Titel/Title: Engineered Wheels for Grinding of Optical Glass

Autor*innen/Author(s): C. Heinzel , K. Rickens

Empfohlene Zitierung/Recommended citation:

C. Heinzel, K. Rickens,
Engineered wheels for grinding of optical glass, CIRP Annals, Volume 58, Issue 1,2009, Pages 315-318, ISSN 0007-8506, https://doi.org/10.1016/j.cirp.2009.03.096.

Verfügbar unter/Available at:
(wenn vorhanden, bitte den DOI angeben/please provide the DOI if available)

https://doi.org/10.1016/j.cirp.2009.03.096.

Zusätzliche Informationen/Additional information:

(https://www.sciencedirect.com/science/article/pii/S0007850609000894)

Abstract: This paper focuses on the evaluation of topographical parameters characterizing the influence on the behaviour and finally the process results by applying engineered diamond wheels in machining hard and brittle materials. Here, coarse-grained, single-layered diamond grinding wheels with electroplated abrasive layers and

Engineered Wheels for Grinding of Optical Glass

C. Heinzel , K. Rickens
Laboratory for Precision Machining
University of Bremen, Germany
Submitted by H. Trumpold (1), Chemnitz, Germany

Abstract
This paper focuses on the evaluation of topographical parameters characterizing the influence on the behaviour and finally the process results by applying engineered diamond wheels in machining hard and brittle materials. Here, coarse-grained, single-layered diamond grinding wheels with electroplated abrasive layers and active-brazed, defined grain pattern have been dressed by a special conditioning process and used in precision grinding experiments on optical glass. The characterization of the abrasive layer topography was done by two topographical parameters, the specific total grain plateau area $A'_{G,total}$ and the average grain cutting edge width $b_{G,a}$, determined by 3D-profilometry of replicated abrasive layers after each dressing step.

Keywords:
Grinding, Tool, Precision

1 INTRODUCTION

Precision grinding of difficult-to-cut hard and brittle materials such as optical glasses, ceramics, cemented carbides, PVD hard-coatings or single-crystal materials has entered a wide area of applications in the optical, automotive, semiconductor and communication industry. Here, the precision grinding process is associated with high surface quality in the range of a few nanometers roughness Sa, low sub-surface damage and form deviations of the machined parts of only a few hundred nanometers [1]. Due to the lack of reproducible and controlled machining processes traditional production steps with several rough and fine finishing processes as well as multiple polishing and measuring cycles are still necessary.
Usually multilayered, resinoid, vitrified or metal bonded grinding wheels with natural or synthetic abrasives and grain diameters from several micrometers down to the sub-micron scale are used for finishing of brittle materials [2]. The disadvantages of these grinding wheels are the limited surface quality and form accuracy of the machined parts caused by high wear rates and self-sharpening effects of the grain-bonding system as well as wheel loading and therefore changes of the abrasive layer topography and configuration during the grinding process. Also, difficulties during the grinding wheel manufacturing process lead to non-uniform grain distributions and grain agglomerations. In addition, periodic dressing cycles for re-sharpening and recreating of the wheel profile leads to time-consuming and expensive machining processes. Therefore, economical batch production of high-precision complex surfaces through continuous grinding processes have to be developed which ensure high component quality and long term process stability.

The paper presents the development of engineered diamond wheels for deterministic grinding processes. In this context, coarse grained, single layer, metal bonded diamond grinding wheels with defined and semi-defined diamond grain patterns have been applied to a novel conditioning process and used in precision notch grinding of optical glass. Here, the progress in dressing of the engineered diamond wheels is quantified by the calculated collision number i_d [3] and two topographical parameters, which will be introduced and were measured by 3D-profilometry of replicas of the grinding wheel abrasive layers. Finally, the dressing state influence of the engineered diamond wheels on the grinding process (here the grinding normal forces F_n) and resulting surface roughness of ground optical glass specimens (here the arithmetical mean height of the surface Sa) is shown.

2 ENGINEERED TOOL DEVELOPMENT

Deterministic machining processes for hard and brittle materials require a precise generation of the macro and micro topography of the applied tool. Due to the stochastic properties of conventional grinding wheels, in e.g., abrasive layer configuration and surface topography, the grinding process itself is governed by stochastically occurring tool-workpiece interactions and different material removal mechanisms.

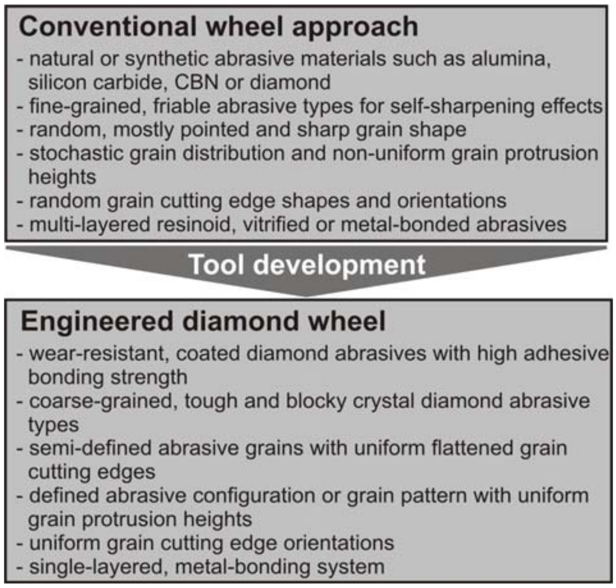

Figure 1: Tool development towards engineered diamond wheels for deterministic precision grinding processes

For the simulation and prediction of process interactions and resulting workpiece quality like process forces, surface roughness and sub-surface integrity, it can be assumed that the usually applied stochastic grinding wheels have to be replaced by ascertainable and definable tools for defined material removal processes. This could be put into practice by tool development (see Figure 1), which will convert the conventional grinding wheel approach to a geometrically and topographically definable abrasive tool. First experimental research work with similar regular spacing brazed super abrasive wheels as well as corresponding tool modelling and process simulation were carried out by Chattopadhyay et al. [4], Aurich et al. [5], Koshy et al. [6] and Wegener et al. [7].

The major advancements of the tool development presented here are the change from weak and wear-afflicted to tough and wear-resistant grain and bonding materials and the use of bigger grain diameters for adequate chip and cooling fluid space. However, the most important element is the dressing with profiling and shaping of single-layered, stochastic distributed or defined placed diamond grains leading to uniform abrasive grain protrusion heights for closely tolerated uncut chip thickness distributions below material dependent critical values for constant and continuous material removal mechanisms. As a result these abrasive layer properties lead to highly defined engineered grinding wheels. Furthermore, this tool development enables the investigation of the topographical influence of the actual abrasive layer surface condition on the material removal process and the resulting workpiece surface quality.

3 GRINDING WHEELS AND PROCESS KINEMATICS

3.1 Grinding wheel properties

The requirements for engineered diamond wheel properties were accomplished by the development of coarse-grained, single-layered diamond grinding wheels and the application of an innovative conditioning process for the adjustment of the wheel run-out error and the abrasive layer topography. In this context, first practical attempts were shown in [8, 9]. The electroplated metal bonding system of the diamond grinding wheels assures the desired high contact stiffness and abrasive support stiffness and avoids grain breakouts during tool life. Furthermore, the use of coarse-grained diamond abrasives increases grinding wheel life due to high grain protrusion heights and high wear resistance resulting in a more cost effective and competitive machining process.

For the research work described in the following, three types of chamfered circumferential grinding wheels (1A, 1B and 2) were designed and applied in dressing processes as well as in grinding of optical glass BK7. The aim was to analyze the influence of the wheel surface topography on the grinding process as well as the resulting surface roughness. Achieving a stable dressing and grinding process, no wheel run-out error as well as ideal adjustment and balancing of the wheel are necessary to avoid process instabilities and vibrations. Hence, grinding wheel hubs made of stainless steel with $d_S = 75$ mm and $b_S = 1$ mm or 3 mm, respectively, were designed and ultra precision turned to achieve excellent concentricity of the wheel peripheral surface. A reference cylinder was included for the measurement and adjustment of the run-out error while wheel mounting after bonding the diamond abrasives (see Figure 2).

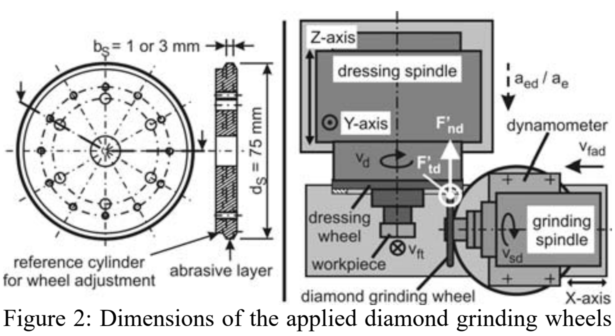

Figure 2: Dimensions of the applied diamond grinding wheels and schematic dressing and grinding setup

Due to the precision turning process of the grinding wheel hub a wheel run-out error $\Delta r < 1$ µm was obtained at the circumferential surface and the reference cylinder surface. After bonding and re-mounting a wheel run-out error $\Delta r < 2$ µm was achieved. Because of small differences in the bond thicknesses of the following electroplating and active-brazing processes (here the circumferential surface with the chamfers were coated), the grinding wheel hub was adapted with symmetric balancing threads providing the possibility to add precision balancing screws avoiding vibrations and non-uniform processes. This precision balancing of the diamond grinding wheel was done directly before the dressing and grinding experiments.

The type 1A and 1B grinding wheels are single-layered, coarse-grained, electroplated grinding wheels with blocky, cube-octahedral diamond grains and stochastic grain distribution, grain diameter $d_G = 151$ µm and different specific areal grain concentrations ($C'_{G,1A} = 30$ mm^{-2} and $C'_{G,1B} = 15$ mm^{-2}, according to wheel manufacturer, see Figure 3). The type 2 grinding wheel is also a single-layered, coarse-grained wheel, but with diamond grains ($d_G = 151$ µm) placed in a defined slightly tilted regular grain pattern (specific areal grain concentration $C'_{G,2} = 5$ mm^{-2}, see figure 3) and active-brazed bonding system. Manufacturing of the defined grain pattern was done by fixing spread diamond grains to glue droplets on the wheel circumferential surface which were deposited automatically by a programmable piezoelectric driven micro droplet supply system [10].

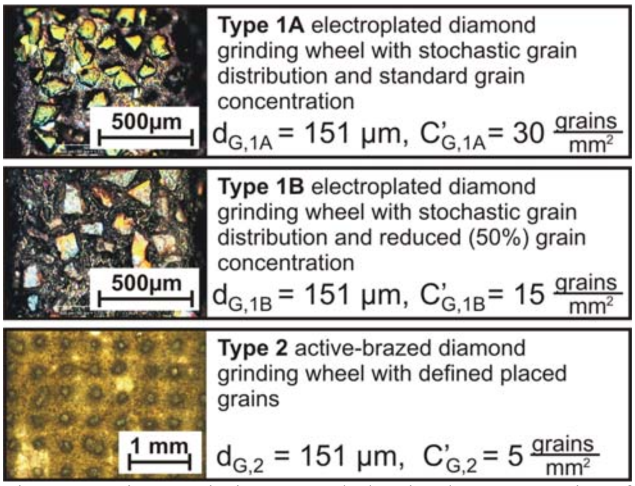

Figure 3: Microscopic images and abrasive layer properties of the applied diamond grinding wheel types

3.2 Dressing process

The novel external-face-plunge-dressing process is set-up on a 5-axes ultra precision machine tool with three hydrostatic linear axes and two air-bearing rotary axes [8, 9]. The dressing of the coarse-grained diamond grinding wheels was done with a fine-grained bronze-bonded D15/C75-diamond cup wheel with a wheel diameter of $d_{Sd} = 150$ mm and a dressing active width of $b_d = 10$ mm. The dressing wheel was mounted to the main spindle while the coarse-grained engineered diamond wheel is attached to an air-bearing grinding spindle on the rotary machine tool axis. The dressing parameters were grinding wheel speed $v_{sd} = 20$ m/s, dressing wheel speed $v_d = 4$ m/s, axial dressing infeed velocity $v_{fad} = 5$ mm/min and dressing depth of cut $a_{ed} = 3$ µm with 10 cycles per dressing interval ($a_{ed,total} = 30$ µm) and the usage of a 2%-emulsion cooling fluid. In order to realize an efficient conditioning process the dressing cup wheel and the grinding wheel rotate in counter direction.

While dressing the diamond tips of the coarse-grained grinding wheel are truncated by the interactions with the grains of the diamond cup wheel. With ongoing dressing cycles and intervals more and more diamond grains of the grinding wheel abrasive layer come into action by the flattening process which leads to an increasing grain plateau area on a uniform envelope of the grinding wheel topography. However, the run-out error of the grinding wheel decreases and a uniform diamond grain protrusion height is achieved. The dressing process as well as the following grinding process was monitored by measuring the process forces with a 3-channel, piezoelectric dynamometer, which was located under the grinding spindle (see Figure 2).

3.3 Grinding process

In order to investigate the influence of the dressing state of the diamond grinding wheels on the material removal process and the achievable workpiece quality notch grinding experiments were carried out on optical glass BK7 after each dressing interval. The grinding experiments were performed on the same 5-axes ultra precision machine tool, with the workpiece specimen fixed to the dressing wheel in the main spindle centre of the machine tool. This set-up enables an error-free procedure by switching from the dressing to the grinding process and vice versa.

Main parameters of the grinding experiments were the depth of cut a_e = 20 µm, the tangential feed speed v_{ft} = 3 mm/min, the grinding wheel speed v_s = 20 m/s and the supply of a 2%-emulsion cooling fluid. The rectangular workpieces of optical glass BK7 with dimensions of 30 mm x 20 mm x 5 mm were polished on both sides and glued into an axial and radial adjustable specimen holding system. Depending on the applied diamond grinding wheel type different notch widths were ground into the workpieces. Therefore, the measured grinding forces F_n and F_t were related to the actual grinding wheel width.

4 ABRASIVE LAYER ANALYSIS AND PARAMETERS

4.1 Abrasive layer characterization

The progress in dressing was monitored by replication of specific abrasive layer segments of the applied diamond grinding wheels after each dressing interval. Trumpold [11] demonstrated a similar approach for surface replications of calibration specimens. The abrasive layer replication was done without demounting the grinding wheel from the grinding spindle to avoid run-out and adjustment errors by re-mounting.

The replication was done twice; first a negative replication of the abrasive layer topography was performed with a two-component mould-making material. This material is based on polyvinyl siloxane (PVS), an elastomer which is mainly used as an impression material for dental replications. The main advantages of the material are the flowability, low reproduction deviations due to negligible differences between original wheel abrasive layer and replicated and hardened negative mould with a shrinking of only 0.16%. Therefore, a high replication accuracy of the grinding wheel layer topography nearly without changes during setting was achieved. Here, mixture and feeding of the compound for the negative replication of the grinding wheel abrasive layer are automatically done within a manual cartridge.

Second, a positive replication of the negative replicated abrasive layer segment was done with a polyurethane polymer (PU), an initially fluidic mould-making and hardening material, mainly used for modeling of small precision parts. This material is characterized by a short setting time and also a very low shrinking rate of only 0.02%.

The two-step replication procedure was performed to ensure the accessibility and the following 3D-profilometry of the grinding wheel abrasive layer segments. Here, a tactile surface profiler (Tencor P15 stylus profilometer) with a ruby stylus (stylus radius of 2 µm, stylus cone angle 45°) was used for the acquisition of the replicated grinding wheel abrasive layer topography. This profilometer is capable of measuring step height, surface roughness and waviness on sample surfaces in a maximum vertical range of 1 mm with a vertical resolution down to the nanometer range. With a line-to-line spacing of 5 µm, the 3D-topography of the abrasive layer with areas of 1 mm^2 for the type 1A and 1B diamond grinding wheels and 4 mm^2 for the type 2 wheel (see Figure 5, right), respectively, were measured with a scanning velocity of 50 µm/s and a measuring frequency of 200 Hz, resulting in a lateral resolution of 0.25 µm in the scanning direction.

4.2 Topographical analysis - definition and results

According to Cinar and Brinksmeier [3] as well as Linke [12], the dressing progress of a superabrasive grinding wheel can be quantified by the collision number i_d. This dressing parameter is a theoretical value, calculated by specific dressing process parameters as well as averaged grinding wheel and dressing wheel layer properties, which represents the number of collisions of a single grain of the grinding wheel abrasive layer with the abrasive grains of the dressing wheel. Figure 4 shows the influence of the collision number i_d on the specific normal grinding force F'_n during grinding of the optical glass BK7 and the resulting arithmetic mean height Sa of the workpiece surface, depending on the applied diamond grinding wheels. The specific force values F'_n show strongly linear trends for all three grinding wheel types, separated by the specific areal grain concentrations $C'_{G,i}$, which can be verified by linear regression analysis with coefficients of determination of $R^2 \geq 0.99$.

Also the surface roughness of the ground workpieces shows a clear relationship to the collision number i_d. Starting from mean heights of approx. Sa = 885 nm (type 1A and 1B) and 1209 nm (type 2) using the undressed grinding wheel, all wheel types are capable of generating surface roughness below Sa = 100 nm after initial dressing cycles ($i_d \geq 0.6 \cdot 10^6$) down to Sa = 20 nm at the end of the dressing process. Here, potential-linear regression analysis lead to coefficients of determination of $R^2 \geq 0.98$.

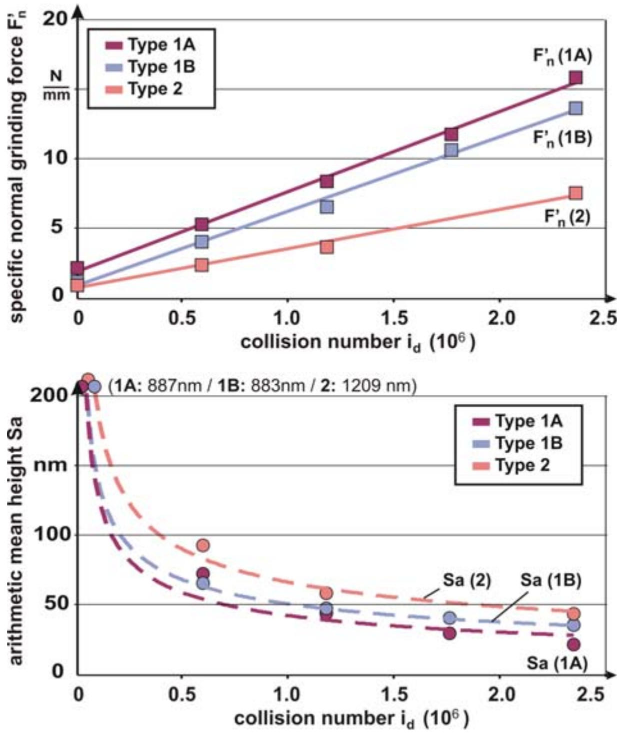

Figure 4: Influence of the calculated collision number i_d on measured values of F'_n (top) and Sa (below) related to the grinding wheel types

However, an important disadvantage of the collision number i_d is that actual changing parameters of the grinding wheel abrasive layer topography are not integral parts of its determination. Therefore, two novel topographical parameters which characterize actual and material removal influencing abrasive layer properties are proposed and were evaluated running the performed dressing and grinding experiments.

First, the total grain plateau area $A_{G,total}$, which represents the grains wear flat area, has been measured to characterize the contact and friction area between all flattened diamond grains of the abrasive layer and the workpiece surface (see Figure 5). $A_{G,total}$ was determined by adding up each single diamond grain plateau area $A_{G,i}$ taken from the 3D-profilometry of the measured replicated abrasive layer segments. Related to the measuring area A_M the specific total grain plateau area $A'_{G,total}$ was used to determine the influence on the specific normal force F'_n and the arithmetic mean height Sa of the workpiece.

Another topographical parameter of dressed engineered grinding wheels was defined with the cutting edge width $b_{G,i}$ of each single abrasive grain, (see Figure 5). Especially the cross-sectional area of the abrasive grains A_{cu}, orthogonal oriented to the cutting direction of the grinding wheel influences the chip formation and material removal mechanisms during the grinding process. Here, the chip width b_{cu} is nearly equivalent to the cutting edge width $b_{G,i}$. To determine the average grain cutting edge width $b_{G,a}$ five to six 2D-profiles were taken of the replicated abrasive layer segments.

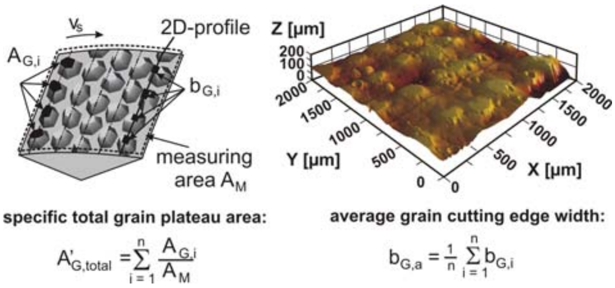

Figure 5: Schematic (left) and measured 3D-topography of a dressed abrasive grinding wheel segment (right, $i_d = 1.18 \cdot 10^6$) and definition of the novel topographical parameters

Figure 6 shows the influence of the novel topographical parameters on the specific normal grinding force F'_n during grinding of the optical glass BK7 and the resulting arithmetic mean height Sa of the ground workpiece surfaces, for the different applied diamond grinding wheels. Both, the specific normal grinding force F'_n as well as the arithmetic mean height Sa show high correlation to the specific total grain plateau area $A'_{G,total}$ and average grain cutting edge width $b_{G,a}$. For F'_n an exponential-linear regression analysis leads to coefficients of determination of $R^2 \geq 0.96$ for $A'_{G,total}$ and $R^2 \geq 0.99$ for $b_{G,a}$, respectively, depending on the applied diamond grinding wheels. A potential-linear regression analysis of Sa leads to coefficients of determination of $R^2 \geq 0.99$ for $A'_{G,total}$ and $R^2 \geq 0.98$ $b_{G,a}$, respectively.

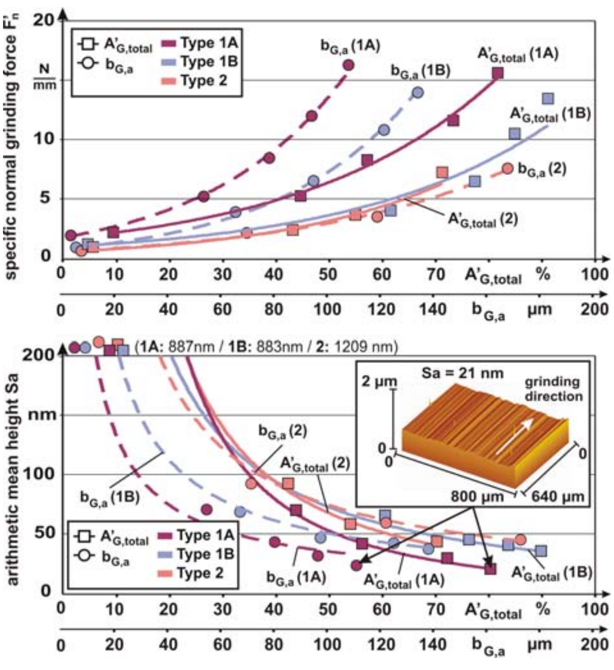

Figure 6: Influence of the measured topographical parameters $A'_{G,total}$ and $b_{G,a}$ on measured values of F'_n (top) and Sa (below) related to the grinding wheel types

Due to the collected values of F'_n and Sa as well as the deduced high coefficients of determination of $R^2 \geq 0.96$, $A'_{G,total}$ and $b_{G,a}$ show the capability to characterize the actual dressing state and grinding capability of the abrasive layer topography of engineered grinding wheels.

5 CONCLUSIONS

This analysis demonstrates the influence of the novel parameters specific total grain plateau area $A'_{G,total}$ and average grain cutting edge width $b_{G,a}$ on the material removal process of optical glass. Both parameters clearly depend on dressing progress and intensity for all used diamond grinding wheel types. However, in contrast to the theoretical collision number i_d, which is strongly a dressing process dependent and dressing tool oriented value, $A'_{G,total}$ and $b_{G,a}$ represent measured areal and dimensional topographical parameters, independent of dressing process kinematics, dressing parameters and tool properties. They directly characterize the topographical condition of the active abrasive layer and therefore the grinding capability of the applied engineered diamond grinding wheels.

From the practical point of view the grinding results show also that not only fine-grained but also coarse-grained diamond grinding wheels can be applied to machine brittle material such as BK7 glass with surface roughness Sa in the nanometer range. For this kind of engineered grinding wheels it is obviously necessary to have topographical parameters characterizing the abrasive layer topography in order to support dressing procedures and grinding process design so that the desired work result, e.g., smooth and damage-free material removal mechanism of brittle materials, can be achieved.

6 REFERENCES

[1] Webster, J., Tricard, J., 2004, Innovations in abrasive products for precision grinding, Annals of the CIRP, 53/2: 597-617.

[2] Marinescu, I.D., Hitchiner, M., Uhlmann, E., Rowe, W.B., Inasaki, I., 2007, Handbook of machining with grinding wheels, CRC Press, Boca Raton, London, New York.

[3] Cinar, M., Brinksmeier, E., 1995, Characterization of dressing processes by determination of the collision number of the abrasive grits, Annals of the CIRP, 44/1:299-304.

[4] Chattopadhyay, A.K., Hintermann, H.E., 1994, On performance of brazed single-layer CBN wheel, Annals of the CIRP, 43/1:313-317.

[5] Aurich, J.C., Herzenstiel, P., Sudermann, H., Magg, T., 2008, High-performance dry grinding using a grinding wheel with a defined grain pattern, Annals of the CIRP, 57/1:357-362.

[6] Koshy, P., Iwasaki, A., Elbestawi, M.A., 2003, Surface generation with engineered diamond grinding wheels: Insights from Simulation, Annals of the CIRP, 52/1:271-274.

[7] Pinto, F.W., Vargas, G.E., Wegener, K., 2008, Simulation for optimizing grain pattern on engineered grinding tools, Annals of the CIRP, 57/1:353–356.

[8] Rickens, K., Grimme, D., Riemer, O., Brinksmeier, E., 2006, Engineered diamond wheels for precision ductile grinding, Prod. Eng. Res. Develop., 13/2:275-280.

[9] Grimme, D., Rickens, K., Zhao, Q., Heinzel, C., 2006, Dressing of coarse-grained diamond wheels for ductile machining of brittle materials, in: Towards synthesis of micro-/nano-systems, JSPE Publication Series No. 5, Springer, London, pp. 305-307.

[10] Burkhard, G., Rehsteiner, F., 2002, High efficiency abrasive tool for honing. Annals of the CIRP, 51/1:271-274.

[11] Trumpold, H., 1957, Untersuchung der Herstellungsverfahren von Oberflächenabdrücken und Oberflächennormalen. PhD Thesis, TH Dresden.

[12] Linke, B., 2008, Dressing process model for vitrified bonded grinding wheels, Annals of the CIRP, 57/1:345-348.