Characterization of micro grinding tools using optical profilometry

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Abstract:

This article presents a method to characterize the electroless plated micro grinding tools using an optical measuring device. Abbott Firestone curve characteristics, such as height distribution, void volume, and material volume obtained from the topography measurements, were used to define the term "volume ratio." This parameter distinguishes the micro grinding tools according to the planar grit density. As a result, micro grinding tools can be classified similar to the conventional grinding wheels.

Keywords:

Micro grinding; Surface topography; Optical microscopy; Profilometry.

Introduction:

In any grinding process, it is essential to know the grinding wheel composition. The type of abrasive, grits size, wheel hardness, wheel structure, and bond type are parameters, which designates the conventional grinding wheel. This information is readily available to the user from the wheel marking system [1]. Of all the parameters, it is essential to know the structure number of the wheel, which indicates the volume percentage of abrasive grits in a given wheel. The higher the structure number, the higher the wheel porosity [2]. A higher porosity provides the space for coolant and chips. In the case of a metal bonded wheel, the free space available in between the grits act as the chip space. However, this porosity information is not readily available for the micro grinding tool because of the randomness in the tool manufacturing process.

The abrasive grits can be deposited onto the micro grinding tool base substrate surface (Figure 1a) by various methods, such as electroplating [3], electroless plating [4], electroforming [5], cold spray [6], and CVD [7]. Irrespective of the method, it is difficult to estimate the volume fraction of the abrasive grits deposited on the tool surface (Figure 1c). Of all the manufacturing methods, the electroless plating method is an economical way to produce small-sized tools. Various factors involved in the electroless plating process complicates the analytical estimation of planar grit density (i.e., number of grits per unit area) on the tool substrate.

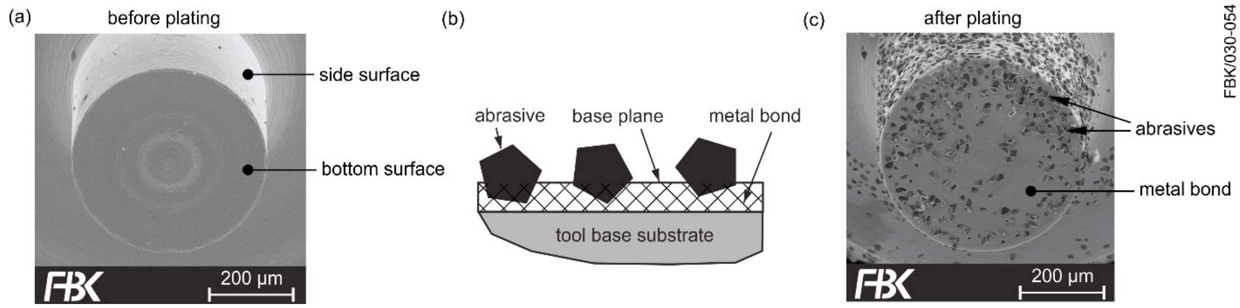


Figure 1. (a) SEM image of micro grinding tool base substrate before coating, (b) schematic of the electroless plated surface (c) SEM image of micro grinding tool base substrate after plating

Several works reported the micro grinding tools application on hard, brittle, and ductile materials [8–10]. Experiments have been performed to understand the micro grinding process mechanics [11,12], improve the grinding performance [13][14], and to test the quality of the tools that resulted from various deposition methods [15]. All these works emphasized the importance of optimum tool and cutting conditions selection. Additionally, in micro machining, the size effect [16] related to the uncut chip thickness (h_m) also plays an important role, which is expressed as [1]

$$h_m = 2\lambda \left(\frac{v_w}{v_s}\right)\left(\frac{a}{2r}\right)^{1/2}\left(1-\frac{a}{2r}\right)^{1/2} \tag{1}$$

where λ is the average distance between the grits on the tool surface, v_w is the feed rate, v_s is the cutting speed, a is the depth of cut, and r is the radius of the tool.

It is evident from equation (1) that apart from the process conditions (v_w, v_s, and a), parameters associated with the tool (λ and r) also influence the uncut chip thickness value. For the successful micro grinding process, it is required to have the h_m value higher than the minimum chip thickness value for ductile materials, and for the brittle materials, the h_m value should be less than the critical chip thickness value [8–10]. It indicates that for the grinding of brittle materials, such as ceramics, it is recommended to have a tool with lower λ value, and for the ductile materials, it should be higher. As mentioned earlier, for the conventional grinding wheels, the wheel marking system helps in assessing the wheel porosity, and hence, λ value. However, for micro grinding tools, this type of information is not available.

Scanning electron microscopy, optical profilometry, and stylus-based methods are commonly used to measure the conventional grinding wheel topography [17]. Because of the smaller tool sizes (< 1 mm), it is difficult to implement the tactile measurement techniques for micro grinding tools despite their accuracy. The application of the SEM technique is time-consuming and also needs post-processing to get the topography information. Several works reported the various physical and stochastic modeling methods for grinding wheel visualization [18]. However, for the micro grinding process modeling and experimental work, it is essential to know the nature of the tool. Few works on the micro grinding tool simulation have adopted the conventional stochastic approach without real topography measurements [19,20]. It is common to use the optical methods in metal cutting process for various purposes, such as process monitoring, tool condition monitoring, and for the characterization of finished surface [21,22]. To the best of our knowledge, the characterization of the micro grinding tools in any method is not yet reported. Hence, in this article, a method has been proposed to characterize the micro grinding tools based on the Abbott Firestone curve parameters that resulted from the topography measurements. As a result, the nature of the grits distribution on the tool surface can be known, which is crucial for a reliable micro grinding process design.

Characterization Method:

Mathematically, Abbott Firestone curve is the cumulative probability density function of the surface profile's height. Heights distribution is the histogram of the surface heights that quantifies the number of points on the surface that lies at a given height. Heights distribution curve obtained from the tool topography measurement shows the grits height distribution in between the minimum and maximum protrusions.

To understand better, various terms used in the topography characterization are defined below:

base plane—the plane, which is placed on the level of the bond as shown in Figure 1b.

mean heighe plane—the plane, which is parallel to the base plane and located at grits mean height.

maximum height plane—the plane which is parallel to the base plane and located at maximum protruded grit.

void volume— the volume of the space in between the base plane and a plane at the set height.

material volume—the volume of the material in between the maximum height plane and a plane at the set height.

It this study, we considered the chip space volume as the void volume, and grits volume as the material volume at the mean height plane. It is evident from Figure 2b, f, and j that if the set plane is close to the minimum protruded grit, then the available chip space volume is also the minimum. If the set plane moves away from the base plane, the chip space volume increases, which is the maximum at the maximum height plane. It is also evident from Figure 2b, f, and j that if the set plane is close to the maximum protruded grit, then the available grits volume is the minimum. In this case also, as the set plane moves away from the maximum height plane, grits volume increases, which is the maximum at the base plane.

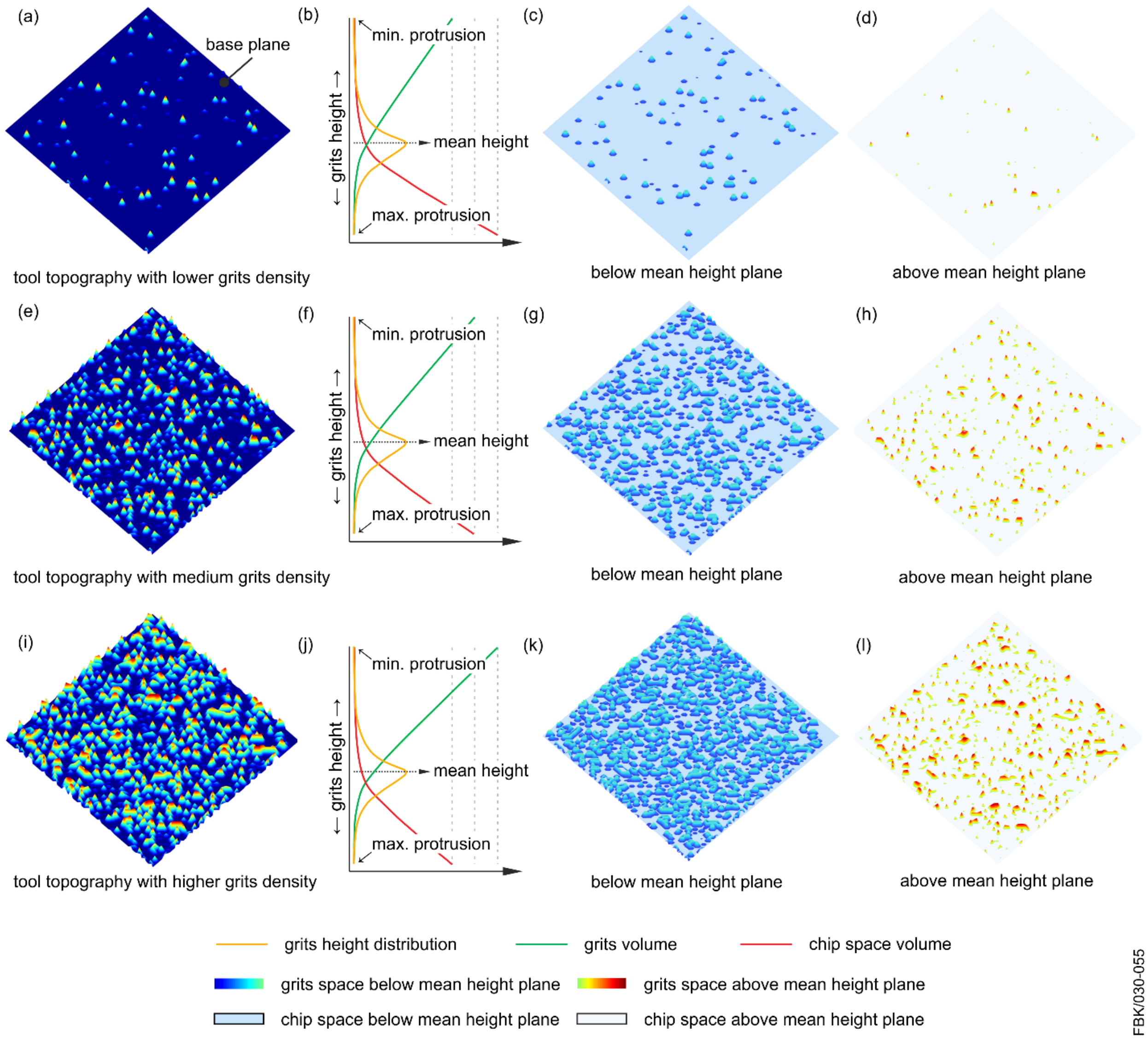


Figure 2. Schematic of (a, e, i) grits distribution on tool surface (b, f, j) heights distribution, grits volume and chip space volume curves (c, g, k) grits space and chip space below the mean height plane (d, h, l) grits space and chip space above the mean height plane (a, b, c, d—with lower planar grit density tool; e, f, g, h—with medium planar grit density tool; i, j, k, l—with higher planar grit density tool).

Schematically, Figure 2 also shows the variation in grits space and chip space with different planar grit density. With reference to the mean height plane, the following term "volume ratio" is established and calculated to characterize the micro grinding tools with the available grits volume and chip space volume data.

$$volume\ ratio = \frac{grits\ volume\ above\ the\ mean\ plane}{chip\ space\ volume\ below\ the\ mean\ plane} \quad (2)$$

If the volume ratio is high, it indicates the structure of the micro grinding tool as "dense," that means, the distance between the grits is less, which can result from either higher grits volume or lower chip space volume. If the volume ratio is low, it indicates the structure of the micro grinding tool as "open," that means, the distance between the grits is high, resulting from either lower grits volume or higher chip space volume. As schematically shown in Figure 2, this parameter volume ratio can consider planar grit density into the account. In the case of tools with lower planar grit density, available grits volume above the mean height plane is less, and the chip space volume below the mean height plane is high. It results in a lower-volume ratio. Similarly, at the mean height plane, available grits volume is high, and chip space volume is less for the tools with higher planar grit density. It results in a higher volume ratio. Based on these statements, it can be said that, for a tool, a higher-volume ratio indicates the higher planar grit density; subsequently, the distance between the grits reduces. Smaller "volume ratio" indicates the lower planar grit density and the higher distance between the grits.

Measurement method:

Steel base substrates with different end diameters (460, 360, 260, 160 µm) were electroless plated with cBN grits of different sizes by adding varying quantity in plating solution, as shown in Figure 3 and also summarized in Table 1.

Table 1: Summary of cBN grits size and quantity used in the plating solution for the tools shown in Figure 3.

Tool number	cBN grits size (µm)	quantity of grits in plating solution (g)
1–4	20–30	3
5–8	20–30	6
9–12	06–12	3
13–16	06–12	6

Varying the grits quantity in the plating solution is one way to produce tools with different planar grit densities. However, in all the cases, the exact amount of the grits deposited to the base substrate is unknown. Apart from this, all the other conditions during the plating process were kept the same and followed the standard procedure [23].

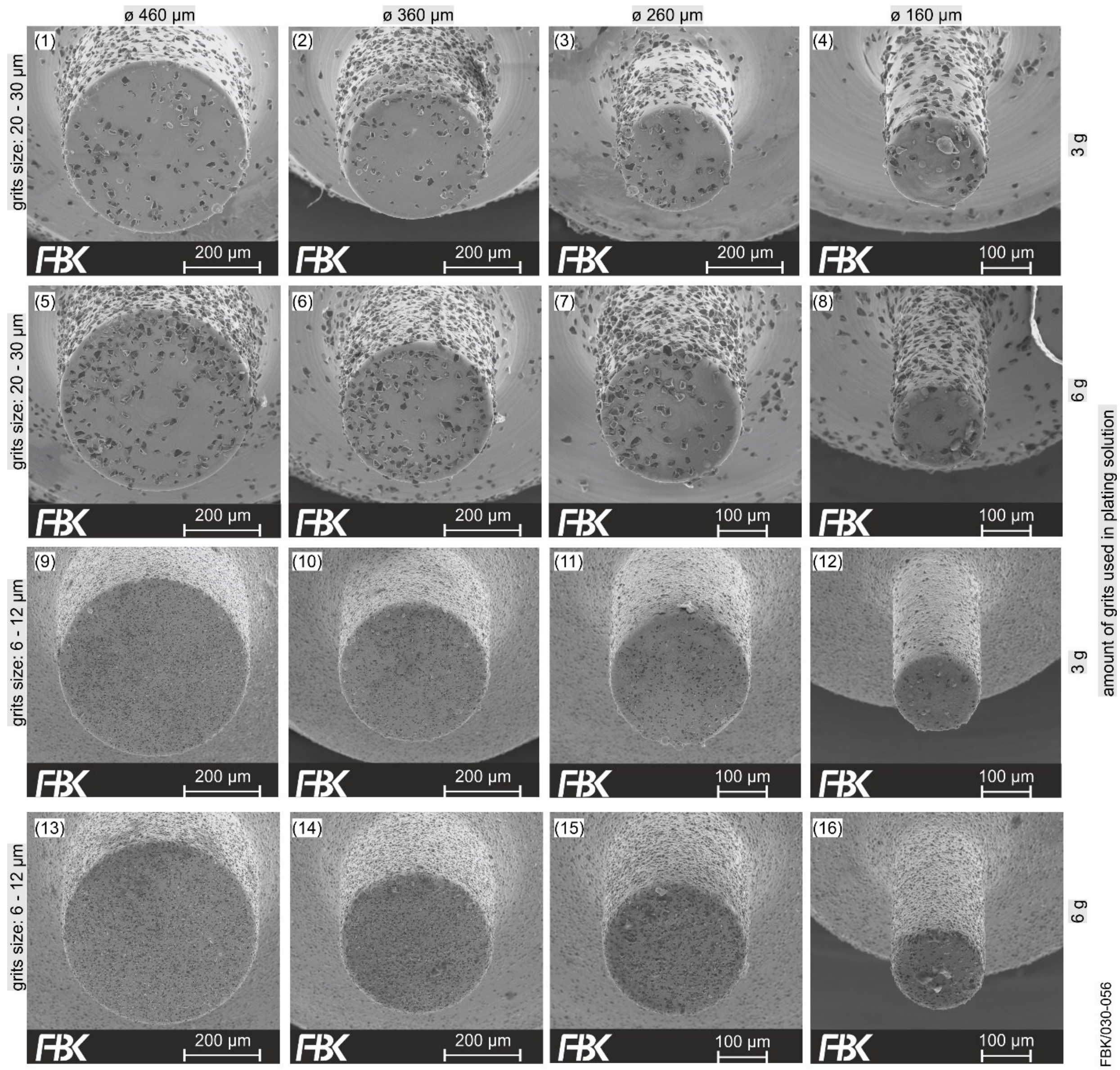


Figure 3. SEM images of micro grinding tools with different base substrate diameters, grits size, and amount of grits in the plating solution

Micro grinding tools produced by the electroless plating were characterized using an optical 3D measuring system MikroCAD supported with ODSCAD software. It has a lateral and vertical resolution, and a measurement range of 0.7 µm, ±35 nm, and 500 µm, respectively. The optical measurement method consists of digital strip projection with micromirror projectors (Digital Micro-Mirror Devices [DMDTM]). In this method, strips with a sinus-like brightness intensity are projected onto the surface of the measurement object, and their image is recorded with a CCD camera (Figure 4).

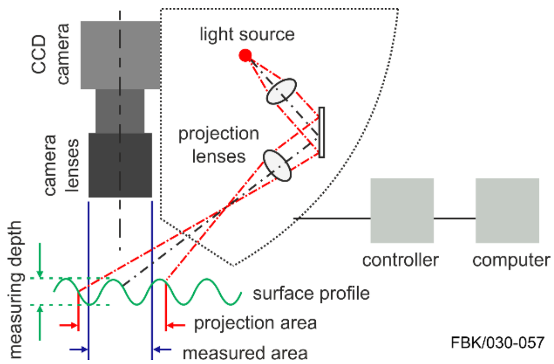


Figure 4. Schematic of the measurement system working principle (adapted from instrument manual).

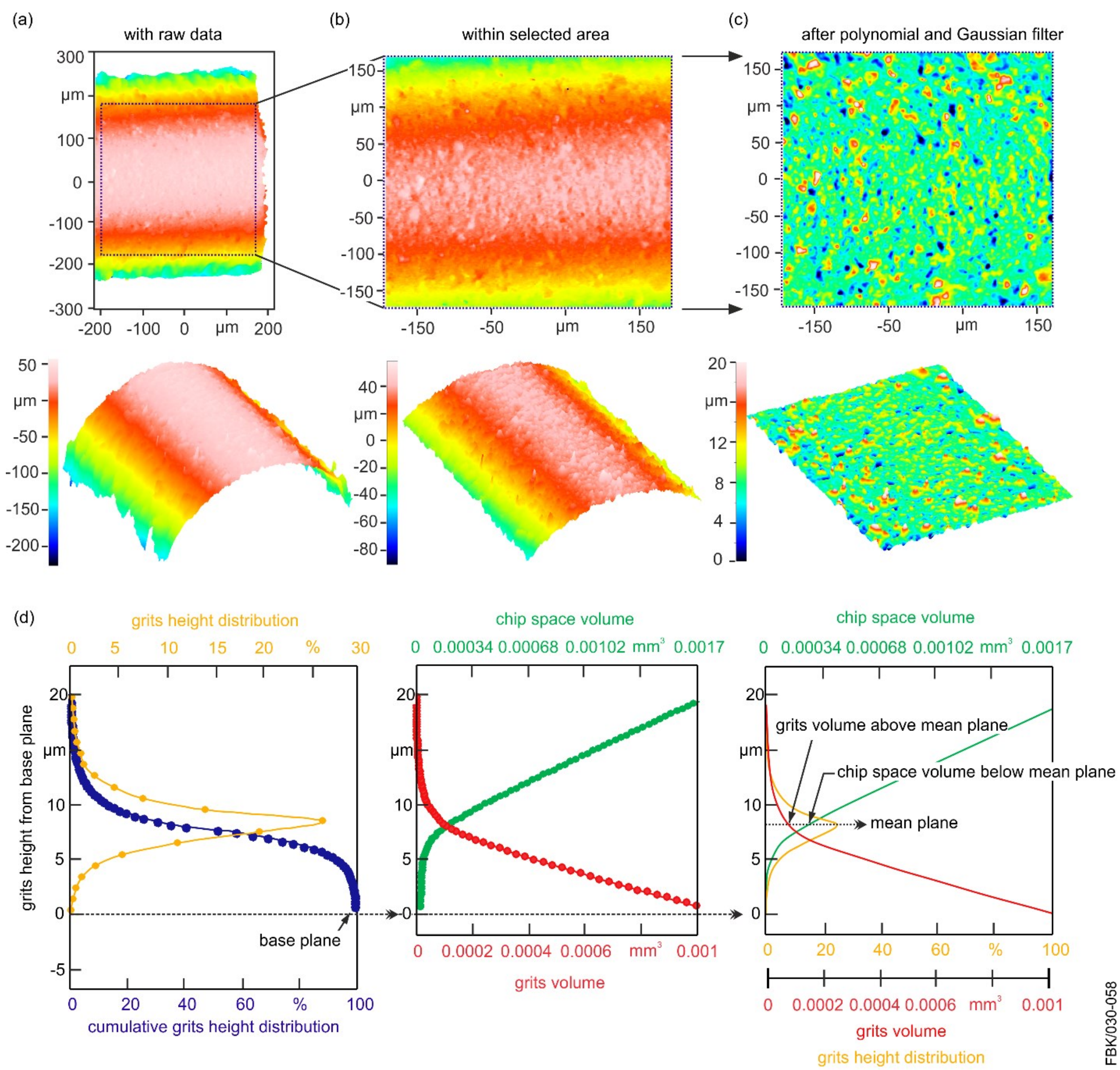
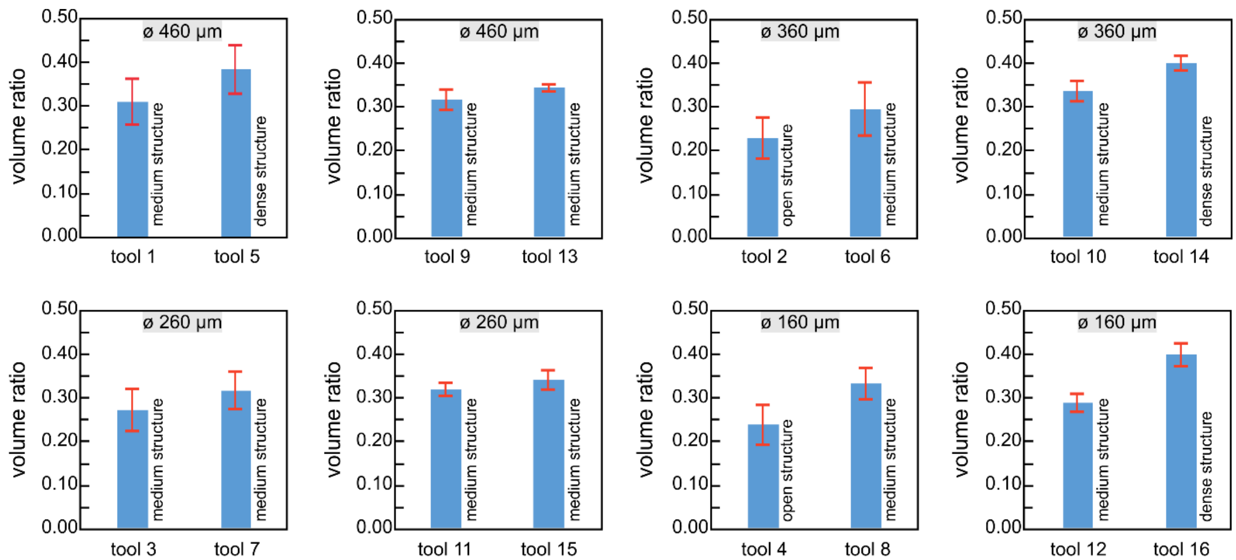


Figure 5. 2D and 3D views of the tool (a) with the obtained raw data (b) within the selected area (c) after polynomial and Gaussian filters (d) variations in grits height distribution, grits volume and chip space volume with the grits height from base palne (one of the sample measurement for tool 5).

The height image of the measuring object is calculated from the position of the strips and the gray value of the individual image points. All the measurements were performed on the tool side surface at four different places (90° separation) within the tool active length part. As explained above, the measurements were performed on all the tools shown in Figure 3. To obtain reliable information for analysis, filters are used to remove noise and macro feature (shape of the tool) derived from the measured 3D profile data. The Gaussian filter is used to remove the measurement noise, and a polynomial filter is used to remove the form of the tool. For clear understanding, the procedure adopted for a single measurement is shown in Figure 5.

Results and discussion:

Based on the topography measurements, the volume ratio of each tool is calculated at the mean height plane. As a summary of all measurements, Figure 6 is given. In Figure 6, a comparison is made in between the tools which have the same grits size and base substrate diameter but there are varying amounts of grits in the plating solution.



	mean height (µm)	grits size (µm)	amount of grits used in plating solution (g)		mean height (µm)	grits size (µm)	amount of grits used in plating solution (g)
Tool 1	8.98 ± 0.57	20 - 30	3	Tool 3	8.65 ± 1.06	20 - 30	3
Tool 5	8.76 ± 0.90	20 - 30	6	Tool 7	8.91 ± 0.84	20 - 30	6
Tool 9	5.28 ± 0.87	6 - 12	3	Tool 11	5.11 ± 0.88	6 - 12	3
Tool 13	5.89 ± 0.75	6 - 12	6	Tool 15	5.25 ± 0.43	6 - 12	6
Tool 2	9.55 ± 0.83	20 - 30	3	Tool 4	8.55 ± 1.25	20 - 30	3
Tool 6	10.38 ± 0.54	20 - 30	6	Tool 8	7.18 ± 0.66	20 - 30	6
Tool 10	4.95 ± 0.55	6 - 12	3	Tool 12	4.75 ± 0.43	6 - 12	3
Tool 14	5.50 ± 0.78	6 - 12	6	Tool 16	4.40 ± 0.04	6 - 12	6

* ø is the base substrate diameter

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Figure 6. Volume ratio and grits mean height for the different micro grinding tools shown in Figure 3.

Using the above Figure 6, the following observations can be made:

i. tools prepared with the higher amount of grits (6 g) in plating solution resulted in a higher volume ratio compared to the lesser amount of grits (3 g)
ii. tools prepared with bigger grits (20–30 µm) shown maximum variations in the volume ratio compared to the tools with smaller grits (6–12 µm)

From Figure 3 also, it is evident that the tools prepared with a higher amount of grits in plating solution resulted in a higher number of grits deposition compared with the lower amount of grits. In that way, it can be confirmed that the proposed term *volume ratio* differentiates the micro grinding tools topography according to their planar grit density. The reason for higher standard deviation values with bigger grits can be attributed to the grit size itself, because grit volume is directly associated with the grit size and an increase in the grit size results in an increase in volume, which is in the order of magnitude 3. Moreover, in the case of bigger grits, it can also be observed that the base substrate with larger diameter resulted in higher-volume ratio. It is because the larger surface areas have a higher probability of retaining the grits during the plating process. Based on the observed volume ratios, the micro grinding tools are classified into three categories as given below and also shown in Figure 6.

dense structure: volume ratio → 0.45–0.35

medium structure: volume ratio → 0.35–0.25

open structure: volume ratio → 0.25–0.15

Conclusions:

A method has been proposed to characterize the electroless plated micro grinding tools based on the 3D topography measurements. The inverse relation between the girts volume and chip space volume with grits height has been used to define the characterization parameter volume ratio. Optical profilometry enables a simple and fast characterization of micro grinding tools. The proposed method was able to identify the planar grit density variation and enables to categorize the micro grinding tools similar to conventional grinding wheels. Topography measurements on the micro grinding tools with different diameters, grits size, and girts distribution confirms the relevance of the term volume ratio with the planar grit density variation.

Acknowledgment:

This work was financially funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 252408385 - IRTG 2057.

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