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Comparison of transparent objects metrology through diamond cutting edge radii measurements

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ABSTRACT

The efficiency of cutting is largely influenced by cutting edge radii. When considering the correct cutting edge radius in the simulations, correct cutting characteristics can be predicted and thus the cutting process optimized. Sharpening the cutting edge of the tool to a specific optimized radius subsequently will improve the service life of the tool, workpiece quality, and performance of cutting. Measuring cutting edge radii of tools already is challenging, especially when measuring cutting edge radii of diamonds cutting tools because of their transparency and their dimension in the micrometer range. Defining a sound framework for selecting the appropriate metrology of transparent objects and clarifying the correct measurement parameters, settings, and proper sample preparation are the main achievement of current work. Tactile profilometer, confocal and focus variation light microscopy, imprinting, scanning electron microscopy (SEM) stereoscopy, and atomic force microscopy (AFM) are used to measure the cutting edge radius of diamonds. The identification of the cutting edge radii are done based on the methodology of the least square circle fit over cutting edge radius, and is determined iteratively. Estimations of uncertainties of the measurements are explained in detail and compared. The same measurement techniques and methodologies can also be applied to measure other transparent or difficult to measure materials. The results of different measurement technologies for the same diamond specimens are compared. In the end, one choice from the utilized measurement methods is suggested based on Analytic Hierarchy Process (AHP), which is one of the methods in Multiple Criteria Decision Analysis (MCDA). The selection process and the proposed set of evaluation criteria can also be applied to other measurements.

Introduction

Optimization of cutting processes without information about cutting edge radii especially in micro-cutting applications is impossible, because cutting edge radii strongly influence the cutting process, i.e. cutting forces, specific cutting energy, cutting temperature, residual stress field in the workpiece, quality of the workpiece after machining and service life of the tool. Klocke [1] has shown that high discrepancies in comparison between simulation and experimental values of feed force and torque in the gun drilling process is due to the nonrealistic assumption of cutting edge radius in the simulation. As shown in [2,3], in turning process feed forces are reduced for sharp cutting edges. Furthermore, in the case of increasing the cutting edge radius in milling, [4] declared that specific cutting energy reduces. Additionally with increasing the cutting edge radius in orthogonal cutting of AISI 316L, it has been proven by [5] that the workpiece temperature increases because of ploughing force on the cutting edge; it is also interpreted as larger edge radius creates larger contact area and consequently frictional heat increases. Moreover, it is revealed in [5] that with increasing the cutting edge radius in orthogonal cutting of AISI 316L, the stagnation zone, where the workpiece material starts to split into forming the chip and the new surface of the workpiece, increases. Therefore, the surface of the workpiece is severely plastically strained by cutting with non-sharp tools, which leads to higher residual stresses. Built-up edges, as indicated in [6], can also be formed in sticky or work hardening materials in case of cutting with non-sharp tools, negative rake angle cutting geometry, slow cutting speed, low feed rate and low cutting temperature.

The main problems in the determination of cutting edge radii of diamond tools with light microscopy are transparency and the very

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small size of diamond, maximum grain size of 710–850 μm, which makes its measurement very difficult. Thus, measurement noise and uncertainty of the measurement in light microscopy may create problems in the measurement process and generate wrong measurement data. Recently, an optical probe is developed by [7] to measure the cutting edge radius of diamonds. White-light interferometer is also used by [8] to measure the cutting edge radii of diamonds. The problem in using a form and roughness tester is positioning, orienting and fixturing the diamond grain as well as the morphological errors coming from the stylus and fixture. A tactile profilometer is used in [9] for measurement of the edge quality of the polycrystalline diamonds. For SEM, the problem is the non-conductivity of the diamond; therefore always sample preparation have to be done and special consideration must be given to have a homogenous and thin layer of metallic coating on very clean diamond samples. Another problem in SEM is defining the correct orientation for diamond grains and sticking the diamonds properly to the SEM-stubs in which the SEM stub can be used in other measurement systems. Some researchers such as [10], have used SEM to measure the cutting edge of single crystal diamond tools after sharpening the cutting edge for ultra-precision turning processes. The main concern about the measurements with AFM is the large macroscopic surface of the sample which makes it difficult to measure large cutting edge radii of diamonds with small scan ranges, i.e. 3 μm in [11]. AFM is used to measure the cutting edge radius of diamonds, such as in [11,12]. For the imprinting process, presence of the air bubbles in the negative of diamonds and choice of proper imprinting material to minimize sticking to the sample and deformation after solidification, as well as bearing high elasticity are the main concerns. The evaluation of the imprinting method for production of the positive replicas are explained in detail in [13]. Furthermore, it is shown by [14], that the cutting edge radius of diamonds can also be copied by indenting the tool cutting edge into the surface of a mild metal and then measure the copy of the profile in metal by AFM. However, the problem for the imprinting in metals is the spring back. The issue of transparency in this study is solved by checking different coatings and using the impression material. All the diamonds are rigorously oriented and glued in special fixtures under microscope. The fixtures are accurately mounted in the form and roughness tester. For imprinting process in this study, the air bubbles are removed by a simple injection mold, which is designed just for this application. Furthermore, pressure and cyclic movement is applied to bring the air bubbles to the surface, in addition to selecting the proper imprinting material.

With help of criteria, which cover the advantages and disadvantages of each of the measurement alternative, and applying the AHP method, the optimum measurement technique based on requirement of the user(s), can be selected. A recent research on decision making and evaluating the inconsistencies in pairwise comparisons judgments are analyzed in [15]. Furthermore, most important criterion and least important criterion are used in [16] in a multi-criteria decision making method. For the comparison of different metrology methods in this study, seven different diamonds are prepared and each of them is measured with five different measurement methods. The analysis of the measurements are done based on one methodology which is the least square circle fit over cutting edge radius that is determined iteratively and is explained in detail in [17,18]. Then uncertainties for each measurement are calculated and the measurements are compared. Results of diamond # 2 from different measurement techniques are shown throughout the paper; however, the result summary using different explained techniques are shown in Fig. 7. The same techniques, which are explained in current work for determination of cutting edge radii of diamonds, can also be used for measurement of other hard to measure geometries and evaluate their surface properties. Measurements of cutting edge radii of some diamonds with particular methods can be found i.e. in [7–10,12,14] and are discussed above. However, characterization of grains for grinding and dressing applications are not reported in literature. Furthermore, the comparison of different measurement methods, calculation of the uncertainties, measurement parameters, and conditions to achieve acceptable results are not found in literature. The same metrology methods can be used for analysis of other transparent objects. Finally, the assessment and selection of suitable metrology can be achieved with the proposed criteria.

Methodology of measurement evaluations

To evaluate the cutting edge radius, 2D profiles from the measurements are used, as theory of cutting is based on cutting edge radii in a plane square to the cutting edge. This is the reason, why cutting edge radius and not form deviation from a given radius is evaluated. To reduce the uncertainty of the evaluations along the cutting edge, averages of several profiles along the cutting edge are extracted and used in the calculations. The procedure, which is used for cutting edge radius evaluations, is explained schematically in Fig. 1.

In brief, this method is based on fitting a least square circle with cutting edge radius that is determined iteratively. It contains five main steps. First, a straight line by least square method is fitted each to the rake and flank faces in the two dimensional profile. These two lines create the wedge angle. Second, from the intersection of the bisector of this wedge angle with the profile of cutting edge, one point is defined. Third, a circle is drawn passing through this point and tangential to the two straight lines corresponding to the rake and flank faces. A new upper limit for the least squares straight line fitting is defined from the points where the circle touches the fitted lines. Fourth, the previous steps are then repeated several times to fulfill the criteria of being tangent to the new least square lines and passes the point (similar to the point in step 2) from the intersection of the bisector with the cutting edge profile. Then the two points in the edge profile, where the curvature starts, are defined. Finally, a least square circle is fitted to the profile using all points within the micro geometry limit for the circle. The circle does not necessarily need to touch the

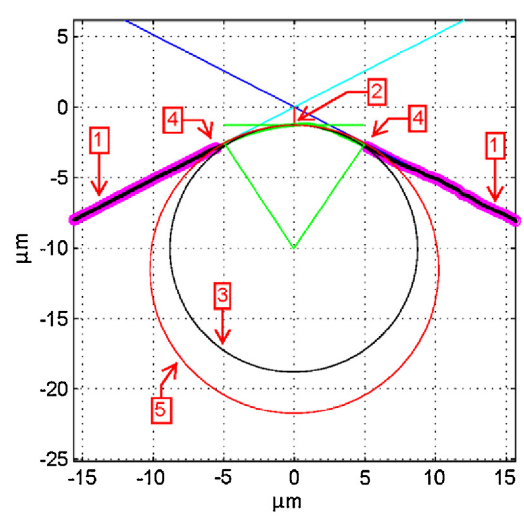

Fig. 1. Methodology of the measurement evaluation based on [17,18]. The five steps which are explained in the Methodology of measurement evaluations section are shown. For diamond edge # 2 measured with Leica confocal light microscope; the black circle has a radius of 8.8 μm and the finally fitted red circle has a radius of 10.2 μm.