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Comparison of cutting edge characterization techniques applied to industrial tools with sub micrometer edge radius

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Abstract

Within micro and precision machining, cutting tool performance with respect to the ability to generate fine surfaces is largely determined by the size of the edge radius, which dramatically affects the minimum uncut chip thickness. In the recent years emphasis has been placed on cutting edge radius characterization. While the measurement techniques from literature can be well suited for ordinary tools with edge radii in the order of tens of microns, tools for fine finishing operations, exhibit edge radii in the sub-micrometer range, which limit the robust applicability of such techniques. This paper presents an investigation on the characterization of ball nose end mill cutting edges with sub micrometer edge radius. For this purpose CBN and WC tools cutting edges were characterized by means of a confocal microscope (Olympus Lext OLS4100). The measurements were validated through reference AFM measurements and the data fitted with known cutting edge determination algorithms. The influence of the roughness of rake and clearance face on the robustness of the edge radius calculation is discussed and the capabilities and limitations of the methods are highlighted.

Key words: Cutting edge, precision machining, ball end mill

1. Issues in cutting edge measurement

Cutting tool performance is closely related to the shape and size of the cutting edge. In micro and precision machining the cutting edge determines the minimum uncut chip thickness that it is possible to remove, directly effecting the surface quality. A full characterization of the cutting edge is difficult to achieve for mainly two reasons. First, a standard definition of what the cutting edge is and how it should be measured is still missing [1]. Second, the dimensional range of the cutting edge for precision machining requires the use of instruments capable of high resolution. The influence of the data fitting algorithm, the selected fitting range and the capability of the instrument must all be considered in order to implement a robust measuring procedure. In this paper two existing fitting algorithms have been tested to fit known edge profiles with variable artificial noise in the data points. The noise aims to simulate the roughness of the profile to assess its influence on the edge radius detection algorithms. The algorithm which has proved to be the most robust has been used to fit data points coming from the measurement of a ball end mill with a confocal microscope. The same tool has been measured with a metrological AFM and the result of the fitting has been compared. Suitability and applicability of instrument and measurement procedure are discussed.

2. Data fitting algorithms

Given a certain model for data fitting, the result strongly depends on the number and range of data point used for the fitting. In order to increase the robustness of the edge radius measurement two algorithms that automatically optimize the fitting range have been tested. The first algorithm performs a least square fitting using a circle. The fitting interval is defined

through an iterative procedure imposing the tangency between the straight lines used to fit rake and relief faces and a circle passing through the intersection with the bisector of the two straight lines with the data points, Figure 1 [1]. The second algorithm fits the data with a second order rational polynomial curve to which the tangency to the lines fitting rake and relief faces is imposed. The fitting interval is chosen by minimizing the sum of residuals of the overall profile. A Nelder-Mead method is used for the optimization problem. The radius of the osculating circle passing from the intersection of the fitting curve with the bisector of rake and relief face is calculated and taken as edge radius [2].

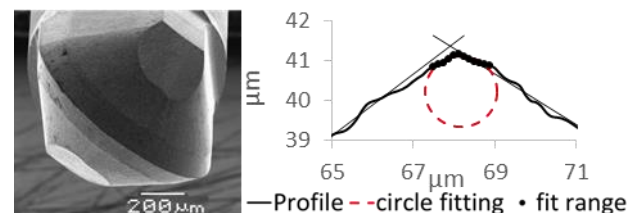


Figure 1. On the left: SEM picture of a cBN tool. On the right: edge fitting using the circle fitting algorithm.

2.1. Algorithm test

A circular and parabolic profile are generated with known edge radius (1 μm and 0.5 μm respectively). Random noise is added to the data points in order to simulate the roughness of the surfaces and spread of the data points. Amplitude of the superimposed noise is proportional to 0.01, 0.05, 0.1 and 0.15 times the cutting edge radius. Knowing the theoretical cutting edge value, the robustness of the algorithms is evaluated by comparing the fitting results, Figure 2. The circle fitting algorithm has proven to be less sensitive to noise and shape of the profile. Its error is consistently below 15% for both circular

and parabolic edge profiles. On the other hand, the polynomial algorithm results in an error up to 34% when fitting a circular profile, and up to 24% when fitting a parabolic profile. It is also noticed that for zero noise the rational polynomial algorithm does not lead to zero error. This is attributed to local minimums in the optimization process. Due to a better performance, the circle fitting algorithm has been used for estimating the edge radius of the measured ball end mills cutting edges.

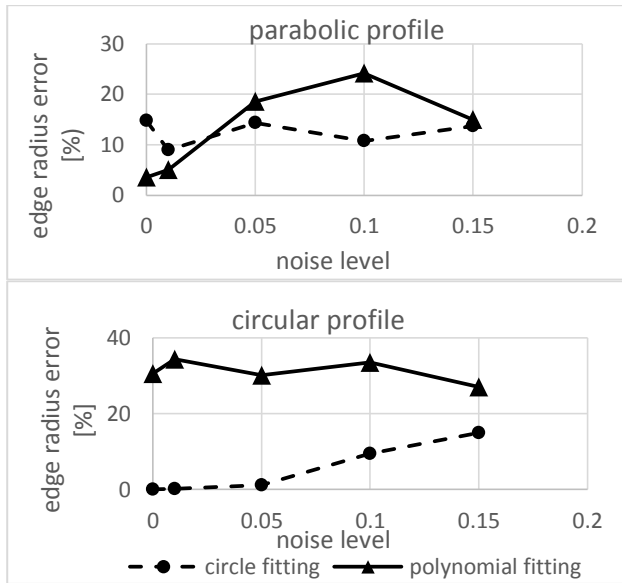


Figure 2. Comparison of the two algorithms fitting a circular and parabolic profile with known radius of curvature and different noise amplitude. The error is given by the absolute value of the difference between actual radius and calculated radius.

3. Tool measurements

Measurements of the cutting edge radius of cBN and WC small ball end mills (1 mm diameter) have been performed using a confocal microscope Olympus Lext OLS4100 and an AFM Park NX20. The tip radius of the AFM has been estimated lower than 16 nm using the circle fitting algorithm and a reference sample. Care has been taken in order to measure the same point of the cutting edge with the two instruments. 2D profiles orthogonal to the cutting edge profile have been extracted from the measurements and used for the data fitting. The space interval between points of the 2D profile is 120 nm for the confocal measurement and 7 nm for the AFM measurement.

4. Cutting edge radius estimation using a confocal microscope

To estimate radius and variability of the cutting edge, ten different profiles have been extracted in different areas of the tool from the confocal measurements. Using these profiles, the calculated average radius of the WC tool is 821 nm with a standard deviation of 315 nm. For the cBN tool, the calculated average radius is 1901 nm with standard deviation of 808 nm. The large standard deviation is attributed to three different sources: errors in the data fitting, variability in the edge geometry and errors in the acquisition of the data points.

5. Comparison of confocal and AFM measurements

To refer the confocal measurement to a traceable instrument, a single profile taken from the confocal measurement has been compared to a profile taken using a metrological AFM. Ideally,

the AFM and confocal profiles should be taken exactly in the same point to obtain a meaningful comparison. However, it is a difficult task. For each measurement (AFM and optical), a profile has been selected in the same identified area. Each profile has been averaged with the neighboring profiles in an area of 5 μm to make the comparison less sensitive to the position. In this way, the influence of the instrument on the measurement can be compared because the selected profile is virtually the same and the same algorithm is used. The fitted edge radius of the selected optical and AFM profiles are shown in Table 1. It can be noticed that the measurements coming from the confocal microscope are in close agreement with the AFM measurements. However, care must be taken when considering the result. For the AFM measurements, no deconvolution of the profile has been applied. It is believed that the influence of the AFM tip radius is small enough to be neglected, considering the dimension of the edge radius. For the confocal measurement of the WC tool, due to the larger point interval, the fitting range used by the circle fitting algorithm consists in only eight points. Due to the low number of data points, the measurement is very sensitive to the noise and roughness of the profile. The differences between values in Table 1 referring to local measurements of the cutting edge, and the average radius values referring to the entire cutting edge profile (see section 4), is attributed to the great geometrical variability of the cutting edge.

Table 1. Comparison between AFM and confocal measurements.

Tool	Instrument	Edge radius [nm]
WC tool	AFM	543
	Confocal microscope	567
cBN tool	AFM	1169
	Confocal microscope	1156

6. Conclusion

A comparison of two algorithms for fitting the cutting edge radius has been made using known profiles. A circular fitting algorithm has proven to be less sensitive to noise and profile shape so it has been selected to fit cutting edge radius measurements of ball end mills. Two different instruments have been used: a confocal microscope and an AFM as reference. The two instruments have shown comparable results. In this paper, a radius of curvature has been taken as representative of the cutting edge but other descriptions are available in literature [3]. While a radius of curvature is relatively simple to calculate, it does not provide information about the asymmetry of the profile that is relevant in the cutting process. Further work will be aimed at evaluating other methods to characterize the cutting edge in a way that is representative of its performance and to better investigate the influence of the surface roughness of rake and relief faces on the edge characterization.

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