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Ultra-precision grinding of optical glasses using mono-layer nickel electroplated coarse-grained diamond wheels. Part 2: Investigation of profile and surface grinding

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ABSTRACT

After finishing the precision conditioning of mono-layer nickel electroplated coarse-grained diamond wheels with 151 μm (D151), 91 μm (D91) and 46 μm (D46) grain size, resp., profile and surface grinding experiments were carried out on a five-axis ultra-precision grinding machine with BK7, SF6 optical glasses and Zerodur glass ceramic. A piezoelectric dynamometer was used to measure the grinding forces, while an atomic force microscopy (AFM), white-light interferometer (WLI)) and scanning electron microscope (SEM) were used to characterize the ground surface quality in terms of micro-topography and subsurface damage. Moreover, the wear mechanics of the coarse-grained diamond wheels were analyzed and the grinding ratio was determined as well, in aiming to evaluate the grinding performance with the conditioned coarse-grained diamond wheels. Finally, the grinding results were compared with that of the fine-grained diamond wheels with regard to the ground specimen surface quality, process forces and wheel wear as a function of stock removal. The experimental results show that the precision conditioned coarse-grained diamond wheels can be applied in ductile mode grinding of optical glasses with high material removal rates, low wheel wear rates and no dressing requirement yielding excellent surface finishes with surface roughness in the nanometer range and subsurface damage in the micrometer range, demonstrating the feasibility and applicability of the newly developed diamond grinding technique for optical glasses.

1. Introduction

Fine grained diamond grinding wheels are often utilized for ultra-precision (UP) grinding of optical glasses in “optical quality” in terms of high form accuracy and low surface roughness. Brinksmeier et al. [1] stated that this material removal process should reach the required figure, roughness, and damage tolerances in one single machining step in order to avoid iterative or additional machining and testing, or, in other words: how can ultra-precision grinding be made more predictable and reliable, i.e. more deterministic?

This requirement turns out to be the biggest challenge for UP-grinding, since it can only be realized with special machine tools with high loop stiffness and special grinding tools which do not wear significantly (or do wear in a predictable way) during operation. Substantial trials have been made to fulfill this requirement, in particular for a combination of electrolytic in-process dressing (ELID) [2–4] and fine-grained metal bonded grinding wheels, with which superb surface finishes (Sa < 2 nm), very little sub-surface damage, relatively high wear resistance (when compared to resin-bonded fine-grained diamond wheels) and relatively high material removal rates could be achieved. However, the disadvantages of fine-grained grinding wheels are high wear rates, needed dressing process to avoid wheel loading while to maintain fine grains sharp and protruded over bonding layer. Therefore, controlling surface quality and figure accuracy remains a problem, especially for machining of large surfaces, due to the continuous wear of the grinding wheel [1]. On the other hand, periodic dressing cycles for re-sharpening and recreating of the wheel profile lead to time consuming and expensive machining processes. Therefore, economical batch production of high-precision complex surfaces through continuous grinding processes has to be developed which ensure high component quality and long-term process stability [5].

To deal with the above-mentioned problem, Brinksmeier et al. [1] propose a possible approach for reducing tool wear in ultra-precision ductile mode grinding by the use of “engineered” grinding wheels (with either stochastic or well-defined grain patterns)

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with large (average grain size >100 μm), "truncated" grains whose tips form a close tolerance envelope surface. Moreover, several researchers have tried this technique in different ways, and valuable results were obtained.

For the simulation and prediction of process parameters and resulting workpiece quality like process forces, surface roughness and sub-surface integrity, Koshy et al. [5], Aurich et al. [6] and Wegener and co-workers [7] have carried out first experimental research work with regular spacing brazed super abrasive wheels as well as corresponding tool modeling and process simulation. With regard to the relationship between grinding performance and grain protrusion height, grain arrangement, grain patterns, grain wear, it can be assumed that the engineered grinding tools (EGT) with a well-defined grain geometry usually have advantages over stochastic coarse grained grinding wheels in terms of predictable material removal processes, lower grinding forces and power, as well as workpiece surface roughness, microstructure, micro-hardness and residual stresses.

Heinzel and Rickens [8] have demonstrated that ductile mode grinding with engineered wheels is possible yielding excellent surfaces comparable, or even superior, to those obtained by ELID grinding, while no appreciable tool wear occurs even after grinding large volumes of BK7 optical glasses with mono-layer nickel electroplated coarse-grained and brazed diamond grinding wheel. They concluded that, from a practical point of view, not only fine-grained but also coarse-grained diamond grinding wheels can be applied to machine brittle material such as optical glasses with surface roughness Sa in the nanometer range.

Rickens et al. [9,10], Brinksmeier et al. [10,11] and Zhao et al. [11] have been dedicating their efforts in utilizing mono-layer nickel electroplated coarse-grained diamond wheels as well as brazed diamond wheels with free or well-defined grain positions to realize ultra-precision grinding of optical glasses. These authors have proposed a conditioning technique for coarse grained electroplated diamond wheels using a diamond cup wheel as a dressing tool. Eventually, a radial run-out error of less than 2 μm was achieved. The applicability of these conditioned grinding wheels was demonstrated by grinding experiments on BK7 [8,11] glass and a PVD-TiNiN coating [9,10] yielding a surface roughness in the nanometer range.

Yasui et al. [12,13] have developed and qualified a new ultra-smooth grinding method for obtaining ultra-smooth surfaces of silicon carbide ceramics and cemented carbide tools with a #140 coarse-grained diamond wheel. Instead of traditional traverse grinding, they used a new grinding method combining cross-feeding the workpiece at high speed normal to the grinding direction with simultaneously feeding it at an extremely slow speed parallel to grinding direction, for eliminating grinding grooves, thereby achieving an smooth surface below 25 nm (Rz). In addition, they also found that the dilution type grinding fluid has a strong influence on the surface roughness in ultra-smooth grinding of silicon nitride ceramics.

Zhao et al. [14–16] have tried to apply copper-resin hybrid bonded as well as mono-layer nickel electroplated coarse-grained diamond wheels in ductile grinding of optical glasses and silicon carbide and investigated the resulting ground surfaces and surface damage. The results show that if the coarse-grained diamond wheels are precision conditioned in terms of a minimized run-out error, a well-defined grain protrusion height, and a constant wheel peripheral envelope, ultra-precision grinding of brittle materials can be realized featuring surface roughness values in the nanometer range and subsurface damage on the micrometer scale with a low wheel wear rate, since only coarse diamond grains are involved in the material removal process.

However, although the above-mentioned investigations have dealt with many issues regarding the coarse-grained grinding technology, there are still many open questions which need further investigation. Do different wheels with different grain sizes, different grinding modes (profile or surface grinding) and grinding parameters result in different grinding results? What exactly is the wheel wear mechanism and the wear rate, or grinding ratio, when compared to fine-grained diamond wheels? Due to the special contact mode of coarse-grained diamond wheels, the force behavior should also be different when compared to that of fine-grained diamond wheels under the identical grinding parameters such as feed rate and depth of cut. What will be the surface and subsurface integrity generated by coarse-grained diamond wheels on different optical glasses? Actually, there are many open questions regarding the application of coarse-grained diamond wheels to the machining of optical glasses.

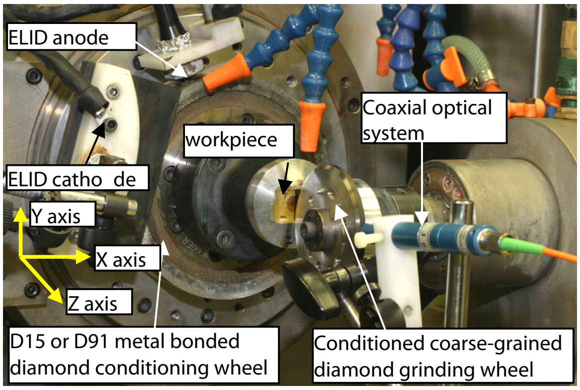

Fig. 1. Set-up for grinding of optical glasses with coarse-grained diamond wheels.

To investigate the above-mentioned questions, nickel electroplated coarse-grained diamond wheels with grain sizes of 46, 91 and 151 μm were applied to grind optical glasses, provided with a minimized run-out error, top flattened diamond grains and a constant wheel peripheral envelope with a precision conditioning technique assisted by the ELID method as reported in Part 1 of this paper. In Part 2, the grinding forces, surface roughness, wheel wear rates, the wear mechanism, as well as surface and subsurface damage were investigated in order to comprehensively evaluate the machining performance of coarse grained diamond wheels for different optical glasses.

2. Experimental set-up

2.1. Grinding operations

When the preceding conditioning process was finished yielding flattened coarse-grain diamond tops, a desired grinding wheel roundness and a constant grain peripheral envelope, the glass specimens were mounted on the conditioning (workpiece) spindle for performing profile grinding (for BK7 and Zerodur) and surface grinding (for BK7, Zerodur and SF6) operations. The experimental set-up is shown in Fig. 1, while the experimental conditions are given in Table 1. Up-cutting and down-cutting were both applied in the profile grinding mode with a depth of cut a_e increasing from 2 to 15 μm (for Zerodur the initial depth of cut was 60 μm), at different feed rates v_{fd} of 2, 4 and 10 mm/min. In the surface grinding experiments, two optical glasses, i.e. BK7, SF6 and Zerodur glass ceramic were machined with identical grinding parameters, i.e. with a depth of cut a_e of 2 μm, a feed rate v_{fd} of 2 mm/min, and a work spindle speed of 200–240 rpm. For both profile and surface grinding (as shown in Fig. 2), the grinding wheel was rotated at a speed of 5000 rpm (corresponding to a cutting speed of 20 m/s). In addition, surface grinding of BK7 with a fine-grained diamond wheel was also conducted with a 7 μm grain size metal bonded wheel