Investigations on the Tool Plate Preparation for Nanogrinding

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Abstract --- Nanogrinding (also known as fixed abrasive lapping), a surface grinding process using a lapping kinematic but no loose grain, is lending itself to ultraprecision machining of advanced ceramics. The process is capable of creating surfaces with minimized surface damages and average roughnesses \( R_a \) in the subnanometer range. The creating of the plate surface, embedding the diamond grains, as well as aligning their summits, is substantially influencing the nanogrinding process. Therefore, studying it, particularly the diamond embedding, seems very rewarding and is the subject of this paper. To analyze the location of diamonds, a combination of scanning electron analysis (SEM), energy dispersive x-ray spectrometry (EDS), and atomic force microscopy (AFM), was applied. As a result, both the location of diamonds as well as conditioning grains could be determined.

Introduction

The surface machining of ceramic mini- and microparts requires processes capable of creating surfaces with average roughness values \( R_a \) in the subnanometer range and minimal subsurface damages [1]. Flatnesses smaller than 10 nm/mm are additional requirements, e.g. for the machining of air bearing surfaces (ABS) for read/write heads of rigid disk drives. The nanogrinding process fulfills these requirements. It is based on a lapping process but in contrast to the loose lapping abrasives only fixed abrasive grains are applied for the material removal. Like lapping, the nanogrinding process uses a fluid to separate tool and workpiece. To achieve a sufficient film thickness, nanogrinding requires a significant grinding plate roughness [2]. This roughness is accomplished by conditioning the plate with a conditioning medium, e.g. pumice, as a first step to create the plate. After the conditioning, loose diamond grains are added and embedded into the plate surface. Both, the embedding of the diamonds as well as the coplanar arrangement of their summits are achieved through a conditioning ring. After diamond impregnation the plate is cleaned and all loose grains are removed.

Grinding Plate Topography

Figure 1 sheds some light on the nature of surface topography change after the different process steps. It presents AFM micro topography graphs of exactly the same region of the plate surface. Left, it depicts the virgin plate after conditioning, at the center it shows the plate after diamond impregnation, and right it presents the plate in a used condition after 60 min. of nanogrinding.

After conditioning

After diamond impregnation

After 60 min. of machining

Fig. 1 Different states of the plate’s surface topography (AFM measurements)

After conditioning, the plate started out with a random profile. The conditioning process resulted in an average and peak-to-peak plate roughness of \( R_a = 1.4 \, \mu m \) and \( R_p = 12 \, \mu m \), respectively. The gouges in the tin surface with a
depth of up to 8 µm are caused by conditioning grains. They represent the space for storing nanograting fluid and removed material during workpiece machining.

However, the diamond impregnation process causes a very distinctive change to the topography. The conditioning ring and the loose diamonds during this process step apparently truncate the peaks, creating some mesa type plateau surfaces in which the diamond grains are embedded. The size of the mesa surfaces is in the range of 5 µm x 5 µm to 30 µm x 30 µm. Deeper parts of the plate's roughness profile are not influenced. During the 10 min. of diamond impregnation approximately 1 µm of material is removed in the peak area of the roughness profile.

The consecutive machining process results only in a very slight further flattening of the peaks and thus in an increase of the mesa surface areas as is depicted after 60 min. of workpiece machining. Only mechanical contact between plate and workpieces and the abrasive action of the removed material particles (with sizes smaller than 5 nm) cause a further material removal of the plate material and therefore plate topography wear.

**Detection and Topographical Analysis of Embedded Abrasives**

For nanograting, typically a two-phase machining process using two different diamond grain sizes has been applied. The first "rough grinding" phase was conducted with 1.5-3 µm diamond, with the grain size chosen for maximal material removal. Optimal surface finish was achieved in the "fine grinding" phase with a 0.5-1 µm diamond grit. One of the key questions unresolved in the past has been at what location the diamonds are being embedded in the surface. To pinpoint these spots, the plate surface was subjected to a combination of scanning electron microscopy (SEM), energy dispersive x-ray spectrometry (EDS), and atomic force microscopy (AFM). Since even detecting diamonds with a size of 1.5-3 µm with EDS was a major challenge (carbon is on the borderline of detectability), the plate analysis was performed for the first phase of the nanograting process. Furthermore, local surface changes occurring through the conditioning process had to be observed and followed.

To do so, a method had to be devised to pinpoint a certain area. This was accomplished by marking a test field with a size of 100 µm x 100 µm at the tin surface. It was accomplished by scratching a frame around it using a diamond tip with a 2 µm tip radius (Figure 2, top). Afterwards, this test field was subjected to an SEM/EDS to detect the abrasives embedded in the tin surface (Figure 2, bottom left). Aside from diamond, pumice grains were found, which were used to roughen up the plate in the conditioning process and remained in the plate. Their portion of the total surface area was determined to be 10-15%. Nevertheless, it was shown that the abrasive pumice grains do not take part in the material removal process during workpiece machining since they do not result in any removal rate.

In the example, six pumice grains and two diamonds are embedded in the enlarged part of the marked field. The results equal a density of diamond grains \( N_d \) of 3,500 per mm².

![Image of SEM/EDX and AFM analyses for the detection and topographical analysis of embedded abrasive grains](image-url)
After the SEM/EDS analyses, the test field was subjected to high resolution topographical AFM measurements (Figure 2, bottom right). The 3D AFM picture shows that the two diamond grains are embedded in one of the plate's mesa surfaces which in this case had a size of approximately 18 µm x 18 µm.

**Grain Protrusion and Grain Location in the Plate**

By performing a 2D analysis, i.e. looking at the plate cross section of the AFM plate measurements, the protrusion of abrasive grains beyond the binding material could be determined. For instance, this is demonstrated in Figure 3 which shows an enlarged view of the upper diamond grain previously presented in Figure 2. The scans show a protrusion in excess of 110 nm in the A-B and 150 nm in the C-D profile.

![Diagram](image)

**Fig. 3** 2D surface cross sections of an embedded diamond grain

The pumice grain at the right hand side of Figure 3 shows significant wear marks. Figure 4 depicts a schematic view of its recession. The conditioning grain was not only truncated, it also ended up with a plateau surface recessed at least 100 nm below a neighborhood diamond grain's cutting edge. This view clearly indicates why pumice as a conditioning grain does not participate in the material removal process during workpiece machining; it already wears during the diamond impregnation process step by contact wear with the impregnating diamond, due to its low hardness (Figure 4).

![Diagram](image)

**Fig. 4** Wear of conditioning grains during diamond impregnation

As result of analyzing different diamond grains in the nanogrinding plate, a protrusion above the mesa surfaces in the order of 50-200 nm was observed for the 1.5-3 µm grit diamond. Preferably, the diamonds embed themselves at the rim of the mesa surfaces as is depicted in Figure 5. Due to the high plastic deformations caused by the embedding processes the tin-matrix increases in hardness in the sub-surface zone by work hardening. This was proven by nanohardness measurements. The hardness increased by a factor of seven from 0.05 GPa to 0.34 GPa. Due to the work hardening, a deeper penetration of diamonds into the plate during workpiece machining seems to be avoidable. Therefore, a long plate life is achieved.
Conclusion

During the different steps of a nanogrinding process, the nanogrinding plate’s microtopography is subject to change. After conditioning, the plate had an average and peak-to-peak plate roughness of $R_a = 1.4 \, \mu m$ and $R_t = 12 \, \mu m$, respectively. During conditioning, mesa type plateau surfaces were created in which the diamond grains were embedded. The consecutive machining process hardly changed the mesa surface, just increased it minutely. By a combination of SEM/EDS and AFM analyses, diamond grains embedded in the plate could be detected and topographically analyzed. The grain density for a 1.5-3 \, \mu m grit is approximately $N_A = 3,500 \, \text{mm}^2$, the grain protrusions above the plate's tin surface were in the range of 50-200 nm. The diamonds preferably embed themselves at the mesa surfaces' rims. Aside from diamond grains, conditioning grains also embed themselves into the plate during conditioning. Due to their low hardness, these grains already wear during the diamond impregnation process and therefore do not take part in the material removal process.

References


Fig. 5 Examples for embedded diamonds in the nanogrinding plate; SEM (left) and AFM (right) analyses