the possibility of evaluating the tool directly using SEM was explored. The MCD tools were coated with 20 Å of platinum and subsequently analysed. Firstly, the ball milling tool was angled in a 5-axis SEM so that the electron beam was tangent to the analysed section of the cutting edge.

Consequently, the focal plane was adjusted to the point where the electron beam tangentially intersected with the ball mill (see Figure 1). Secondly, a direct cutting edge analysis was carried out of a damaged section of the tool. A chip in the cutting edge effectively provides a cross section of the tool.

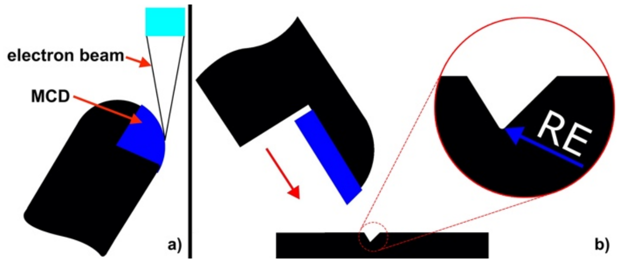

Figure 1. a) Setup of the tangential direct SEM measurement and b) schematic diagram of the indentation procedure – the red arrow shows the feed motion

Subsequently, a reversal method is investigated. The cutting edge of a stationary tool is pressed into a soft workpiece, similar to indentation hardness tests. The tools were indented into a 99% pure copper workpiece with an indentation depth of 5 µm. This material has a combination of high density, large Young's modulus and low yield strength, which is a favourable combination of characteristics for this purpose [13]. As a result, the elastic deformation after the indentation will be minimal [13]. Drawing upon the research conducted by Zhang et al., the impact of elastic deformation on measurement results falls within the low single-digit nanometer range. They found that for indentation depths larger than 200 nm the elastic recovery can be ignored [12]. Furthermore, the chemical interaction between the tool and the copper workpiece should be minimal.

Prior to the indentation procedure, the face of the part was fly cut with an MCD tool to achieve a single digit nanometric surface. The indentations were performed on a Kern Micro HD precision CNC machining centre, which provides a positioning accuracy to within 1 µm. All of the evaluated tools have a flat rake (i.e. no helix) and a single flute and were held in the spindle in a standard powRgrip holder. The length of the tools was set using a Blum laser tool setter and finetuned by milling a flat surface at a location measured by a touch probe. The spindle angulation was found using a dial test indicator swept over the rake and the position held through the NC control. The indentation was performed at a speed of 5 mm/min with a 1 s dwell time at the final depth. The cutting edges of all the tools were inspected pre and post indentation and process induced damage was not found.

Three specific tools were evaluated: tool A ('Standard') was an MCD tool which was a 6.206 mm MCD ball mill with a 0° rake from Contour Fine Tooling BV; tool B was a new, 6 mm MCD ball mill with a -30° negative rake and a chemically assisted rake finishing process from Edge Technologies; and tool C was a new, 2 mm BL-PCD ball mill with a 0° rake and polished rake and flank from SUMITOMO ELECTRIC Hartmetall GmbH. Because the evaluated tools are ball mills, the resulting reverse artefact to be evaluated is a V groove (see Figure 2), which gets gradually shallower towards one end. Therefore, the depth of the indentation can be in the range of µm at the tip even if the depth requirement for the evaluation is in the tens of nanometres range.

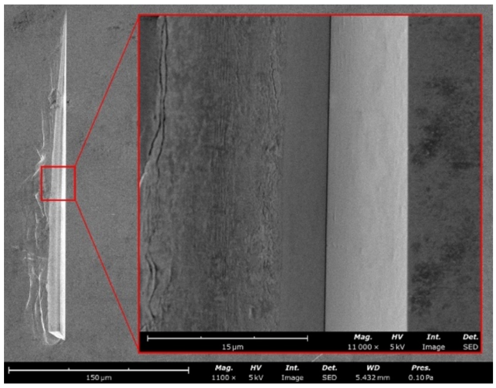

Figure 2. Top view of the indentation made with tool A

The AFM measurement of indentations is done using the Park Systems NX20 in non-contact mode. The lateral imaging resolution was set to 4.88 nm. The AMF probe limitation has to be taken into account for cutting tools with a 0° rake angle either by measuring indentations shallower than the RE or indenting the workpiece at an angle. Here the cutting tools with a 0° rake angle were indented with a B axis angulation of 35°, while the spindle was oriented appropriately as shown in Figure 2 b). As a result, the indentation features walls angled over 90° from the top face, allowing access for the AFM probe tip.

The second approach to evaluating the indentations was a combination of FIB milling and SEM imaging using the In-Beam SE detector. The analysis was done on a Tescan XEIA3. Before the FIB milling the area was coated with platinum to reduce process-induced damage of the surface as well as the curtaining effect. Figure 3 shows the entire sequence of steps where the surface is firstly coated with platinum and subsequently the FIB cut is made at a specified location.

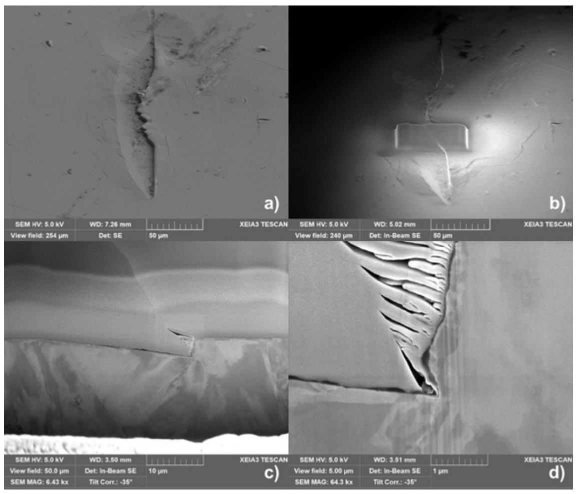

Figure 3. The sequence of the SEM analysis: a) the raw indentation in the workpiece, b) coated with platinum, c) a side view of the indentation and d) a micrograph of the cutting edge with a view field of 5 µm. Note that this analysis method is not limited by the geometry of the indentation.

3. Results and discussion

3.1. Direct measurement of MCD

Using the direct SEM approach has a smaller risk of damaging the cutting tool during the analytical process. Apart from manipulation, coating and the electron beam, there is no interaction with the tool. The results from the direct SEM analysis with the tangent approach are displayed in Figure 4. The mean RE value measured with this method was 146 nm with standard deviation (SD) of 7 nm at a point 30° from the tool rotation axis. However, this approach has several drawbacks. Precision is crucial in placing the focal plane precisely where the electron beam is tangential to the cutting edge, which is a task heavily reliant on the operator's precision and highly susceptible to human error. The rotation of the tool along its axis is another critical step, greatly dependent on the operator and impactful on the results. Furthermore, the section of the cutting edge above the focal plane causes blurring due to electron beam blockage, diminishing the clarity of the measured feature.

This method is straightforward in terms of preparatory steps, but its precision and repeatability are constrained because the correct focal plane setting which affects the results is susceptible to operator error. Therefore, all the samples should be analysed by the same person with meticulous care to ensure the validity of the results. This method is better suited for comparing several significantly different tools rather than for precise measurements.

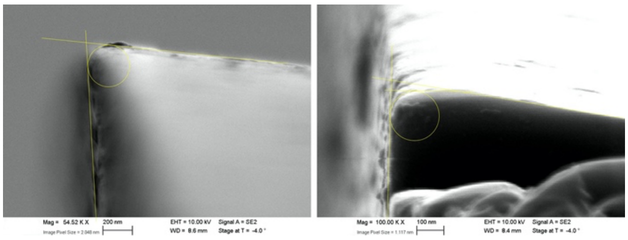

Figure 4. a) Direct measurement of the RE using the SEM beam tangent to the ball mill and b) direct measurement of the RE at a chipped section of the cutting edge – tool A.

SEM imaging of a section of the cutting edge damaged by chipping offers a clear visual representation of the cutting edge shape (effectively a cross section), and finding the correct focal plane is more straightforward with this method. However, it is only suitable for the analysis of used and damaged tools. Additionally, the section of the cutting edge that is to be analysed cannot be freely selected. Any measurement results will have to be corrected if the imaged plane is not normal to the cutting edge.

The direct RE measured at the chipped section (see Figure 4 b)) of a used MCD tool (tool A) was 89 nm with SD of 3 nm. This value aligns with the edge reversal method (FIB-SEM) in which the same section of the cutting edge was measured, yielding a value of 88 nm with SD of 2 nm. In the same setup, this approach can be employed for comprehensive wear analysis of tools, as wear marks (e.g. VB wear, chipping of the cutting edge) are visible and measurable. Larger sections of the cutting edge can be evaluated than the single cross section in the FIB-SEM reversal method.

3.2. Measurement using the reversal method

3.2.1. Evaluation of RE using AFM

The combination of the indentation method and AFM measurement as demonstrated by Zhang et al. and Chen et al., involves a dedicated nanoindentation device with a depth setting below 200 nm [9], [10]. One of the disadvantages of measuring deep indentations is that AFM probes with a high aspect ratio need to be used and that a significant height difference between the original surface and the indentation might influence the result and cause damage to the probe. Therefore, here a shallow section of an indentation left by a circular cutting edge is scanned.

Even with a shallow section the material displaced around the indentation and the resultant burrs (see Figure 2) hinder the measurement process. The resulting scans do not follow the expected shape of the indentation and show a significantly higher RE than the other methods (leading to improbable values). It was also found that this measurement method is sensitive to the meticulous alignment of the sample as well as its cleanliness. Future research should focus on resolving the deficiencies in the current understanding of RE AFM measurement, specifically its process parameters, challenges, and optimal settings. Owing to these complexities, further exploration of this method was not pursued.

3.2.2. Evaluation of RE using FIB-SEM combination

Evaluation of the cutting edge radius combining the reversal method and FIB with SEM imaging provides a clear image of the micro geometry for a given cross-section. The procedure is definitive and replicable. This method can be used for any tool material and the precision of the edge radius is limited only by the SEM resolution. Unlike AFM this measurement is not constrained by the geometry of the indentation. For instance, tool C underwent indentation with a rake face perpendicular to the top surface of the copper workpiece, and the corresponding evaluation is depicted in Figure 5 b).

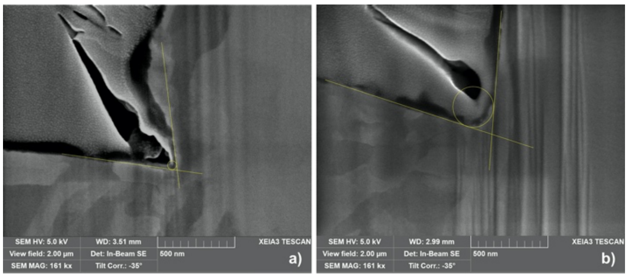

Figure 5. Evaluation of the RE of a) tool A and b) tool C with rake face indented perpendicular to the top face of the copper workpiece

It is worth noting that only a single cross-section of the cutting edge can be imaged at a time. This limitation restricts the possibility of averaging, a common practice in standard RE evaluation with optical methods. In further research a series of FIB cuts and SEM measurements could be done to achieve the averaging effect and obtain a more comprehensive analysis of a cutting edge section. Furthermore, the observation of tool wear is not as straightforward as other methods, even though the change in the rake angle caused by VB tool wear is still clearly noticeable (see Figure 6).

All three tools are assessed with this method, with tool A intentionally evaluated at a spot where a significant portion of the cutting edge is chipped away. This spot exhibits the smallest RE, allowing for the evaluation of the resolution limit of this method. The resulting RE 27 nm with SD of 3 nm for tool A at this specific section, can be determined from Figure 5 a).

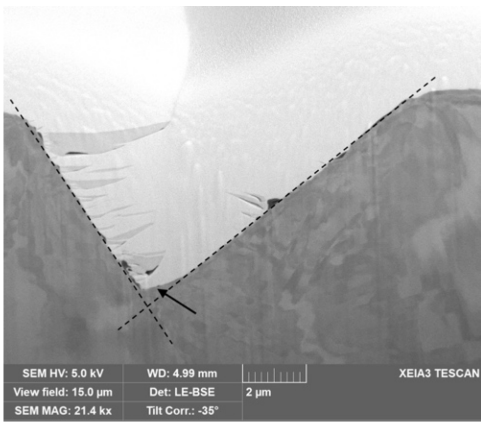

Figure 6. The arrow indicates VB tool wear on the flank face of an MCD tool.

Tools B and C were measured using the same approach, and the resulting RE for tool C was 126 nm with SD of 5 nm. However, achieving precise measurements for tool B proved challenging due to the excessive curtaining effect near the RE area (see Figure 7). This limitation highlights a potential pitfall of the measurement method. Curtaining in each sample must be assessed, and appropriate FIB milling parameters need to be established to minimize the associated effect, along with thorough cleaning of the sample before the FIB-SEM process.

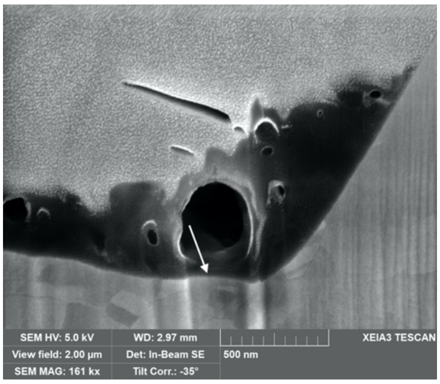

Figure 7. Analysis of indentation created by tool B, with the arrow indicating a feature (wave) resulting from the curtaining effect, which hinders effective RE measurement.

4. Conclusion

This work presents existing and novel approaches, all of which are viable for the measurement of cutting edge geometry and RE in ultra-sharp cutting tools.

Direct SEM – This method consists of direct observation of a tool using an SEM. It is a valid option which gives accurate results for the assessment of damaged tools that effectively have a physical cross section (i.e. chipping) of the cutting edge. In addition, the tool wear can be analysed. The application of this technique on new tools is constrained due to the tangential approach of the electron beam. This approach complicates the identification of the correct focal plane and results in blurring in the measured area.

AFM reversal method – The cutting tool is indented into a soft ductile workpiece and the reverse artefact is scanned using AFM, from which the RE is measured. As demonstrated in prior research, this method is viable. Here it was found that it is sensitive to material displacement around the indentation and requires meticulous sample preparation for successful outcomes. A notable gap in the current literature is the lack of detailed descriptions of the AFM measurement process, its parameters, and potential challenges, which future studies should aim to address.

FIB-SEM combination – This novel method also relies on analysis of the reverse artefact of the cutting edge. Using FIB milling a cross section of the indentation is revealed with minimum process induced damage, and this is subsequently imaged by SEM. It can be reliably used for RE measurement of ultra sharp cutting tools. Additionally, there is no restriction of the indentation geometry. This analysis can be hindered by the curtaining effect caused by FIB milling, which needs to be monitored. Future work should focus on a reduction of the curtaining effect, ensuring accurate and repeatable results.

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