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# Atomic force microscope for in situ micro end mill characterization - Part II: Development of an algorithm to characterize the cutting edge radius of micro end mills

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Micro milling processes are e.g. used to produce customized micro parts and structures. Most micro end mills with diameters below 100 µm are single edged and made of cemented carbide. The minimum cutting edge radius for these tools is limited by the grain size of the cemented carbides and usually is of the same magnitude. The cutting edge radius in micro and nano cutting operations is one of the critical parameters. It directly effects the amount of friction and ploughing present in the cutting area, the tool wear and the resulting surface quality. To characterize the cutting edges of micro milling tools, an atomic force microscope (AFM) is needed. Other measuring instruments do not offer the required resolution. However, the tools do not exhibit a uniform cutting edge profile or a constant cutting edge radius. Grain pullouts and defects introduced during the tool grinding process highly influence the cutting edges. Thus, a statistical evaluation of the entire cutting edge is required to derive a representative value of the cutting edge radius.

Part I of this paper series described the integration of an AFM into a desktop sized machine tool as well as the measuring workflows. This part II presents a cutting edge characterization algorithm implementation tailored to single edged micro end mills. The AFM measurements taken with the procedures outlined in part I are imported into a python based algorithm. The dataset is then automatically processed, and the resulting mean radius and variance of all cutting edge profiles is compared to manually evaluated values.

micro milling, micro end mill, tool measurement, cutting edge characterization

## 1. Introduction

The cutting edge radius is a critical parameter in micro and nano cutting, as it effects friction and ploughing mechanisms in the cutting zone. Specifically micro milling is characterized by a high cutting edge radius to chip thickness ratio, resulting in high abrasive wear of the tools [1]. For cemented carbide micro end mills the cutting edge radius is in the range of the substrate's grain size (down to about 100 nm) and cannot be further reduced [2]. As the tool wear increases and the micro end mills lose their sharpness, surface quality and cutting forces are negatively impacted [3]. To characterize tools of this size optical quantitative measurement techniques are no longer suitable, as they are limited in lateral resolution by the Rayleigh criterion. Visual inspection of a tool's cutting edge in a scanning electron microscope (SEM) does not allow for quantitative inspection of individual cross sections and can only be used as a qualitative estimate of the overall cutting edge radius. Atomic force microscopes (AFM) are the only available solution that can measure cutting edges with resolutions down to the nanometer scale [4].

Part I of this paper series presented the integration of an AFM into a desktop sized machine tool and the advantages of having the measuring equipment in the same machine tool as the tools to be measured are being applied. In addition, it presented the measuring methodology and measurements of a coated and uncoated tool in comparison. In this part II, an automated evaluation of the cutting edges measured with the AFM is proposed, which allows to derive a representative value of the cutting edge radius independently from the evaluated cutting edge cross sections and is insensitive to different operators. As the cutting edge is composed of individual grains, it is not sufficient to evaluate the cutting edge radius for few distinct locations. The non uniform cutting edge profile and the varying cutting edge radius result in large variations of the measured radii depending on the measuring location. The algorithm in this paper aims to resolve these issues by introducing a python-based algorithmic evaluation method that is deterministic, significantly faster than manual evaluation, and considers a large area of the cutting edge.

## 2. Measuring equipment and micro tool geometry

The surface data in this paper was measured with a NaniteAFM from Nanosurf[1]. Further information on the AFM selection, integration and the measuring methodology can be found in part I of this paper series. The AFM is integrated into a desktop sized machine tool we developed in previous work (see [5] for a full description), which enables milling and subsequent tool measurement without reclamping. The micro tools measured are single edged cemented carbide (91 % WC, 9 % CO, grain size 200 nm) micro end mills with a diameter of 50 µm, which were manufactured on an ultra precision lathe with a grinding unit. For a detailed description of the tools' geometry and manufacture, we refer to [6] and [7], respectively. The measured area of the primary cutting edge is located just below the cutting edge corner at the tool tip, as illustrated in the SEM image in Figure 1.

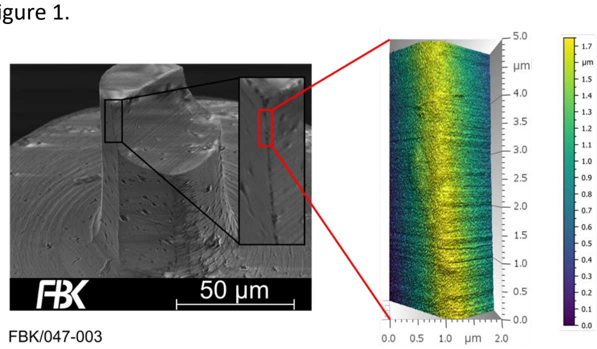


**Figure 1: SEM image of micro end mill with indicated AFM measurement area and corresponding cutting edge surface measured by AFM**

## 3. Cutting edge evaluation algorithm

There are lots of methods and parameters for characterizing a cutting edge in use throughout literature and industry. Most widespread is the characterization by fitting a circle into the cutting edge area and taking its radius as the resulting parameter. However, this method is not capable of distinguishing between different asymmetric or chamfered shapes and cannot describe them. Thus, it is only applicable when the true cutting edge geometry shows close resemblance to a circle.

For measuring the cutting edge radii of the single edged micro end mills we use (diameters of 50 µm and below), this is the case and parameters describing cutting edge asymmetry are not required. The geometry is a result of the grinding process for manufacturing the tools and their substrate material: Both rake and flank face are ground flat towards the cutting edge, with no overlaid profile or additional cutting edge preparation (as that would increase the edge radii significantly). Figure 2 illustrates this with a collapsed view of the 3D surface profile along the axis of the cutting edge, the mean cutting edge profile and a fitted least squares circle for radius determination. As the cutting edge is formed by individual grains, the resulting edge profile is rounded with a radius in the order of magnitude of the grain size.

Therefore, the approach in this paper is to fit a least squares radius into the rounded portion of the cutting edge. While there is proprietary software available that can characterize and fit cutting edges with profiles, these usually do not allow importing full 3D surface datasets or even single cross sections of the cutting edge (e.g. GFM ODSCAD[1]). While topography software allows to fit lines and radii into cross sections, this needs to be done by hand and can only be semi automated. Further, when developing an algorithm, its parameters can be tailored to single edged micro end mills, as the general shape and properties of their cutting edge is the same.

### *3.1. Development approach and data filtering*

The algorithm was developed within python 3[1], an open-source high-level programming language with computational capabilities similar to Matlab[1]. This makes the algorithm highly portable and has the advantage of not relying on a specific software or workstation, like e.g. a solution with a topography software with embedded scripts would. The solution was implemented with object oriented programming, creating an object for each cutting edge cross section and one top-level object for the cutting edge surface. This creates a streamlined software, with data structured into just one variable and displaying the results. No user interaction is required aside from selecting the measurement file and choosing whether to save the results. To start the cutting edge characterization, the top-level object is

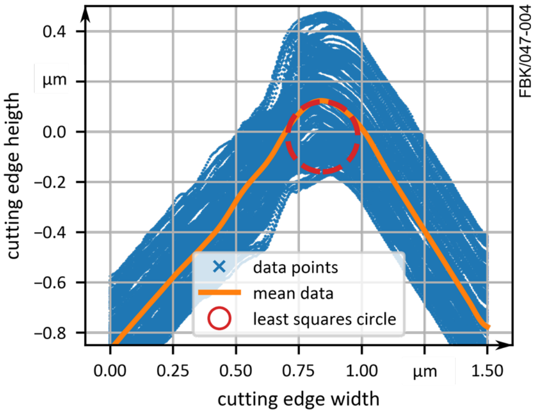


**Figure 2: 2D scatter plot of AFM surface data with mean cutting edge profile and fitted least squares circle**

created with the dataset from the AFM measurement. The exported .csv dataset is imported into the python environment and subsequently sorted into the individual lines, each representing a cutting edge cross section. For each line, a cutting edge cross section object is created, in which each cutting edge radius is calculated. After the radius value is available for all cross sections, the top level object calculates the total radius based on the evaluation metrics of the individual cross sections. The results are then returned and plotted for easy visualization.

The raw data is filtered as single cutting edge profiles inside the objects, rather than applying a two dimensional filter on the measurement surface. As the data has been measured by the AFM line for line, no additional noise is present in the second dimension, and the data should be filtered along the measuring direction. For this, a second order Savitzky Golay filter with a windowing length of 23 was employed. This filter was chosen as minimal loss of resolution and good signal smoothing could be achieved after adjusting the filter parameters via trial and error. The standard line resolution used for the cutting edge measurements is 256 points. If the AFM measurement has a higher resolution, the value is linearly scaled to reflect the actual number of points. The same is true for all absolute values present in the computations. Figure 3 shows the smoothed cutting edge surface and a singular cutting edge profile after filtering.

### *3.2 Algorithm development and testing*

The fitting routine inside the cross section objects first determines the rounded edge area of the cutting edge. This is one of the key advantages compared to manual area determination, as this removes the operator's subjectivity and yields a unique solution for each cutting edge section. For this, the method of fitting a circle tangent to the flank and rake face regression lines

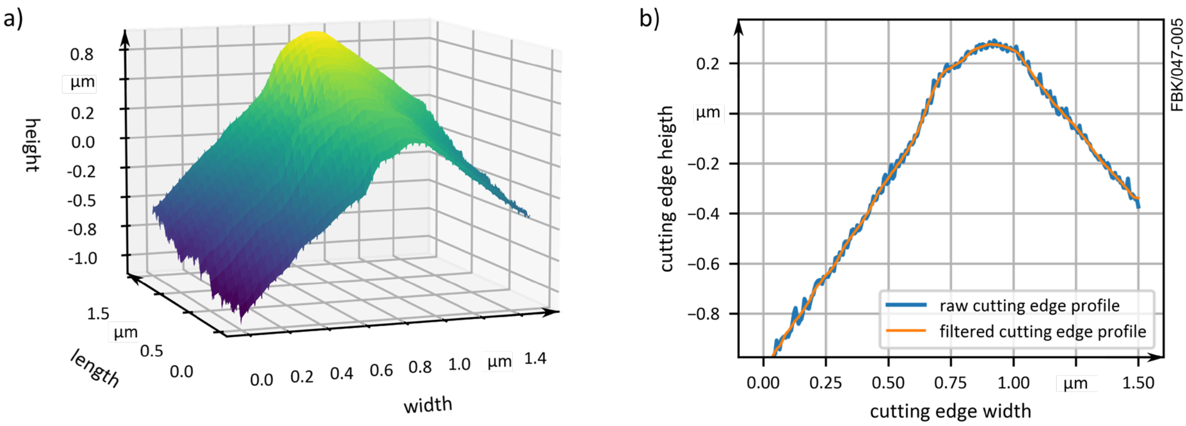


**Figure 3: Cutting edge surface (a)) and single cutting edge profile (b)) after applying the Savitzky Golay filter**

inside the cutting edge profile as proposed in [8] was used. Figure 4 illustrates the iterative procedure with the numbers as implemented in the algorithm: In the first step, both tool faces are modeled with separate regression lines (1) based upon 30% of the most outer data points going inward from the left and right end of the measurement area, respectively. The point where those ideal tool faces intersect is considered the ideal tool tip location (2). With the flank and rake face known, the wedge angle (3) is calculated along with the bisector line (4). The closest data point to the ideal tool tip on the bisector (5) is then taken as boundary condition for the next step, together with the regression lines. With the imposed tangency of the lines, a circle passing through the point on the bisector is constructed. This yields two solutions, a circle with its center above the cutting edge profile and one with its center below the profile, and hence inside the tool (6). For this calculation, the rather complex analytical solution was used, as symbolic solving of this problem is not feasible performance wise. With the inside circle fitted, the data points closest to the tangent location of the circle and the regression lines (7) are taken to describe the area containing the rounded edge portion. These are used in the following iterations as new endpoints for the regression fit of both flank and rake face. This process is repeated until the delta between the area calculated in two iteration steps (left and right border combined) is below 5 data points. If the algorithm does not converge after 10 iterations, it will stop and mark the cross section as an error. However, the majority of cross sections does converge after 3 to 4 iteration steps.

After the iterative process is finished, the area of the rounded cutting edge portion is known. If any errors occur during the area determination algorithm, e.g. an empty or negative area, an error flag is raised for later identification of the profile. Dummy values are then assigned for the radius to avoid numerical errors. After visual inspection of numerous profiles it was concluded that the fitted inside circle (6) slightly underestimates the real cutting edge area. Thus an offset was added to the area for the following radius determination, increasing it by five data points at the left and right border, respectively. This can also be seen in Figure 4, with the red cross markers (8) representing the adjusted area versus the calculated area indicated by the black markers (7).

With the adjusted area of the rounded edge portion of the cutting edge, the cutting edge radius is determined by fitting a least squares circle to the data. The result of this can be seen in Figure 2, in which the radius of the mean data cutting edge profile was

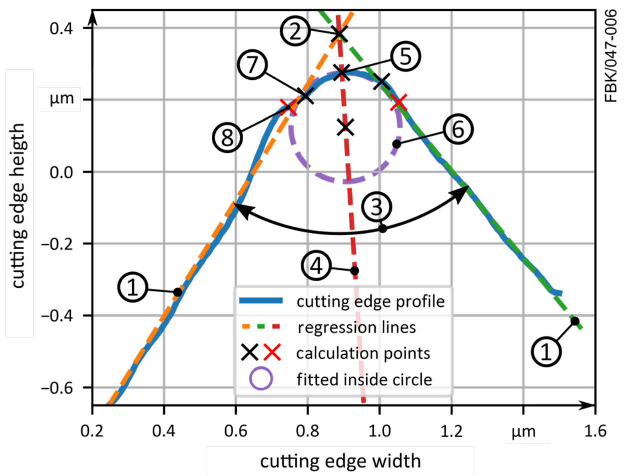


**Figure 4: Method for calculating the rounded cutting edge portion**

determined with the above algorithm. To reject outliers and bad fitting results, an outlier flag will be raised for the cross section in question if any of the following conditions are met:

1) The variance of the least squares fitting routine in relation to the calculated radius is above 45%.
2) The difference in radius of the inside circle from the area determination to the least squares circle is above 35%.
3) The R-squared criterion calculated for the least squares solution is below 0.75.

If a cross section is deemed an outlier, it will not be taken into account for calculating the overall radius of the cutting edge. After each cross section object has been created and its radius has been calculated, the average cutting edge radius of the tool is calculated. All cross sections flagged as errors or outliers are not considered, and the inverse variances of the individual cross sections are used as weights for calculating the arithmetic mean. This ensures that large radii with high variance, like e.g. at grain pullouts, only influence the average by a smaller degree and is an advantage over measuring the radius with a mean cutting edge profile. The algorithm then computes the standard deviation and confidence interval for the cutting edge radius based on the two sided 95th percentile of the student T-distribution. The results are returned in the console or saved to file and plotted as individual radii over the length of the cutting edge. Figure 5 shows such a result plot for a measured micro end mill.

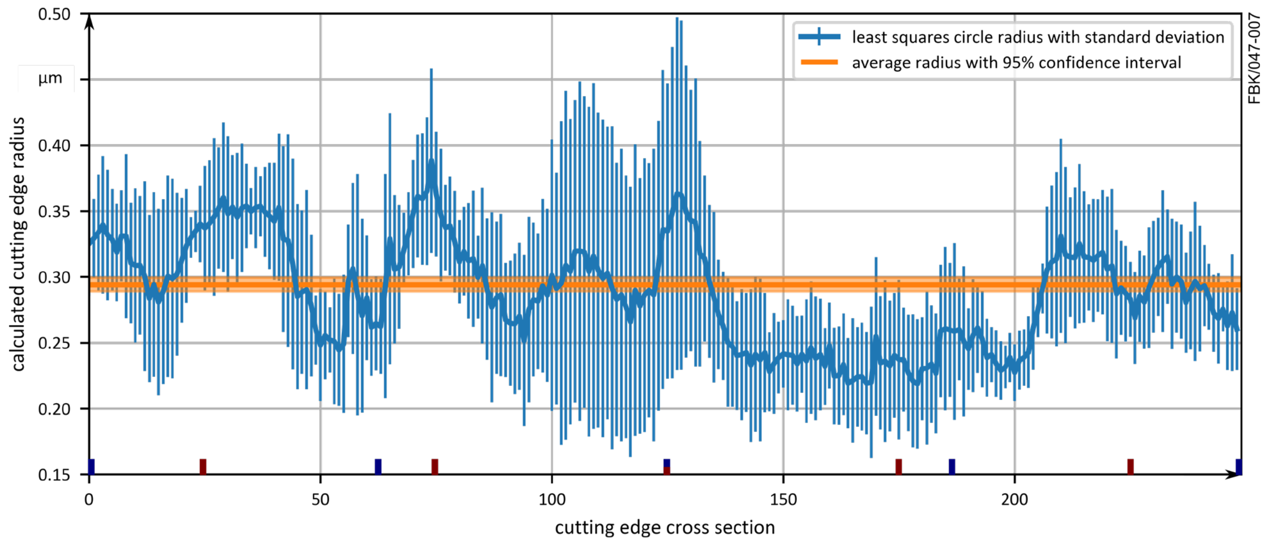


**Figure 5: Result plot of the cutting edge radius determination algorithm displaying the calculated radius for each cross section**

### 3.3. Comparison to manual evaluation and results

To show the advantages of the automated analysis, the same cutting edge measurement was evaluated manually and with the algorithm. Five individual cross section were fitted with a circle by hand, as well as with the algorithm. The sections were equidistantly spaced over the cutting edge length, as shown by the dark blue and red markers on the x-axis of Figure 5 for sections #1 and #2, respectively. In addition, two different operators evaluated the cutting edges independently. This approach was chosen to show the influence different evaluation locations and operators have on the measuring results. Table 1 compares the results obtained from the manual and automated evaluation of the individual sections and the total result of the algorithm.

The values obtained fluctuate depending on the operator and the measuring locations. Especially the standard deviations differ for both the operators/algorithm and the locations, showing the influence of the subjectivity of the operator's individual measuring procedure and of the uneven cutting edge profile. In Figure 5, the deviations of the radii along the cutting edge can be clearly seen, explaining the different results for the measuring locations #1 and #2. Overall most evaluated radii underestimate the cutting edge radius, with fluctuating standard deviations based on the operator. Also, as only five sections were evaluated, the 95% confidence interval would be even larger than the standard deviations. In contrast, the algorithm (across the entire dataset) delivers a much smaller confidence interval and thus a more reliable and unbiased result. In addition, the algorithm computing time is only a few seconds, while the time for manual evaluation of this micro end mill was about 15 minutes per operator.

The quality of fit from the algorithm also can be visually inspected in 3D. Figure 6 shows the cutting edge surface with a cylinder overlay. The cylinder is based on the radius calculated, and runs along a linear regression of the circle centers of all evaluated cutting edge cross sections. As can be seen in the surface plot, the cylinder is located right inside the cutting edge, with equal portions of the surface above and below it.

**Table 1: Comparison of the same cutting edge evaluated by different operators and at different cross section locations**

| evaluated by | cutting edge radius result | |
|---|---|---|
| | sections #1 | sections #2 |
| operator 1 | 275.4 nm ± 41.3 nm | 265.9 nm ± 27.9 nm |
| operator 2 | 273.6 nm ± 59.0 nm | 299.1 nm ± 55.4 nm |
| algorithm | 278.5 nm ± 25.3 nm | 287.2 nm ± 38.1 nm |
| algorithm total result | 294.0 nm ± 5.3 nm (95% confidence interval) | |

### 4. Conclusion and outlook

An algorithm to determine the cutting edge radii for micro end mills measured by means of an AFM was developed. The algorithm automatically filters the measurement data, identifies the rounded portion of the cutting edge, fits a least squares circle for each cross section, and ultimately calculates the average radius. It has been shown that the algorithm is capable of judging the cutting edge radius of measured micro end mills very well and is independent of errors otherwise introduced through operator methodology and measurement locations. Utilizing the algorithm, efficient evaluation of multiple end mills can be performed and compared across different sets of measurements easily, which would not be the case for manual evaluation.

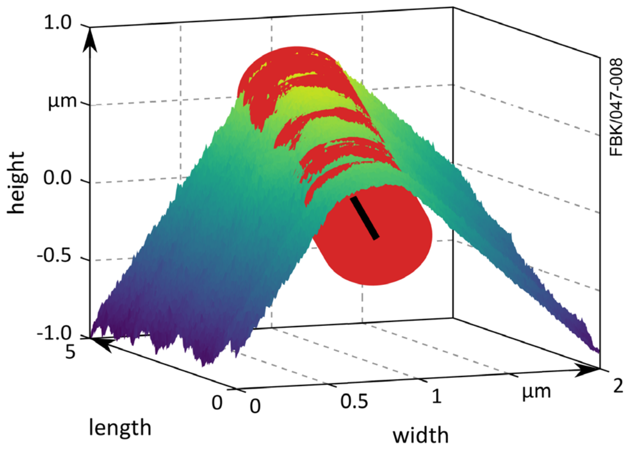


**Figure 6: Visual representation of the calculated cutting edge radius with a cylinder inside the cutting edge surface**

Further improvements to the algorithm could be made by calculating a roughness profile running along the determined cutting edge as a parameter for the micro end mills' cutting edge roughness. Also, with the known radius and the wedge angle, a flattened surface profile of the cutting edge could be extracted and areal roughness parameters could be computed. This would allow a complete characterization of the cutting edge, and possible correlations between the radius uncertainty and the roughness level could be analyzed.

Overall, the integrated AFM and the evaluation algorithm presented in this paper series enable new investigations into the micro milling process by allowing to characterize the cutting edge topography of micro end mills.

### Acknowledgements

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[1] "Naming of specific manufacturers is done solely for the sake of completeness and does not imply an endorsement of the named companies nor that the products are necessarily the best for the purpose. "

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