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Wear Mechanism and Quantification of Polycrystalline Diamond Milling Cutter in High Speed Trimming of Carbon Fiber Reinforced Epoxy

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Abstract

The use of Poly Crystalline Diamond (PCD) cutters in machining of composite material is increasing. Understanding their wear mechanism and clarity on wear measurement methodology will lead to their productive usage and cost justification. This study focuses on understanding wear in PCD milling cutters at the micro, macro level, and its physical characterization when employed for fibrous composite machining. This leads to the development of a proposal for a clear methodology on consistent wear measurement, which includes a suitable selection of techniques and identification of wear parameters. Continuous diamond skeleton structure made during binder infiltration is captured in worn out PCD edge with the help of scanning electron microscopy. Overall wear process appears to be a complex mixture of losing binder, smaller grains, and pieces of continuous diamond skeleton. This results in cavities of various shapes and forms on the cutting edge making substantial variations in edge recession and edge width. After analyzing, different tool parameters, it was found out that the distance from apex to edge roundness of clearance or rake face is a reliable and repeatable wear parameter. These are shown to be comparable between different wear locations, flutes, and tools suggesting higher wear predictive capabilities. Among different techniques, three-dimensional high-resolution profile scanning of the cutter has been identified as the most efficient tool for tracking wear at regular intervals in tool life prediction studies.

Keywords- Tool Wear, Polycrystalline diamond cutter, Wear mechanism, Optical Scan, Tool parameters

1. Introduction

Parts and components made from Carbon Fiber Reinforced Polymer (CFRP) require to be machined after cure. Although current composite manufacturing techniques produce near final shapes of the end product, these parts are subjected to one or more machining operations to achieve final shape and dimensional tolerances. Turning, milling, trimming, and drilling are examples of commonly used post cure machining operations carried out on the CFRP parts. The inherent fact that composite materials consist of two or more phases differentiates their machining needs from conventional materials. For instance, in the case of CFRPs, carbon fiber type, orientation, and structure can play a role. Likewise, matrix content and its different mechanical and thermal properties can influence the machining processes. Consequently, compared to machining homogenous material, the tools used in machining composites have to bear more severe loading from heat resistant and abrasive carbon fibers along with alternating cutting forces and thermal stresses [1, 2, 3].

Tungsten carbide and PCD tools are found to perform well for post machining operations in CFRPs like edge trimming. Due to poor surface finish and higher wear rate, High Speed Steel (HSS) tools are not used for these materials. Carbide tools provide flexibility in attaining complex geometries and are preferred for rough cutting. On the other hand, PCDs are used for fine and final cuts perhaps due to their relatively higher cost.

PCD tools are recognized for their superior features such as hardness and wear resistance. They are manufactured using compacting and sintering methods where grains of diamond is first mixed with a binder like cobalt. The presence of cobalt improves the toughness of PCD and enables the random orientation of the diamond particles. The compacted PCD is integrated into a tungsten carbide substrate for imparting mechanical strength and impact resistance [4, 2].

The unwanted removal of material from the cutting edge or its permanent deformation causes tool wear. Compared to other tools, wear in PCD is complex and caused by both intrinsic and extrinsic factors. The intrinsic factors include the microstructure and mechanical properties while extrinsic factors comprises dynamic loading and machining parameters [5, 6]

Although flank wear is the widely used measure of tool wear because of its simplicity and easiness in measurement, it cannot be the sole criteria for explaining the wear of PCD cutters. For example, in the milling study [7] performed on a unidirectional CFRP of 90° fiber angle using double straight edge PCD cutters of 10 mm diameter, a quantity V_x was defined to quantify tool wear. It is the ratio of the measured area containing uniform flank wear, non-uniform flank wear, and the edge wear, to the width of cut. The research also divided wear in PCD into three regions- run in, quasi steady state and accelerated wear. Run in wear is the stage of high wear and is explained by the rapid wear of the tool layers during manufacturing. The exposure of fresh diamond crystals leads to quasi steady state wear. Higher cutting forces and subsequent microchipping is the reason for accelerated wear. Similar results were also reported which highlighted the rapid increase of tool wear in the beginning followed by a slow growth with cutting length [8].

Ferreira et al. [9] investigated the influence of cutting length on flank wear for different tools and concluded that tool wear is lowest for PCD compared to carbide and ceramics tools. The strong correlation of cutting speed, feed force, and surface roughness on tool wear were also reported in the study. A similar study also reported that at intermediate cutting speeds, wear of discreet diamond crystal from the cutting edge and flank face was developed. At higher cutting speeds, fibers are broken, and cracks are formed which leads to microchipping [7, 10]. By using optical microscopy, Kolar and Masek [11] conducted a tool life test by taking cutting speed, feed speed and radial depth of cut as 300 m/min, 0.05 feed per tooth , and 3 mm respectively. The tool life criterion was taken as 0.1 mm flank wear. It was shown that PCD tools experienced six times less wear than coated carbide tools.

An interesting correlation of temperature with tool wear was discussed in the face turning study of carbon/phenolic ablative composites with PCD cutters by Sreejith et al. [12]. The authors defined cutting force as a product of specific cutting pressure, feed rate, and depth of cut. An intermediate optimum cutting speed of 300 m/min and an optimum temperature of 300 °C to 350 °C offered an almost steady specific cutting pressure and is the most suited speed for machining CFRP leading to lower wear. More recent studies have also stated that the performance of PCD tools can be compromised at around 700°C [13] and the surface damage of the PCD appears to occur around 600 °C accompanied by extensive binding phase extrusion of PCD. Micro-cracks, both at the grain boundaries and in the grains are reported with the increase of temperature to 700 °C [14, 15, 16]

The type and size of diamond grains used in the PCD cutter also influence tool wear. The presence of fine diamond grains in PCD makes the cutting edge sharp after grinding while coarse diamond grains can lead to blunt cutting edges. In addition to this, tool wear and erosion of particles are high in fine grain size while brittleness and breakage of particles are high for coarse grain sizes [17]. This was also confirmed in the turning study of aluminum alloy-based metal matrix composite using PCD of different diamond grain sizes on graphite/epoxy composite material at a cutting speed of 3.81 m/s [18]. Thus, medium grain size is preferred over both small and large grain sizes to achieve minimum flank wear [5]. Apart from grain sizes, the frequency and magnitude of cutting forces increase the pressure on the cutting edge. This can lead to the development of cracks paving way for microchipping of diamond crystals. At cutting speeds exceeding 9.42 m/s, accelerated wear starts which reduces the flexural strength and stiffness of the PCD tool thereby facilitating easy removal of diamond crystals [7, 19].

Studies have also pointed out that tool wear in PCD is mainly present at the tool tip and the triangular wear region developed on the bottom surface [8]. The propagation of this wear is attributed to the development and initiation of micro cracks along the diamond/binder grain boundaries leading to rupture of the tool material. This was explained by Qing [5] et al. by machining laminated flooring with Al_2O_3 overlay using four different PCD cutters of different diamond grain sizes at a feed rate of 0.2 m/s and depth of cut 3 mm. The two wear characteristics are intergranular wear and partial cleavage fracture. Of these, intergranular wear is the dominant one and is developed when the grain boundary is worn out due to variable loading. On the other hand, cleavage fracture is developed when the diamond grains are broken along the cleavage plane. Localized dynamic loading on the cutting edge, tool tip oscillation, oxidation wear, and degradation at higher temperature are expected to be the cause of tool failure, spalling, notching, and cracking respectively [12].

Although the existing literature covers most of the qualitative and quantitative aspects of tool life and its underlying factors, the studies in the calculation of tool wear of PCD are not conclusive due to the complexity of the problem and dependence on experiments. Jia et al. [7] noted that there is no consistent quantitative methodology of PCD tool deterioration evolution in the machining of CFRP. Arsecularatne et al. [20] admitted in their study that they are unable to identify dominant tool wear mechanism in PCDs while comparing them with other types of cutters for machining metal alloys. This is primarily because there is a limited amount of literature available on the wear of PCDs in machining CFRPs, and certainly without in-depth and conclusive verdict.

This is possibly due to the fact that wear measurement is not very easy for these tools. It is a tedious job to measure wear with conventional optical microscope due to limitation on control of depth of field, low resolution, and reflective nature of diamond particles. Robust microscopy including SEM can become expensive resource for measuring gradual wear after regular intervals particularly when wear is very small while taking fine cuts. Most of the tool wear studies using SEM are performed for the characterization of the deterioration and limited data is available on gradual wear for example with respect to the cutting length. Perhaps it is difficult to take images after every few units of cutting length as machines are programmed to conduct continuous operation at the same tool setting. Moreover, it is almost impossible to view the cutting edge exactly at the same location every time. Although expensive, three-dimensional laser scanning meteorology system has a great potential to be employed for measuring wear at regular intervals during long term machining trials. With tool geometry- specific scanning systems, wear parameters specific to cutting conditions, tools, work piece and parameters can be identified and recorded. Furthermore, the technique will also permit identification of reliable tool parameter in investigating tool wear. This work focuses on understanding the wear mechanics of polycrystalline diamond tools, develop a clear methodology for wear measurement and identification of wear parameters.

2. Materials and Methods

Edge trimming operation was performed on a three axis CNC router (MultiCam®, Texas, USA). A 500 mm long, 10 mm thick CFRP blank was clamped to the machine table so that the long side can be trimmed along the edge in a climb cutting configuration (Figure 1). The material was a plain-weave multidirectional CFRP laminate (Strata Manufacturing PJSC®, Al Ain, UAE) with a fiber orientation [0/90°]. The radial depth of the cut was held at 10 mm. The router is CNC programmed to perform 40 repeated cuts on the plate to obtain 20 m of the cutting length.

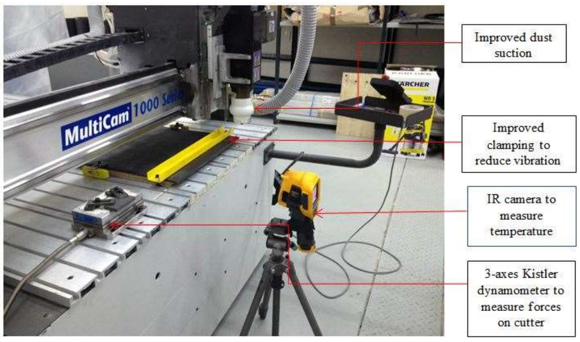


Figure 1- Cutting set up.

The PCD tool used in this study is a Cruing® two flute milling tool with 10 mm diameter, 120 mm total length, and 30 mm polycrystalline diamond flute length (Figure 2, Figure 3). The diamond wafer is brazed onto the carbide tool shank. The shank surface is treated with sandblasting technique. A tri-axis piezoelectric dynamometer (Kistler® Type 9272) and a power cell (Load Controls Inc®) was used to measure force and power during the machining process.

Figure 2- Two flute PCD milling tool.

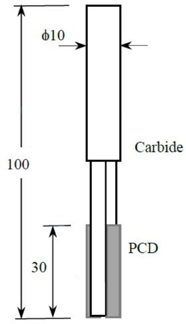


Figure 3- Schematic of PCD tool with relevant features and dimensions.

A thermographic camera (Fluke® Ti400) captured the temperature of the cutter. The camera was placed about 500 mm away from the cutting zone and was focused on the machined surface. As the cutting tool passed by the field of view of the camera, thermal images were captured at the speed of one frame every three seconds. The temperature recorded by the infrared camera was adjusted for the emissivity of the tool. Figure 4 shows a schematic diagram of the line of sight of the camera and the tool location while machining. Emissivity of the cutter (0.83), and the work piece (0.85) were determined by heating the two materials to a known temperature while partially masking their surfaces with a black electric tape of known emissivity. The emissivity setting for each material was varied in the thermography image processing software until the temperatures of the masked and unmasked surfaces were matched.

After completing every 4 m of cutting, the tool was taken off the machine and observed under a tool makers microscope and measurement of flank wear was conducted according to ISO 8688-2. After completing 20 m of cutting, the tool was examined under optical as well as scanning electron microscope (Quanta™- FEI250 ESEM). The elemental analysis of the materials in the tool was conducted using Energy Dispersive X-ray Spectroscopy (EDS). Commercially available dedicated metrology module (Edge master © along with Alicona® Infinite Focus G5) is used to take cutting-edge profile measurements. PCD cutter is removed from the tool holder and measurements are made with this optical profile measurement technique which is based on focus variation. A schematic diagram of wear with different measured parameters in a typical section of the PCD flute is shown in Figure 5.

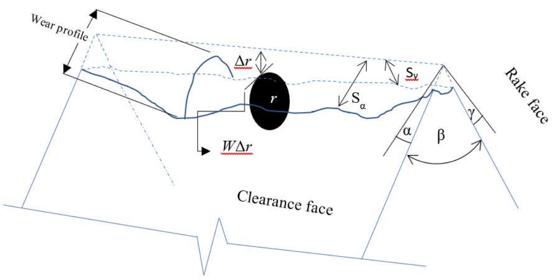


Figure 5- Schematic diagram representing a section of PCD with wear. Dashed line denotes virgin edge prior to cutting.

Description of measured parameters are given below.
γ : Rake angle
α : Clearance angle
β: Wedge angle
r : Radius of the cutting edge
Δr : Shortest distance from the intersection of the dotted lines (apex) to the fitted circle
$W\Delta r$: Edge width or length of the tangent line at the Δr point between the left and right fitted lines
S_γ : Distance between apex (shown with dotted line) and the end of the rake roundness
S_α : Distance between apex (shown with dotted line) and the end of the clearance roundness

3. Results and Discussion

3.1 Tool temperature

The temperature on the tool is measured in every pass and is plotted against the number of passes. A typical infrared image captured during a pass is shown in Figure 6. Figure 7 and Figure 8 illustrate the average and maximum tool temperature readings with respect to the cutting length. Maximum temperature is the highest temperature value in the cutting zone in each of the images. Cutting zone is an approximate square area with the width of tool diameter and height of work piece thickness. Average temperature is the mean temperature value in the cutting zone.

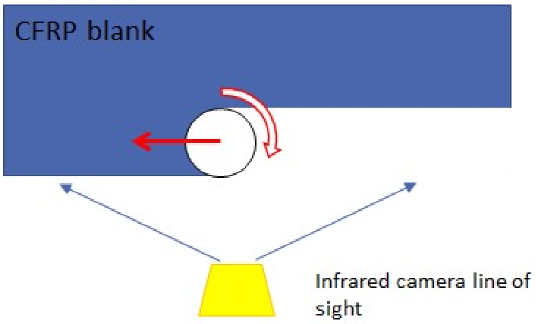


Figure 4- Schematic representation of position and line and sight of thermography camera.

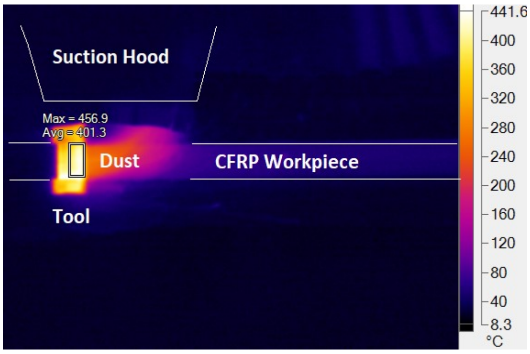
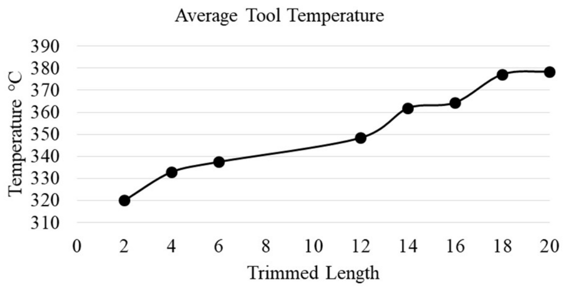


Figure 6- Infrared thermogram captured during the trimming operation.

The initial increase and subsequent stable temperature regime of PCD tool materials can be explained based on the optimum hardness of the tool material. PCD is a homogenous mixture consisting of grains and binder however it has less hardness as compared to a single crystal diamond. Initially, there is an increase in temperature for a decremental change in hardness. However, with the further reduction in hardness, specific cutting pressure becomes steady and leads to the development of a stable temperature regime. The tool temperature also exceeds the glass-transition temperature of the matrix resin which is around 150 °C and this could affect the resin composition. However, the temperature was far less than that required for tool failure through the thermal degradation process which is approximately 600-700 °C [14, 15, 21]. In the current study, although both average and mean temperatures increases with the cutting length, they remain well below that critical limit. Hence, it can be concluded that wear is not driven by cutting temperature.



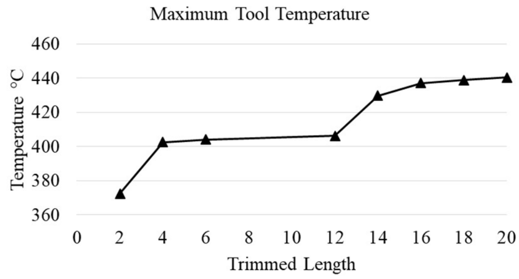


Figure 7- Average tool temperature in the cutting zone at different cutting lengths.

Figure 8- Maximum tool temperature remains below the critical limit of 600- 700 °C

3.2 Wear Measurement

To analyze tool wear, flank wear was used. Maximum flank wear corresponds to the maximum width of the wear land on the clearance face. Wear of the cutting edge after cutting manifested itself in the form of edge recession and edge rounding visible in optical microscopy. Figure 9 shows images of one flute of each cutting tool at the end of the cutting trials (20 m of linear cutting distance). The cutting parameters are spindle speed 10,000 rpm, feed speed 1000 mm/min, and depth of cut 10 mm. Wear is visible on each of the flutes and extends along the edge for around 10 mm, which is the thickness of the CFRP laminate. The location of the unworn edge is represented by a thin dashed line on the image. Images are taken using optical microscopy at three to four different locations along the length of the PCD wafer and are stitched together to present the whole wear land of 10 mm cutting depth.

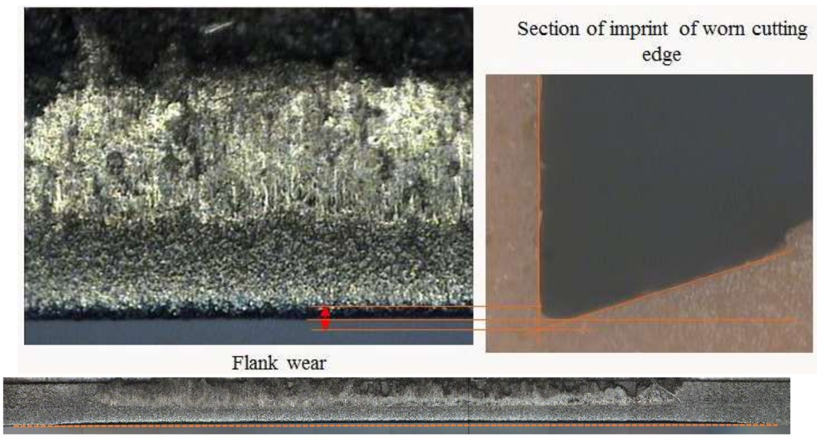


Figure 9- Magnified image of the section of PCD used for cutting taken with optical microscopy.

Although wear can be clearly seen with optical microscopy and recession in the wafer can be measured to a certain extent none of the wear parameter can be clearly quantified including differentiation between wear land on clearance and rake surfaces. Wear land appeared to be very small, and the resolution of the microscope is not enough to capture any measurable quantities related to wear. This is consistent with studies that reported wear land to be below 50 µm after trimming 120 m of the work piece length [7]. Moreover, given the fact that diamond grain size is usually in a range of 3 to 15 µm, it is almost impossible to classify wear mechanics. Furthermore, highly reflective surface of PCD doesnot lend itself for the accurate quantitative measurements including wear and geometric features. This problem is exacerbated by the additional light required under the microscope at low aperture values. It is very difficult to view and differentiate surfaces due to reflection. This problem can be avoided by orientating the tool to avoid reflection however this usually result into incorrect and inconsistent measurements of the geometry between different cutting passes for example wear depth.

3.3 Scanning Electron Microscopy

Scanning electron microscopy has already been used for high resolution imaging of polycrystalline diamond wafers brazed to cutting tools. Unworn and worn cutting edges after 20 m of cutting are shown in Figure 10 and Figure 11 respectively. A clear sharp edge at the apex of clearance and rake edges is visible in unworn edge with little detail of grain boundaries on either of the faces. Due to wedge angle, it is challenging to observe both rake and clearance surfaces with the same amount of brightness. One face always tends to be darker than the other regardless of the orientation of the PCD wafer under the electron beam. Sharp image throughout the depth of the field is difficult to obtain due to the steep gradient along each surface, which makes most of the image blurry except the limited point of focus. Wear land can be seen on both rake and clearance face as a pitted surface in Figure 11.

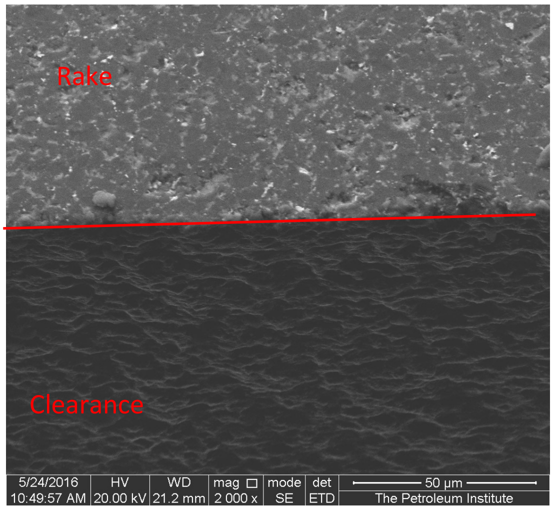


Figure 10- SEM images of the unworn PCD edge. Solid line across the image demarks rake and clearance face

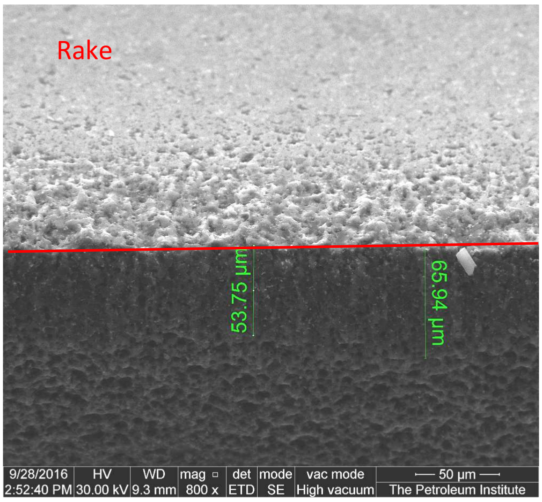


Figure 11- SEM images of the worn PCD edge of a worn tool. Wear land dimension is below S_{α}

Measurement of the width of the clearance area can be estimated by assuming the end of the pitted territory as the end of the wear. It varies across the length of the wafer and is shown between 55 to 65 µm on clearance face. A high-resolution image of an unworn edge is shown in Figure 12.

The overall image shows a homogenous structure with little or no clear boundaries between diamond grains and the binder. This agrees with findings reported in [22] and [23] where authors argued that binder infiltration and liquid phase sintering result in diamond skeleton formation. In Figure 12 a distinct feature with sharper edges as compared to its vicinity is marked with a dotted line. Given a standard PCD composition, this feature qualifies for a diamond crystal, or a cluster formed during compaction process [23].

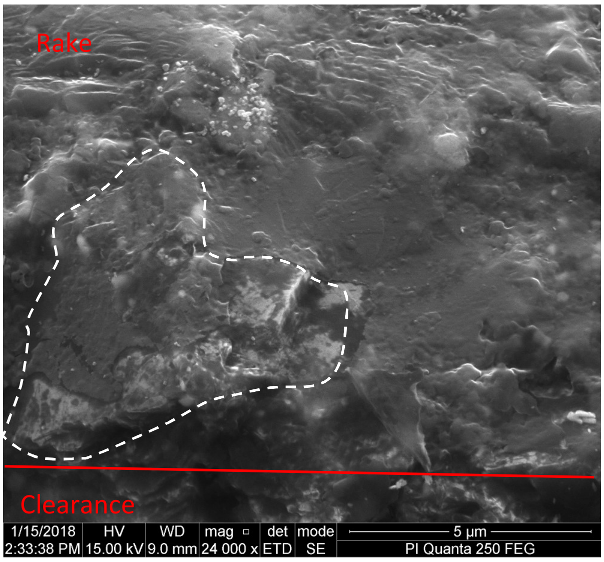


Figure 12- Unworn PCD edge close up. Dotted line encloses crystal structure. Sharp edges are visible. Solid line across the image separates rake and clearance faces.

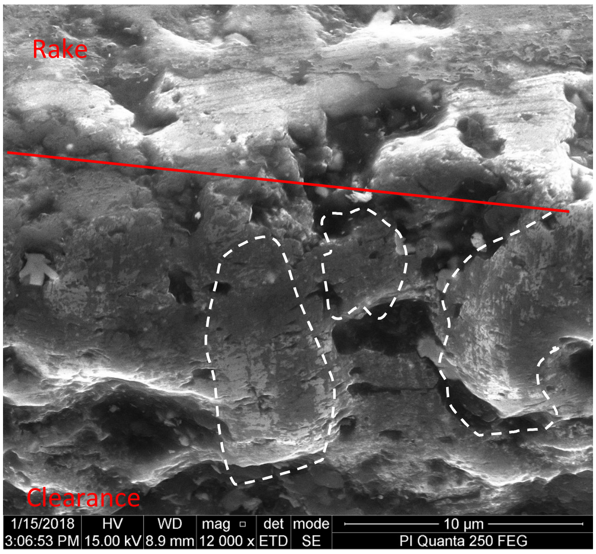


Figure 13- PCD cutting edge showing wear. Continuous diamond skeleton structure is clearly visible. Holes with smooth edges in the structure are due to the loss of binder.

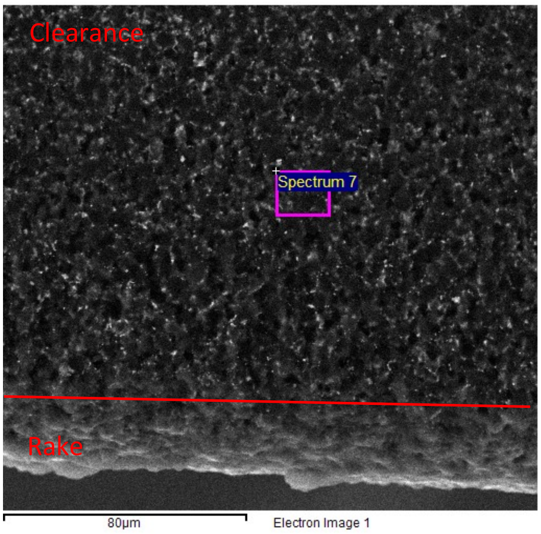


Figure 14- Magnified PCD wafer under SEM. Region enclosed by small pink circle is the representative area for EDS analysis. Solid line across the image demarks rake and clearance face

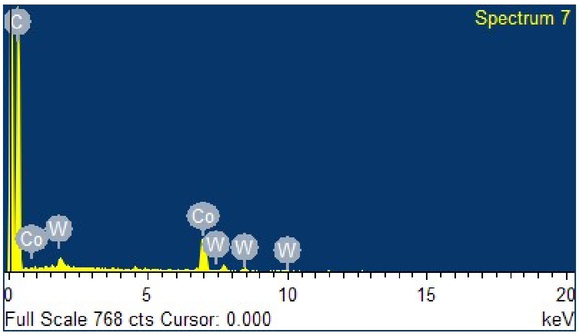


Figure 15- Elemental analysis of PCD wafer with EDS. Carbon, cobalt and tungsten are identified in PCD wafer with highest content of carbon representing diamond crystals.

3.4 Energy dispersive x-ray spectroscopy

The exact content of tool materials is not available since most of the manufacturers maintain such information under their commercial proprietary. In order to understand the wear mechanism, the Energy Dispersive X-ray Spectroscopy (EDS) technique is employed to carry out elemental analysis for the identification of materials particularly in the polycrystalline wafer of the tool. This technique provides an approximate estimation of the content of PCD. It shows the majority of content consisting of carbon element which indicates diamond particles with a small amount of cobalt and tungsten which are used as a binder in this PCD. A typical EDS analysis of a tool is shown in Figure 14 and Figure 15. A square area of approximately 30 x 30 µm is analyzed slightly away from the edge on the wear land on the clearance side. This area is sufficient to cover a few diamond crystals with binder material holding them together and thus can provide a fair idea about the content of the polycrystalline wafer though it does not provide detailed information for example if the binder is in a particular alloy form. EDS analysis is carried out on two tools and the average weight percentage of these elements in a typical tool is given in the table below.

Table 1: Estimated PCD wafer content by weight percentage

Element type	Weight percentage
Carbon	90.65
Cobalt	7.35
Tungsten	2.00

This analysis is comparable with results reported in [24] where the authors observed 90.5% diamond, 7% tungsten, and 2.5% cobalt. Although the weight percentage of tungsten and cobalt are opposite, the diamond content is strikingly similar.

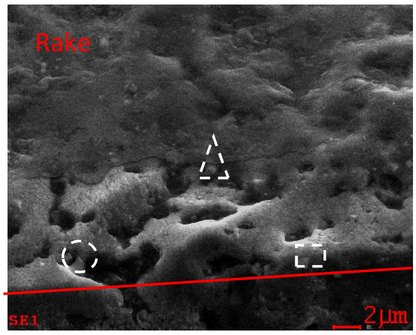


Figure 16- SEM image showing areas with high concentration of tungsten. Dotted lines enclose pockets of tungsten concentration. Solid line across the image demarks rake and clearance face.

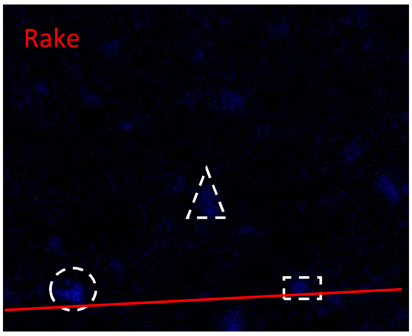
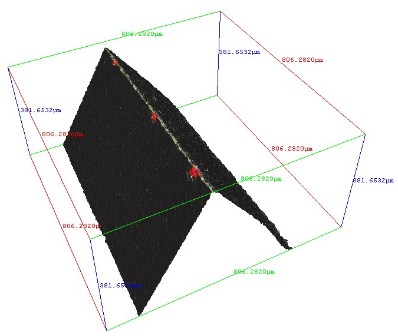


Figure 17- Electron spectroscopy-based mapping showing tungsten concentration enclosed by dotted lines.

A further EDS mapping of the distribution of elements in worn out PCD wafer is performed. Cobalt appears to be well distributed across any given area. Meanwhile, tungsten shows localized concentration inform of pockets as well. Perhaps tungsten is not as well distributed as cobalt during the infiltration step. Figure 16 and Figure 17 show such mapped images where tungsten pockets can be seen exposed near the cutting edge of the PCD wafer. It seems that these pockets of tungsten are removed by the abrasion process leaving pits and holes in the PCD wafer. Figure 13 shows a close up of the worn edge. It is a smooth continuous skeleton structure having pits, holes, and cavities of various sizes. It might be possible that the binder squeezed between the diamond structures is removed first leaving small holes in the continuous diamond structure. Smaller grains of diamond developed due to fracture during cold compaction are also lost, leaving behind relatively larger irregular pits. Both of these forms of loss of material make diamond structure weaker. Parts of this structure must still retain microscopic thermal residual stress due to sintering in the PCD wafer manufacturing process [25]. Such residual stress might cause the disintegration of diamond into small pieces. These loose particles can be brushed out by abrasive carbon fibers resulting in a weaker hollow vulnerable diamond structure with a smooth surface due to abrasion and erosion. Once a relatively larger piece from the hollow continuous diamond structure is lost, it leaves the surface underneath exposed for repetition of the same process. These microscopic images clearly show no sign of gross fracturing, microchipping [15], or subgrain microchipping [26] reported in the literature for a rock cutting. However, pullout of grain [27] and grain cluster and smooth wear [15] appears to exist in machining of fibrous composites. Although authors [23, 15] argued that smooth wear is due to carbon dissolution into work piece, it is not possible to identify it in the current work as CFRP work piece itself has carbon as a major content. Also, it is worth mentioning that smooth wear seems to be at continuous diamond structure formed during the sintering process.

3.5 Cutting-edge profile measurements- Optical Scan

The process is carried out exactly at the middle of the cutting edge of the tool using Edge master© along with Alicona® Infinite Focus G5 metrology module. The tool is placed under the scanning probe so that the apex of the cutting edge or wear land is facing the probe. The center point is located by setting a reference to the bottom edge of the tool. Since cutting was carried out 4 mm above the bottom of every tool and the width of the work piece is known, the same location was used every time for consistent results. That is 9 mm from the reference at the tool end.



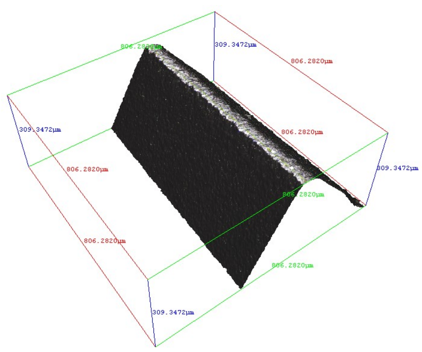


Figure 18- Sample section of a virgin cutting edge. 3D topology of a section of cutting edge prior to cutting. Red marks show any inconsistency in the edge form under 3 µm.

Figure 19- 3D topology of a section of worn cutting edge after machining 20 m of length. Flat land at the apex shows wear scar.

Each scan covers 800 µm length of the cutting edge with resolution of known distance between each reading. In the current study a resolution of 200 slices is used which provides reading at approximately every 4 µm. A representative tool profile is obtained based on the average values of all parameters collected across all slices. At the same time, profile at every resolution point can be viewed to see the edge profile at individual grid line. Almost all parameters shown in Figure 5 can be measured with efficiency through optical scanning technique. Three-dimensional topography provides an easy visualization of the scanned surface.

Figure 18 and Figure 19 show such topography of new and worn PCD cutting edge respectively. 800 × 800 × 300 µm section of each type of edges provide a visual comparison of sharp edge and worn edge with wear land. Figure 20 and Figure 21 show the cross-sectional view produced with average values obtained across a complete section of 800 µm. Measurements are taken every 4 µm resolution along the length of the section and some of the individual profiles taken at that resolution are shown in Figure 22.

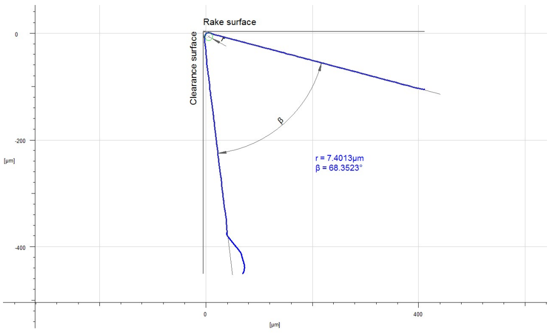


Figure 20- Average profile of unworn part of flute. All dimensions are in µm and angles are in degrees.

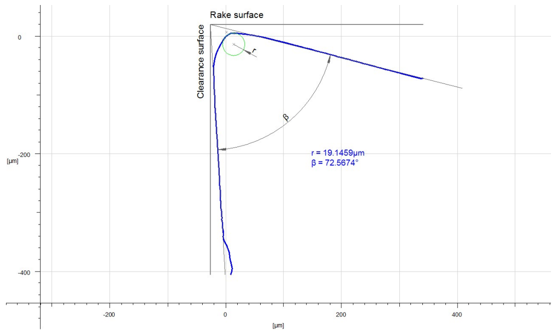
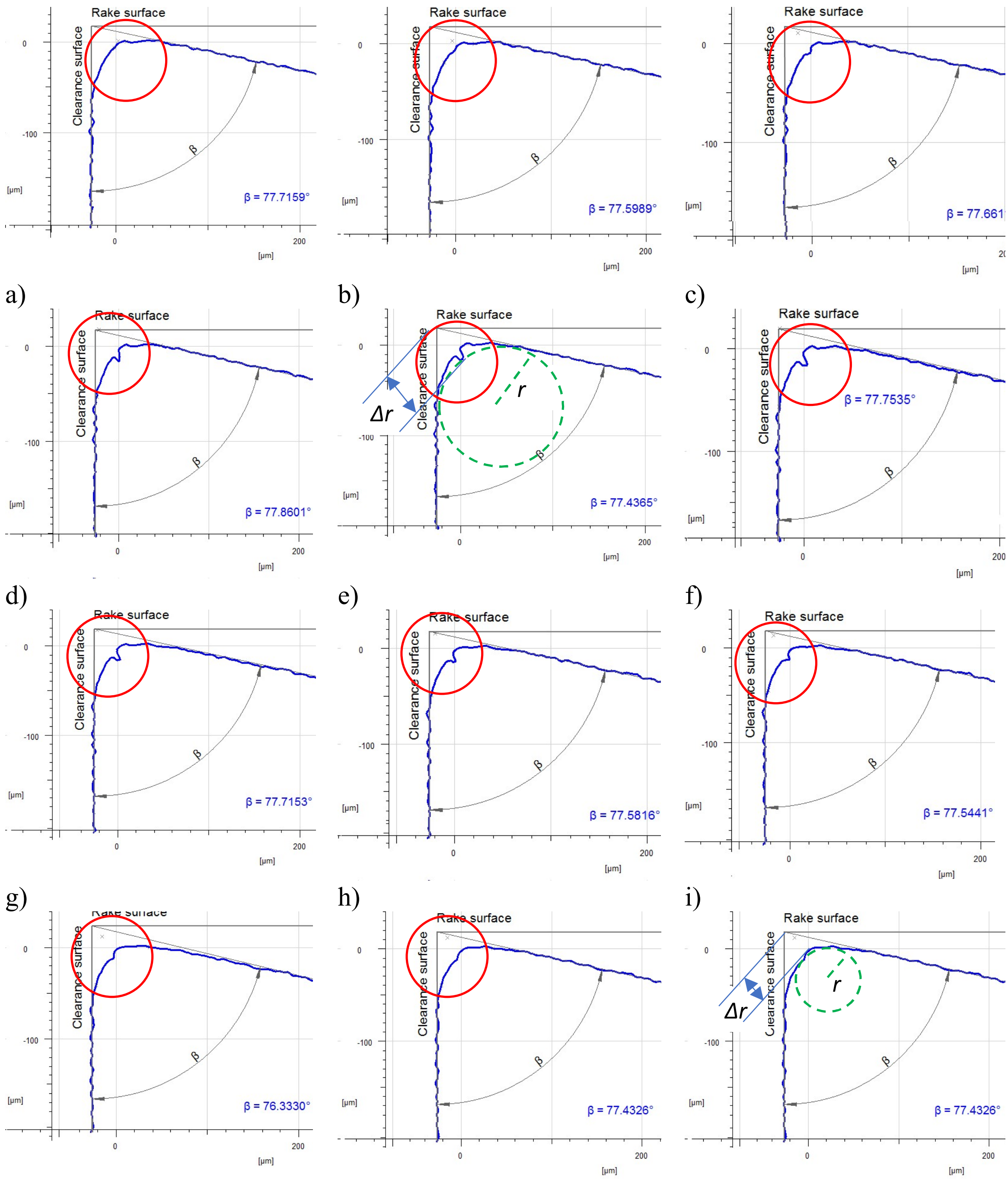


Figure 21- Average profile of worn part of the flute. All dimensions are in µm and angles are in degrees.

Edge recession Δr and edge width WΔr measurement has been reported in the literature for quantification of wear in a similar type of tool profile, perhaps due to their simplicity and ease of measurement with optical scans. It can provide an approximate equivalent of total wear land on clearance and rake side. Even if microscopy is employed instead of 3D scanning system, it is relatively easier to measure total wear land on the rake and clearance side as compared to measuring edge recession. The latter requires obtaining the current tool edge profile, drawing an imaginary original edge profile, and then measuring the difference. It is based on many assumptions including projection of the original edge profile. At the same time, the reflectivity of light from diamond particles makes it challenging to clearly differentiate regions of interest on either the clearance or the rake side.

Total wear land on both clearance and rake sides representing approximate edge width, on the other hand, is easier to measure, being a worn irregular surface. Such measurement can be confirmed by employing robust techniques like SEM through which edge width can be measured with relative ease as compared to edge recession. Furthermore, edge recession has an inherent challenge that the reference point lies at the unworn edge lost during the cutting operation. Thus, edge width remains an easier candidate criterion for measuring wear in PCD tools through conventional as well as advanced measurement techniques. Edge recession Δ*r* , edge width WΔ*r*, and the shortest distance from apex to edge width *r* are all interrelated particularly for a typical PCD cutting edge used in the current study. Such relation can be explained using a set of images in Figure 22.



j) k) l)

Figure 22- Consecutive cutting edge profiles at resolution of approximately every 4µm along the length of cutting edge. Encircled region in red shows the variation in profile depicting the loss of material around 40x20 µm. This can be a single, a cluster of a few diamond crystals or piece of a continuous diamond skeleton. Comparison of green dotted line in Figure (e) and (l) shows effect of the localized cavity on the variation of edge recession Δr. All dimensions are in µm.

Each image is a cross section profile of the tool worn edge at 4 µm intervals along the worn edge. Thus, the total length of 48 µm is shown at regular intervals in 12 images. Close observation at the tip of the cutting edge shows the development of a crater which starts to appear in the first image Figure 22 (a) and vanishes in the final image Figure 22 (l). The depth of the crater is maximum in Figure 22 (e). A red circle is shown in every figure to highlight the crater. It is perhaps due to the loss of a cluster of diamond grains or edge of the diamond skeleton structure made of diamond precipitant during liquid phase sintering. It can be estimated that the volume of the cluster is around 45×15 ×10 µm which is substantially higher than what an average single grain can occupy. Hence it can be assumed that this particular example is not due to the loss of a single grain. It is relevant to mention that dimensions of such cavity, in particular depth is difficult to estimate with SEM.

Accordingly, an optical profile measurement system and scanning electron microscopy are required to measure and visualize the dominant form of wear in PCD tools. This three dimensional optical metrology captures the variation in profile along the cutting edge. Such variation in profile causes substantial and abrupt variation in edge recession Δ*r*, edge width WΔ*r* and consequently to the radius of the cutting edge. Thus measurement of any of these parameters has substantially large variation even across a small length of 800 µm.

Figure 23 shows such variation in edge width between 10 µm to 50 µm across the length of the cutting edge. Similarly, Figure 24 represents edge width variation across both flutes of the same tool and different tools. Only minimum, maximum, and average values of the edge width for an 800 µm scan is shown. It can be observed in this figure that even average values have a substantial variation among both flutes and both tools. Using such a parameter for tracking wear can be a challenge for obtaining conclusive results, since it lacks repeatability. This is particularly important in scenarios where a substantially large number of machining trials involving long cutting lengths are involved. A typical example is the tool life prediction of PCDs for machining fibrous composites. The same observation is extended to edge recession and edge radius which are interdependent and exhibit similar trends. Figure 22 (e) and (l) also show localized variation in *r and* Δ*r* due to the lost edge, leaving cavity behind.

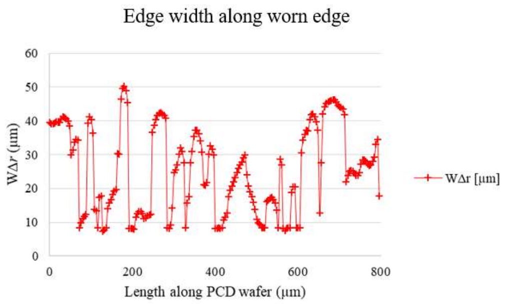


Figure 23- Profile of edge width along a typical worn edge. Data variation is attributed to wear in form of cavities due to loss of parts of diamond skeleton structure or grains. Obtained by profile scanner (Alicona®) and difficult to measure with microscopy.

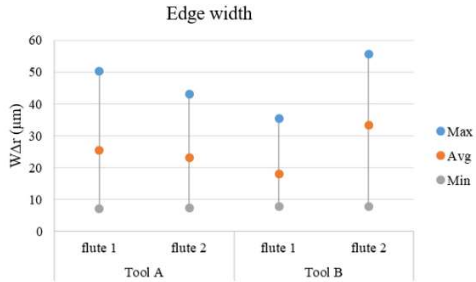


Figure 24- Maximum, average and minimum values of edge width. Comparison between different flutes and tools. Note data scatter as compared to Figure 26.

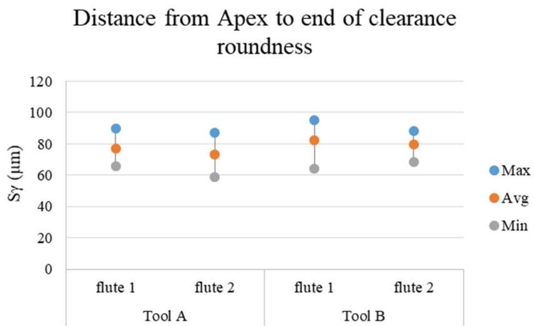


Figure 25- Maximum, average, and minimum values of distance from apex to the end of clearance roundness. Comparison between different flutes and tools. The overall average is about 80µm obtained by profile scanner (Alicona®)

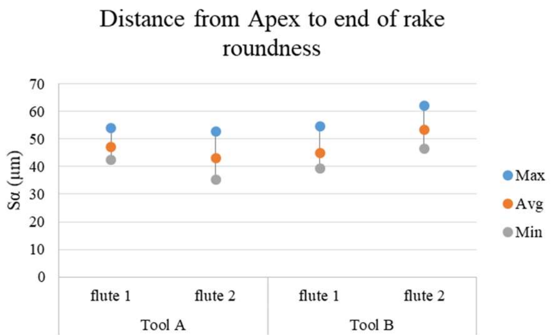


Figure 26- Maximum, average, and minimum values of distance from apex to the end of rake roundness. Comparison between different flutes and tools. The overall average is about 45 µm obtained by profile scanner (Alicona®)

Generally, while measuring wear in any given cutting edge, all parameters including distance from the apex to the end of the roundness, edge width, clearance, and rake angle should be analyzed. Standard deviation in data for all parameters should be considered. High resolution profile cross section should be monitored to understand the dominant mode of wear in that cutting edge. A parameter should be chosen that is repeatable and can be tracked. Meanwhile, it is interesting to note that rake, clearance, and wedge angle do not provide wear indication as these values remains the same or show a negligible change in this study. This is possibly because, the material removed during wear is too small and has minimal effect on rake, clearance and wedge angle. The difference in wedge angle is very small between new and worn edge as shown in Figure 20 and Figure 21.

On the other hand, distance from the apex to the end of clearance roundness (Sγ) exhibits relatively better repeatability as shown in Figure 25. The average values are within 10 µm variation. A further close insight is provided by presenting measured values of (Sγ) for the whole of scanned length at 4 µm resolution. The overall variation is within 20 µm around the mean and it is repeatable for both flutes of the same tool (Figure 27). The same conclusion can be made for this parameter when a comparison is made between different tools (Figure 28). Although there is a variation in measured values, these have better consistency as compared to other parameters, for example, the variation in edge width (Figure 23).

S_α (distance from apex to rake roundness) exhibits the same behavior (Figure 26). However, it has a smaller magnitude compared to $S\gamma$ in all scenarios. This can be attributed to the nature of the wear. Loss of diamond on the edge creating a cavity does not abruptly vary the distance of edge roundness from the apex, consequently causing gradual wear and consistently comparable worn edge. Hence it can be concluded that while measuring wear in PCD the distance from the apex to the end of the roundness proves itself as the best candidate for measuring wear.

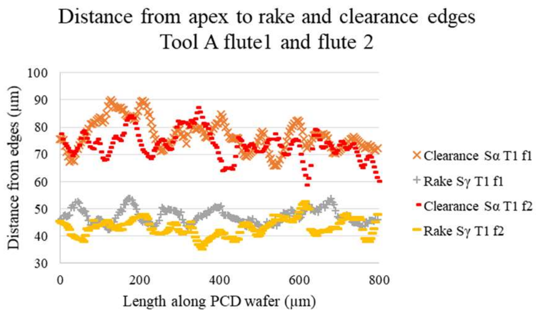


Figure 27- Distance from apex to start of edge roundness at clearance and rake face obtained by profile scanner (Alicona®). Comparison between two flutes of the same cutter.

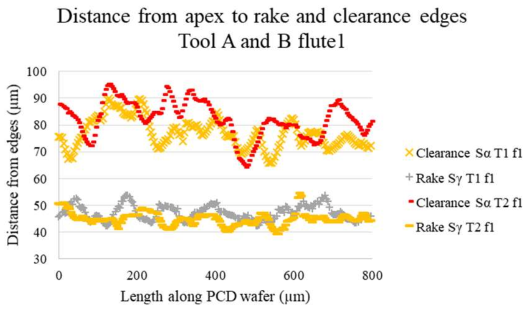


Figure 28- Distance from apex to start of edge roundness at clearance and rake face obtained by profile scanner (Alicona®). Comparison between two flutes of two different cutters

4. Conclusions

The wear mechanism in polycrystalline diamond tool is characterized and presented. Quantification of wear is proposed, and wear parameters are identified for consistent monitoring and tracking of wear particularly for measurement at regular intervals in wear studies. Wear of PCD in milling cutter exhibits complex degradation attributed to its manufacturing process and mechanical loads during machining. It is shown that cutting temperature does not drive wear in such tools as it remains below the critical temperature of 700 °C reported in the literature. Thus wear in PCD is primarily mechanical in nature and specifically because of abrasion caused by carbon fibers. PCD at the microstructure level consists of a diamond skeleton structure made up of diamond precipitation formed during binder infiltration. Binder and smaller grains are lost first leaving the hollow diamond skeleton susceptible to smooth wear and removal. This exposes the diamond structure underneath which goes through the same deterioration process resulting in cutting edge getting receded. This complex deterioration process makes the wear measurement a difficult process leading to inconsistency and variation of measured values. Pits and cavities formed at the cutting edge is primarily due to loss of binder, smaller grains, and pieces of diamond structure. Bigger cavities caused by broken diamond skeleton structure cause substantial variation in edge recession and width measurement. The depth of these cavities is not measurable with a scanning electron microscope. However, high resolution profile scanning equipment can quantify it. Variation in these localized features results in significant deviation in data which cannot be compared even between different flutes of the same tool. Rake, clearance, and wedge angles remain insignificantly affected due to these localized damages. On the other hand, distance from apex to the roundness of the clearance surfaces show more consistency across the cutting edge, between the flutes of same tool, and even between different tools. Abrupt profile change of the cutting edge due to cavities has minimal effect on the variance of value for this parameter. Thus, lending itself to be a potential candidate for wear studies requiring wear measurement on regular intervals for longer cutting lengths. The success of using this parameter for tool life prediction requires continuous study comprising frequent measurement with profile scanning and electron microscopy which is proposed as a future study.

CRediT authorship contribution statement

Farrukh Hafeez: Investigation, Writing-Original draft, Conceptualization, Visualization. **Deviprakash Jyothishmathi Devan:** Investigation support, Literature review & editing, data curation, software **Jamal Sheikh-Ahmad:** Supervision, Methodology, Validation. **Fahad Almaskari:** Software, Data analysis, Resources, Funding acquisition, Project administration.

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