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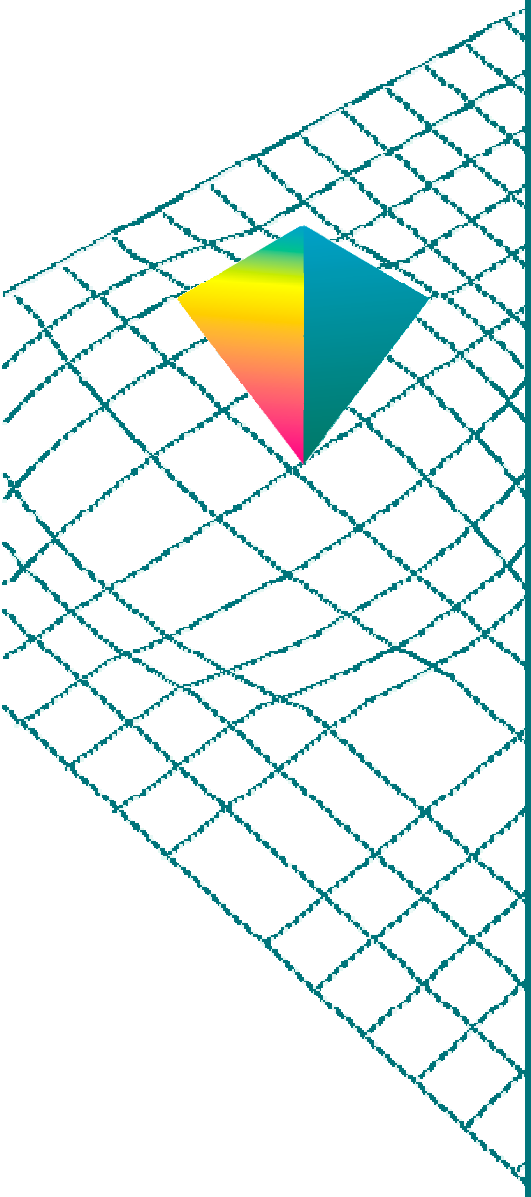

50. Internationales Wissenschaftliches Kolloquium

September, 19-23, 2005

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Mechanical Engineering from Macro to Nano

Proceedings

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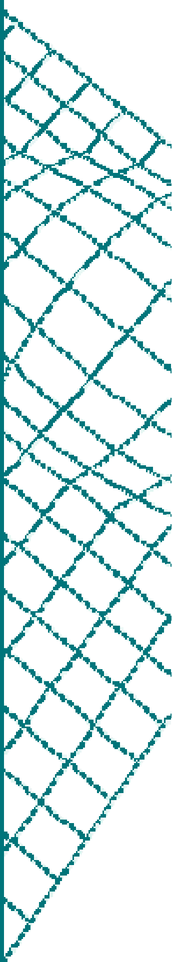

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50. Internationales Wissenschaftliches Kolloquium
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Precision Conditioning of Coarse-Grained Diamond Wheel for Ductile Grinding Brittle Materials

ABSTRACT

A novel conditioning technique for the precise and effective conditioning of nickel electroplated monolayer coarse-grained diamond grinding wheels of 91µm grain size was developed to realize ductile grinding of brittle materials. During the conditioning process, a copper bonded diamond grinding wheel (91µm grain size) dressed by ELID (electrolytic in-process dressing) was applied as conditioning tool, a force transducer was used to monitor the conditioning forces, and a coaxial optical distance measurement system was used for in-situ monitoring the modified wheel surface status. The experimental results indicate that the newly developed conditioning technique is applicable and feasible to generate run-out error of bettre than 2µm as well as the required wheel topography and grain geometries. Contour grinding tests on BK7 prove that the well-conditioned wheel is capable of realizing ductile grinding of brittle materials.

Keywords:
Coarse-grained diamond grinding wheels; Conditioning; Brittle materials; ELID; Run-out error.

1. Introduction

A disadvantage of using fine-grained diamond wheels to grind brittle materials in ductile mode is the large wheel wear rate caused by the dressing and grinding process, which limits the achievable figure accuracy and the maximum material removal volume, especially in case of grinding large free form optical surfaces.

Monolayer nickel electroplated coarse-grained diamond grinding wheels featuring grain sizes of approx. 100µm, however, could be a promising solution of the wheel wear problem, provided that they are well conditioned in terms of top-flattened diamond grains and a minimised wheel run-out error.

In conventional point of view, monolayer wheels can not be dressed, because they have only a single abrasive layer which is attached by an electro-plating process to the peripheral surface of the metal base plate. And wheel life ends when the layer no longer provides the required performance, therefore it is not possible to achieve a virtually steady-state in the grinding process because of the only one layer of diamond grains. However, in case of machining of brittle materials like ceramics and glasses with small material removal rate, the wheel components are subjected to only minor abrasive attack by the chips removed from the workpiece, resulting in long wheel life due to low wear gradient over grinding time [1], which is of a real matter in ductile grinding of large free form optical surfaces.

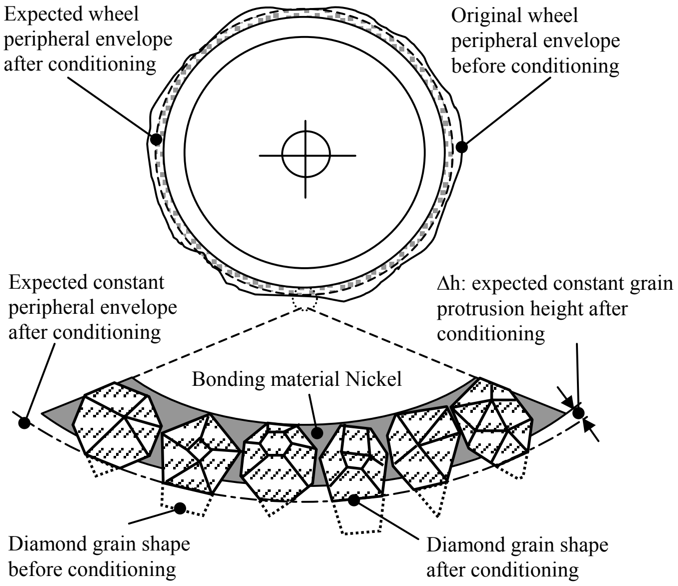
Based on this idea, several researchers have tried to apply this new diamond wheel in ductile grinding of brittle materials [2, 3, 4, 5, 6, 7, 8]. Brinksmeier et al. [2] have proposed a conditioning technique using a diamond cup wheel to dress the coarse-grained diamond wheel and obtain radial run-out errors of less than 2μ, and finally ductile mode taper grinding was realised on optical glasses. Akira Kanai et al. [3] have proposed a new design of diamond wheels where the abrasives are monocrystalline pillar diamond and the orientations are aligned. Surely this kind of wheel is a perfect choice but at the moment it is very difficult to be manufactured. Wakuda et al. [4] have proposed a truncating method to dress coarse-grained CBN wheels in grinding hardened steel and obtained a mirror-like surface with Ra 0.05μm. Hwang [6, 7, 8] et al. have used unconditioned electroplated diamond wheels on high speed grinding of silicon nitride, by which the wheel wear, wheel life, wheel topography and grinding mechanism were investigated. However, there have been no reports so far on the successful application of coarse-grained diamond wheels on ductile contour grinding of optical glasses.

2. Principle and experimental setup of the conditioning process

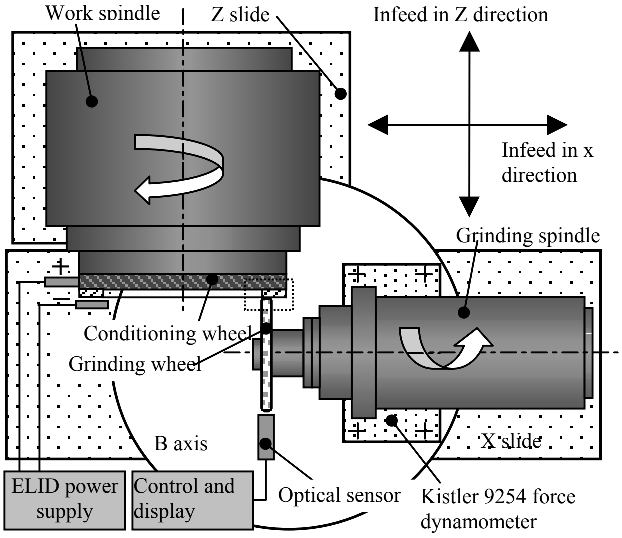
As illustrated in Fig. 1(a), firstly from the macro point of view, both the periodic and non-periodic waviness caused by the wheel base manufacturing error and the uneven electroplated nickel layer contribute to the wheel run-out error, which will result in a dynamic problem of an unbalanced wheel and a kinematic problem of impacting with the specimen to be ground; secondly from the micro point of view, diamond grains in axial direction and peripheral direction with different protrusion height will result in different depth of cut per grain, of which some grains will penetrate beyond critical depth of cut and therefore induce brittle damage.

Based on this consideration, an applicable conditioning process for coarse-grained diamond wheels should fulfil the following tasks: eliminating the wheel waviness to obtain a sufficient run-out, as well as removing the highly protruding grain tops to obtain flattened grains with a constant peripheral envelope and a constant protrusion height Δh. To meet these requirements, an experimental system illustrated in Fig. 1(b) was designed. Fig. 1(c) shows that the cup shape metal-bonded diamond conditioning wheels of 91μm grain size were mounted on the work spindle and were dressed by ELID (electrolytic in-process dressing), as well as the conditioned grinding wheel were in-situ monitored by the optical distance measuring system to determine whether the wheel run-out error was within the desired tolerance of 1-2μm.

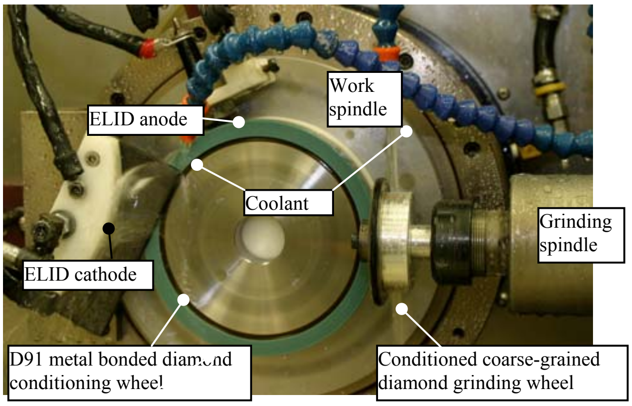
In order to achieve a high material removal rate, both the conditioning wheel and the conditioned grinding wheel rotate in counter clock-wise direction, e.g. the converse tangential direction at the contacting point. During the conditioning process the conditioning wheel rotates at 500rpm while the conditioned grinding wheel rotates at 5000rpm. The applied general depth of cut a_p (infeed of the conditioning wheel in Z direction) was in a range of 1-3μm and the feed rate v_{fd}



(a) Prerequisite for coarse-grained diamond wheels applied in precision grinding of optical glasses.



(b) Top view of the setup of ELID assisted conditioning process for coarse-grained diamond



(c) Experimental setup of the conditioning

Fig. 1: Experimental system.

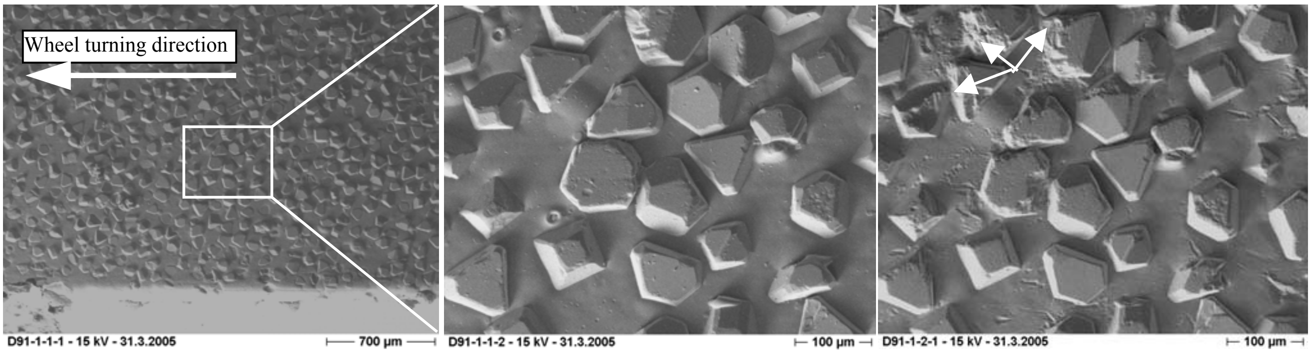
(infeed of conditioned grinding wheel in X direction) was 4-10mm/min.The whole conditioning procedure is: balancing the conditioned grinding wheel -> conditioning the grinding wheel -> checking the wheel run-out error and the diamond grain morphology by means of a replica method -> balancing the conditioning grinding wheel again -> continuously carry on the conditioning process -> until the ideal wheel surface state is obtained.

During the conditioning process, the conditioned grinding wheel surface status was in-situ monitored by a coaxial optical distance measurement system. Due to the low sampling rate of this system (maximal 1000Hz sampling rate), all conditioned coarse-grained grinding wheels were rotated with 900rpm, i.e. 7.5 revolutions per second to measure the run-out errors. Run-out error of different parts (left, middle and right) alongside the wheel peripheral envelope were sampled, as well as the corresponding wheel surface topography were replicated at the same wheel areas by vinyl polysiloxane impression material in aiming to investigate the improvement in flattening the coarse diamond grains during the conditioning process. A Kistler 9254 force transducer was mounted between the grinding spindle and the B axis table to monitor both conditioning and grinding processes. An atomic force microscope (AFM) and a white light interferometer (WLI) were used to measure the ground glass surface quality; a large chamber scanning electronic microscope (LC-SEM) was used to monitor the diamond grain status of the conditioned grinding wheel; the replica (resin replica duplicated by vinyl polysiloxane impression material) of the conditioned grinding wheel surface morphology were photographed by WLI and a conventional SEM.

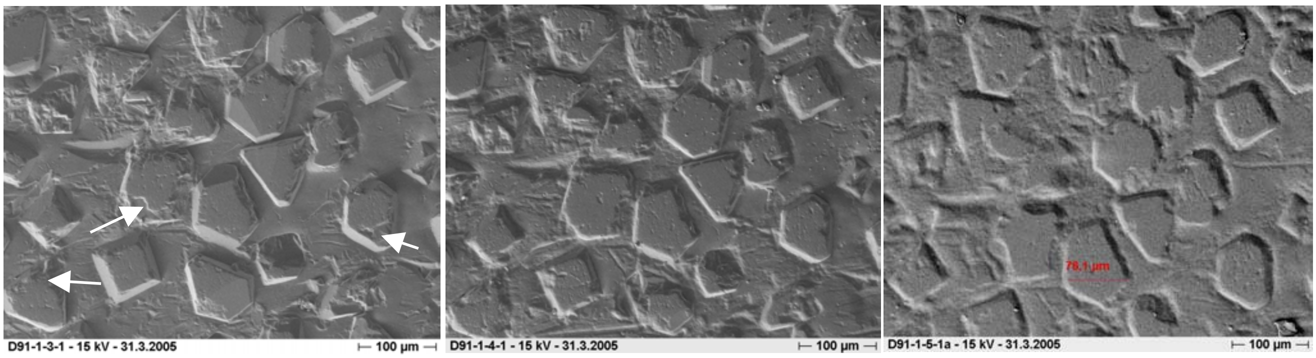
3. Experimental results and discussions

3.1. In-situ monitoring the modification of diamond grain morphologies during the conditioning process

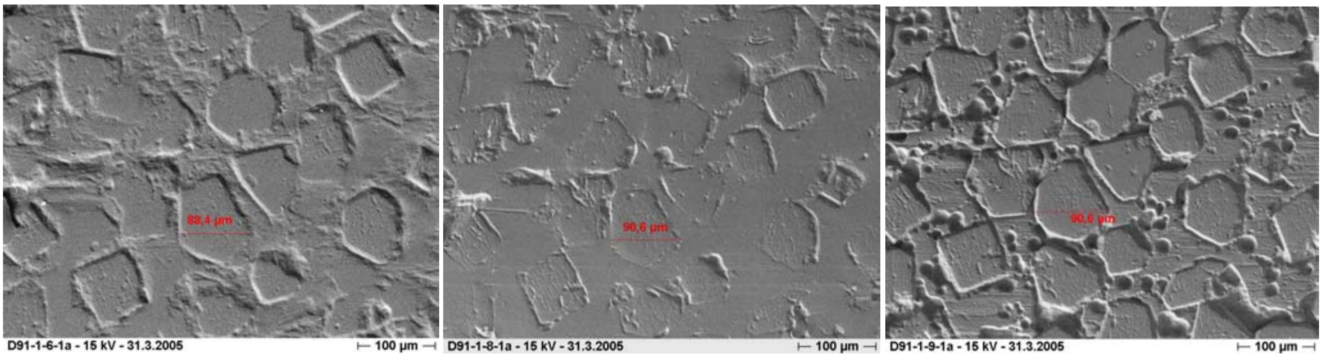
During the conditioning process, the modification of diamond grain morphologies was in-situ characterised by a SEM on resin replica taken for each 30μm infeed in Z direction, shown in Fig. 2(b)-(h). Fig. 2(i) indicates the wheel surface topography after the following ELID process. Fig. 2(b) shows the original surface topography featuring incorporated diamond grains with different geometries and different protrusion heights. After 30μm infeed in Z direction, partial diamond grains were started to be truncated with an unsteady state featuring shedding and fracture occurred, especially at the first contact point with the conditioning wheel along the grinding wheel turning direction, according to Fig. 2(c). After 60μm infeed, Fig. 2(d), more diamond grains were involved in truncating action and resulting in a bigger grain top surface area, while the bonding material has not yet been touched. Some shedding and fractures still happen on diamond grains which are marked by arrows in the figures. From Fig. 2(e)-(h) we can see the conditioning process operates in a steady state featuring no further shedding and fracture and bigger grain top surface area (or bigger grain surface bearing ratio) generated, the grain protrusion height gradually decreasing to zero. Because the surrounding bonding material can prevent diamond grains from being damaged by the conditioning wheel, so at this stage it shall be a perfect state for conditioning the grinding wheel. However, diamond grains with zero protrusion height can not be used in grinding due to the lack of chip space In order to solve this problem, ELID was applied to dress the grinding wheel after the finished conditioning process. The oxidised layer formed by ELID was removed by an Al_2O_3 stick. The final wheel diamond grain morphology with a protrusion height is shown in Fig. 2(i).



(a) Original wheel surface status. (b) Magnified view of (a). (c) After 30µm infeed in Z



(d) After 60µm infeed in Z (e) After 90µm infeed in Z (f) After 120µm infeed in Z



(g) After 150µm infeed in Z (h) After 210µm infeed in Z (i) After ELID process.

Fig. 2: SEM images for recording the successive conditioning process of identical coarse diamond grains on the 91µm grinding wheel using a 91µm diamond conditioning wheel by means of replica

3.2. Conditioned wheel surface topography characterised by WLI

2D and 3D images of the wheel surface topography after the conditioning process are shown in Fig. 3. The 2D image indicates that coarse diamond grains were completely conditioned with flattened surfaces without shedding, fracture or dislodging, which also verifies that electroplated bonding material has the very strong holding strength for super abrasives. The 3D image shows that even the bonding material nickel was well ground, there was a grain protrusion height in range of 1.5 to 2μm.

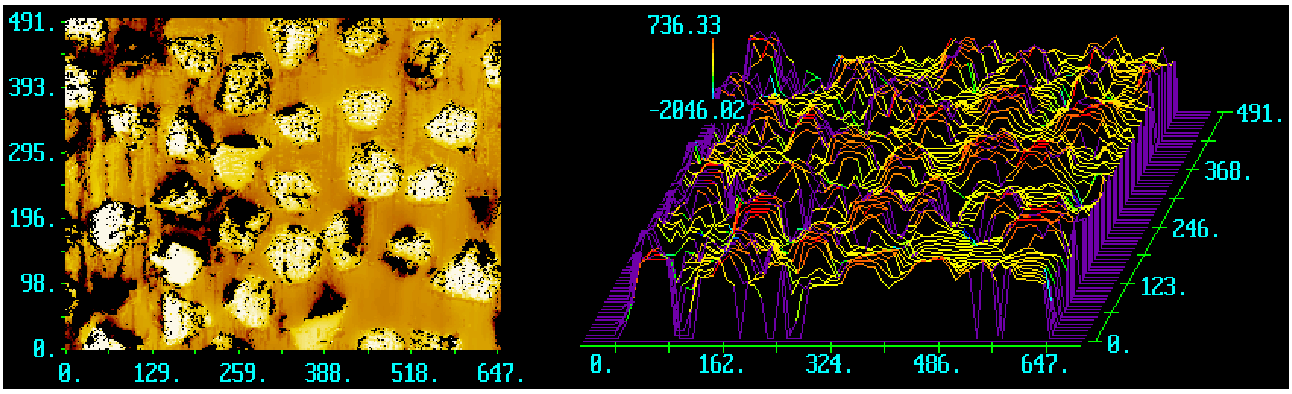


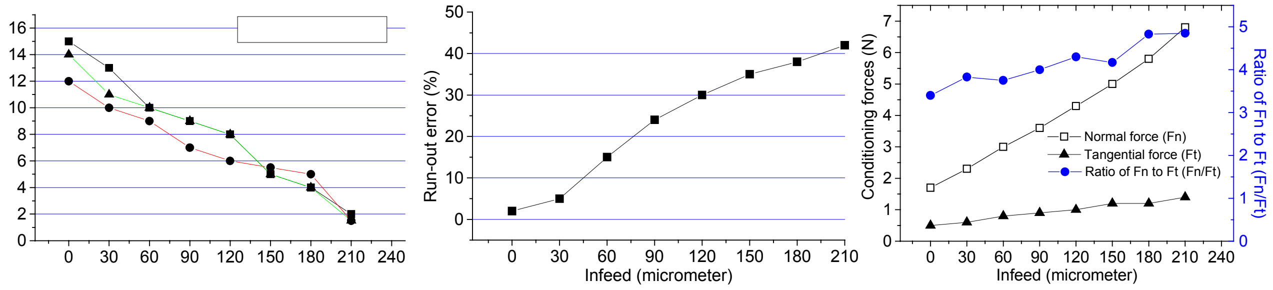
Fig. 3: WLI analyzed results of the conditioned 91μm coarse-grained wheel by the 91μm conditioning wheel with a 2μm average grain protrusion height and a 42% bearing ratio of the grain

3.3. Wheel run-out error, diamond grain bearing ratio and conditioning forces versus infeed in Z direction

From Fig. 4(a) it can be seen that on the wheel surface along different original wheel peripheral envelopes different run-out errors occur. As the conditioning process is carried out, these run-out errors decrease with a constant convergent velocity to identical values of around 1.5μm after a total infeed of 210μm in Z direction. This also means that in order to remove the protruded part of around 15-20μm in depth, the 91μm conditioning wheel itself must recess in depth of around 180-185μm, in a G-ratio of 10% of the conditioned grinding wheel to the conditioning wheel.

Fig. 4(b) shows the improvement of the bearing ratio analysed by WLI software from the original almost 0% to the final value of 42%: in the first stage the bearing ratio increases with a big increment while in the final stage with a small increment, means bigger material removal rate in depth of wheel radial direction during the first conditioning stage than that during the final conditioning stage.

With regard to the normal and tangential force, both of them increase linearly as the infeed increases due to larger and larger contacting area were generated continuously, indicated by Fig. 4(c). However, the force ratio for this 91µm grinding wheel does not increase in a big degree, indicating a steady truncating process still existing between the conditioning and the grinding wheel.



(a) (b)

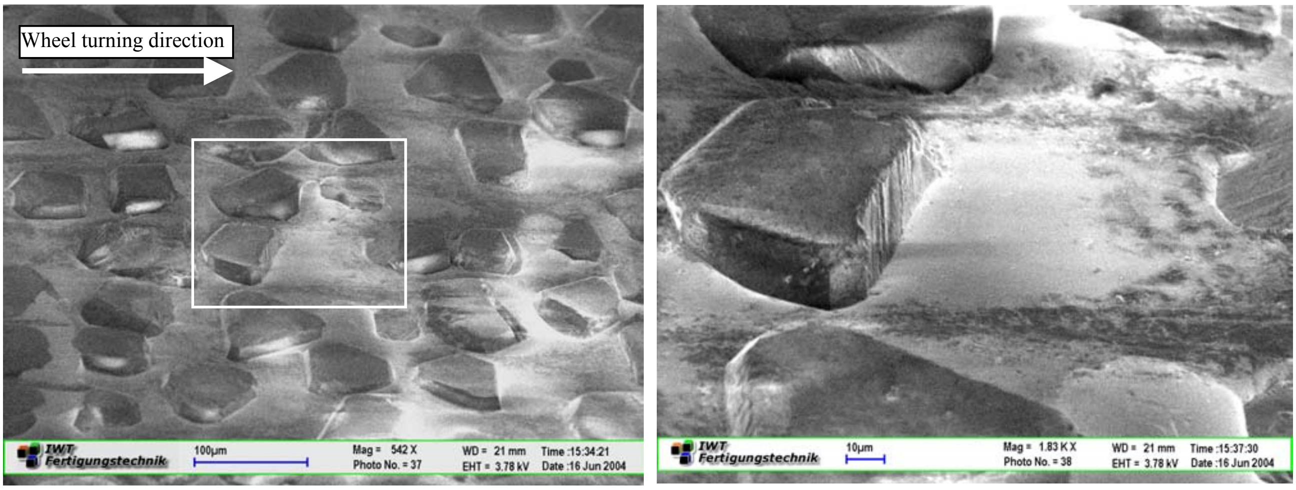
Fig. 4: Run-out error (a) (peripheral lines measured left, center and right on the wheel); bearing ratio (b) of the 91µm grain-sized wheel during conditioning process; grinding forces and force ratio (c).

3.4. Diamond grain morphologies characterised by LC-SEM

Fig. 5 shows coarse diamond grain morphologies after the conditioning and the following ELID process, corresponding to Fig. 2(i). This was done by removing the well-conditioned grinding wheel from the grinding spindle and analysing it in a LC-SEM. From fig. 5(a) it can be seen that all diamond grains were well conditioned featuring flattened top surfaces with a constant grain protrusion height of about 10µm, due to effect of ELID process (a Al_2O_3 stick was used to remove the oxidised layer formed by ELID process). Fig. 5(b) shows a detail of (a) of well conditioned diamond grain embedded in the bonding material. The conditioned diamond grain top morphology indicates a steady conditioning process resulting in the smooth surface without shedding, fragment and fracture. This could be explained by the fact that at an early stage the grain protrusion height was removed by the conditioning wheel, and then the bonding material and diamond grains were truncated simultaneously. Therefore diamond grains were embedded and protected by the bonding material, avoiding cracks and chipping. In addition, the bonding material is still strongly holding coarse diamond grains even after a long conditioning process, which shall be a key issue in guaranteeing the following ductile grinding process since identical diamond grains will be involved in contacting the workpiece surface during the entire grinding process.

3.5. Taper cutting tests on BK7

When the conditioning processes was finished, taper cutting tests were carried out on BK7. The purpose of this test is to investigate the un-uniformity of coarse diamond grains' distribution in wheel's axial direction by taper cutting which can generate footprints on the ground surface. The BK7 specimen was fixed on the work spindle with an inclined angle in Y direction, and then the grinding wheel moved from top to down on the specimen surface with an increasing depth of cut (taper cutting) under a feed rate of 10mm/min.



(a) Well-conditioned 91µm coarse diamond (b) Magnified details of (a).

Fig. 5: LC-SEM images of 91µm coarse diamond grain morphologies after conditioning and ELID

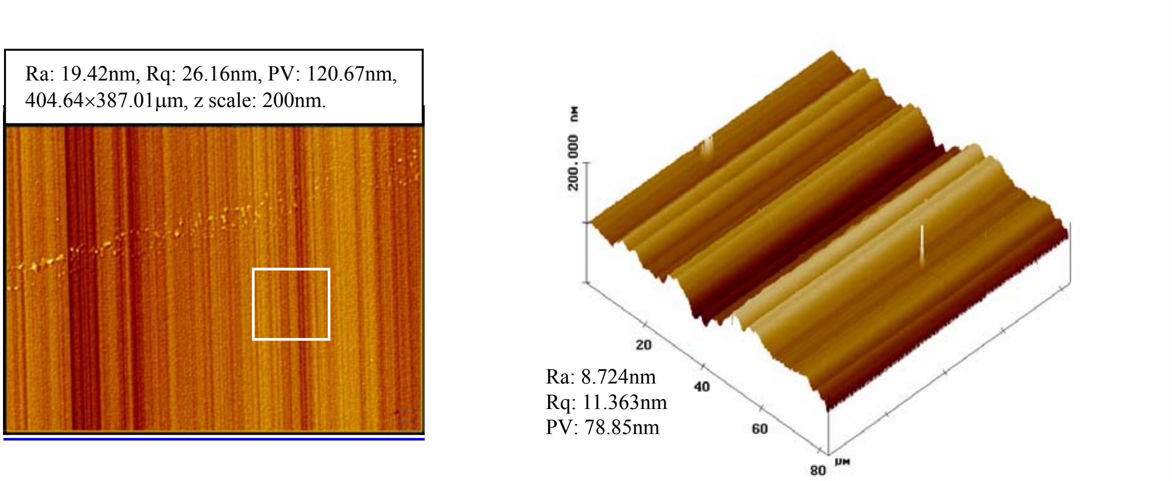


Fig. 6: Ground BK7 surfaces topography by WLI (left) and AFM (right).

From Fig. 6(a) it can be seen that the ground BK7 surface has a PV (peak and valley) value of 120.67nm (by WLI), indicating the un-uniformity (defined as the in-homogeneity of protruded diamond grains' peripheral envelope) under 404.64µm width in wheel axial direction is also 120.67nm for the well conditioned 91µm grinding wheel. While according to the AFM result (shown in Fig. 6(b)), under 80µm axial width the corresponded grains' un-uniformity is 78.85nm. However, the above mentioned un-uniformity does not impact the grinding performance in taper grinding. Both WLI and AFM images prove that the conditioned grinding wheel is able to carry out totally ductile grinding of BK7, which is verified by regular grinding marks reprinted from the wheel's surface profile. The generated surface roughness values in Ra are 19.42nm (by WLI) and 8.724nm (by AFM) correspondingly.

4. Conclusions

The newly developed conditioning technique featuring ELID to dress the conditioning wheel, as well as using coaxial optical distance measurement system to monitor the improvement of the conditioned wheel run-out error, and combining with other optimised conditioning parameters, is able to minimise wheel run-out error to be better than 2μm, constant grain peripheral envelope and flattened diamond grain top surface for 91μm grain sized diamond wheel. The method is proved to be applicable and feasible in conditioning electroplated monolayer nickel coarse grained diamond grinding wheels.

The preliminary taper cutting results indicate that the conditioned grinding wheel could be successfully applied in grinding of optical glasses in ductile material removal mode, implying its expected prospect in precision contour grinding of optical glasses with high surface and sub-surface integrity.

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