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Effect of dressing on the process mechanics and material separation mechanisms in finishing of cemented carbides with fine diamond grinding wheels

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ABSTRACT

Finishing of WC–Co cemented carbides with resin bonded fine diamond grinding wheels was studied with emphasis on dressing. The variation of dressing conditions generated grinding wheel topographies from smooth, plateau-like to rough, quantified by areal surface texture parameters. Analysis of forces, specific grinding energy and surface roughness establishes how dressing-defined grinding wheel topography governs finishing behaviour. Smooth grinding wheel conditions yielded the lowest workpiece roughness but higher forces and specific grinding energy, whereas rough grinding wheel conditions reduced mechanical load and energy at the expense of surface finish. SEM revealed Co-binder smearing and WC-grain flattening on the finished surfaces.

1. Introduction and motivation

Grinding and finishing of cemented carbides, a widely used cutting tool material [1], is of major importance in manufacture of high performance cutting tools. The manufacturing process chain comprises several grinding operations and preparation processes to generate tool shape and to control surface topography and integrity [2]. Finishing operations may also be directly integrated into the grinding process steps to further enhance the tools' cutting performance [3]. Different fine-grained diamond grinding wheels can be utilised for such finishing.

As is well known for conventional grinding wheels and operations, dressing governs grinding wheel performance and the grinding process behaviour [4], as well as surface integrity [5]. For precision applications and finishing operations with fine-grained diamond grinding wheels, dressing conditions – and thus the resulting grinding wheel topography – are essential for the attainable surface quality as well [3,6]. Nonetheless, there is still a lack of knowledge about how dressing conditions affect process behaviour in the finishing of cemented carbides, even with widely used bonding systems in tool grinding such as resin bonds. It is unclear to what extent such fine-grained diamond wheels behave similarly to conventional grinding wheels, and how dressing conditions influence the process mechanics as well as the material separation mechanisms in finishing of cemented carbides.

Thus, the aim of this work is to gain a fundamental understanding of the finishing of cemented carbides with resin bonded, fine-grained diamond wheels with emphasis on the role of dressing. Based on a detailed characterisation of the dressed grinding wheels, the mechanical loads during finishing, the resulting workpiece surface topography, and the material separation mechanisms are examined to determine the governing process interactions.

2. Materials and experimental procedure

Fundamental investigations covering the entire process chain from dressing to finishing were conducted to understand the mechanisms of surface generation in finishing of cemented carbides with fine diamond grinding wheels as a function of dressing and grinding wheel conditions.

2.1. Diamond grinding wheels and finishing operation

A fine grain cemented carbide (WC–Co) with a cobalt content of 10% and an average WC grain size of 0.6 µm was selected as workpiece material. The samples had a cuboidal shape (60 mm x 20 mm x 8 mm). The top surface (60 mm x 8 mm) was pre-ground and partly finished (40 mm x 8 mm). The dressing and finishing investigations were conducted using two resin bonded fine diamond grinding wheels of shape 1A1, with an initial diameter of $d \approx 100$ mm and a width of $b \approx 10$ mm (Fig. 1a). Both wheels have a diamond grain size of $d_G \approx 8–15$ µm and a concentration of C100. The grinding wheels differ in bond specification with respect to the use of fillers according to the manufacturer's information. To ensure that the observed dressing-topography-process relationships are not limited to a single grinding wheel specification and are therefore transferable, both wheels were included in the investigations.

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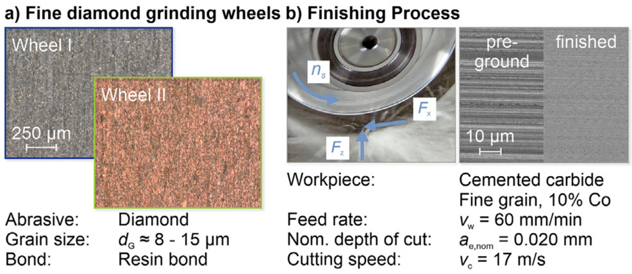

Fig. 1. Specifications of the grinding wheels and the finishing process.

The grinding and finishing processes were conducted on a five-axis grinding centre (Adelbert Haas GmbH) using a surface grinding configuration. The operations were performed in down grinding and grinding oil was used as cooling lubricant. For the initial grinding operation, a diamond wheel with grain size D54 was chosen. The pre-grinding process was carried out with a feed rate of v_w = 100 mm/min and a depth of cut of a_e = 0.5 mm. The pre-ground surfaces, which served as the basis for the finishing operations, have an average initial roughness of Ra_{init} = 0.39 µm and Rz_{init} = 2.9 µm. To investigate the influence of dressing conditions during finishing, the finishing process parameters were kept constant, Fig. 1b Based on the cutting conditions chosen, the nominal equivalent chip thickness is h_{eq} = 0.001 µm.

Both the pre-ground and finished surfaces exhibit an anisotropic topography at different roughness levels characterised by unidirectional grinding marks, as shown by the SEM images in Fig. 1b The forces during finishing were quantified using piezoelectric sensors, which are integrated in the grinding machine tool. The force components in *X* and *Z* directions were determined (Fig. 1b), which approximately correspond to the tangential force F_t and the normal force F_n, respectively. Based on the measurement of the effective depth of cut, the specific grinding energy e_c was then calculated from the forces and the material removal rate and used as a quantitative indicator of material separation efficiency.

To characterise the surface modification of the cemented carbide specimens, surface roughness was measured by tactile profilometer (MarSurf XR 20, Mahr GmbH; λc= 0.8 mm, ln = 4 mm). In addition, detailed surface and subsurface analyses were performed using SEM (GeminiSEM 450, Carl Zeiss Microscopy GmbH).

2.2. Dressing and characterisation of grinding wheel topography

The conditioning of diamond grinding wheels is conventionally carried out using silicon carbide dressing wheels [7,8]. Such tools are also suitable for effective dressing of fine diamond grinding wheels [3]. Accordingly, cylindrical silicon carbide dressing wheels with grain size F240 were used to dress the resin bonded wheels. The dressing wheels had an initial diameter of $d \approx 250$ mm and a nominal width of $b \approx 10$ mm. Traverse dressing with reciprocating axial dressing feed rate v_{fad} was conducted on a dedicated dressing machine (Rudolf Geiger Maschinenbau GmbH) with emulsion as coolant. The ratio of dressing speeds q_d is a key factor affecting the grinding wheel condition and, consequently, grinding behaviour [4]. Thus, different dressing speed ratios were applied to generate different grinding wheel conditions (Fig. 2).

The dressing speed ratio q_d was varied in ten steps (±0.8 to ±7.2; Δq_d = 1.6), considering up and down dressing equally. The circumferential speed of the fine diamond grinding wheels during dressing was selected with v_{sd} = ±2 m/s. The depth of dressing cut was set to a_{ed} = 10 µm ($a_{ed,tot}$ = 150 µm), and the overlapping ratio was $U_d \approx 8$. Accordingly, ten different dressing conditions were investigated, whereupon each parameter set, including the subsequent finishing operation, was conducted three times. Aiming to understand the process mechanics and the material separation mechanisms during finishing of cemented carbides as a function of dressing conditions, it is essential to characterise the grinding wheel topography after dressing as an input to the finishing operation. Hence, the dressed wheel surfaces were analysed at three circumferential positions using an optical surface measurement device (Confovis DuoVario, Confovis GmbH).

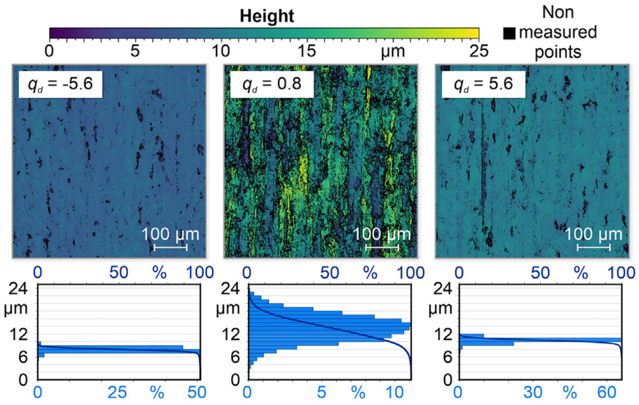

Fig. 2. Topography characterisation of the grinding wheel, wheel I.

Fig. 2 shows three representative conditions of a fine diamond grinding wheel obtained with different dressing parameters. The height maps and material curves reveal distinct grinding wheel-dresser interactions during dressing of the resin bonded wheels. High dressing speed ratios in both up and down dressing resulted in a comparatively smooth wheel topography. In contrast, dressing at q_d = 0.8 produced a rough and inhomogeneous wheel topography, characterised by grooves. The height data indicate that the grinding wheel topography is dominated by the overall wheel surface structure rather than by single grains.

3. Process interactions between dressing and finishing

3.1. Surface topography of dressed grinding wheels

Based on the height data of the dressed grinding wheel surfaces (Fig. 2), areal surface parameters were quantified to describe the resulting wheel topographies. The overall roughness was characterised by *Sq* (root mean square height), while *Spk* (reduced peak height) and *Svk* (reduced pit depth) quantify the peak and pit components, respectively. The results are summarised in Fig. 3.

The grinding wheel roughness values exhibit a comparatively smooth surface for up dressing processes and down dressing at high dressing speed ratios. The highest grinding wheel roughness occurs for down dressing at q_d = 0.8 and q_d = 2.4. Hence, trends known from

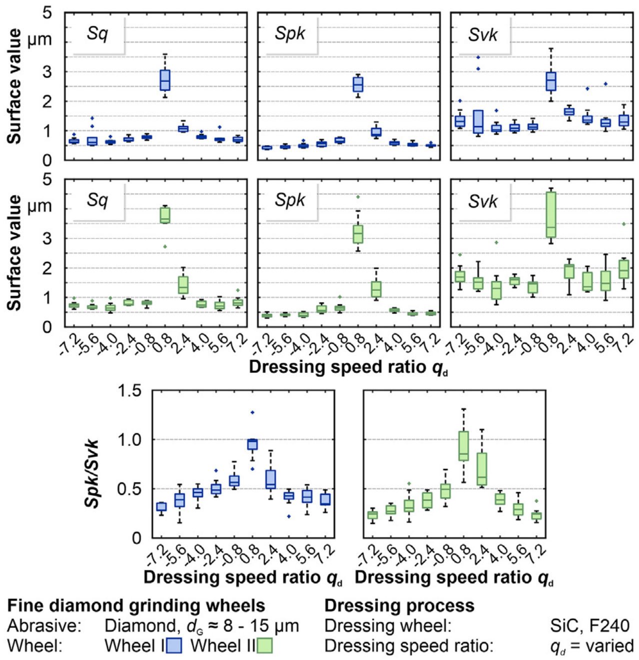

Fig. 3. Quantification of the dressed grinding wheels' surfaces.

rotary dressing of conventional grinding wheels [9] can be transferred to dressing of resin bonded fine diamond grinding wheels with conventional vitrified dressing wheels. The resulting grinding wheel topography is governed by the contact conditions and grain trajectories during dressing [10,11], which determine the aggressiveness of the dresser-wheel interaction [7,12]. The evolution of *Spk* with dressing speed ratio follows the trend of *Sq*. The reduced pit depth *Svk* shows increased scatter. Nonetheless, the largest pit depths occur at q_d = 0.8. The ratio *Spk*/*Svk* provides a further indicator of whether the dressed surface is dominated by protruding peaks or by deep pits relative to the surface core. It increases nearly linearly for up dressing (q_d = −7.2 to −0.8), reaching its maximum for the roughest wheel condition. Moreover, higher q_d values in both up and down dressing result in a smoother, more plateau-like wheel topography.

3.2. Process behaviour depending on the dressing conditions

The analysis of the grinding wheel topography reveals insights into the resulting wheel conditions. To assess how these conditions affect finishing of cemented carbides, Fig. 4 summarises the process responses – forces, specific energy and surface roughness of the finished specimens.

The finishing operation is a sensitive process with comparatively low material removal. Differences between the nominal and effective depth of cut, which arise from the addition of different factors such as stiffness or run-out, affect the level of the forces. To account for this and to reveal the influence of the dressing conditions, the forces are evaluated as specific forces normalised by the actual effective depth of cut. The latter was determined from the change in specimen height before and after finishing measured with a tactile sensor for workpiece analysis integrated in the grinding machine. The mean levels of the process forces were F_t = 7.6 N and F_n = 121 N for wheel I and F_t = 8.8 N and F_n = 88.6 N for wheel II. The normal forces are much higher than the tangential forces, which is also reflected by the grinding force ratio μ. The mechanical loading is lowest for the roughest wheel condition (q_d = 0.8). The trend corresponds with the specific grinding energy, indicating more efficient material separation for rougher grinding wheel topographies. The grinding force ratio in finishing shows the same correlation to the dressing speed ratio as the wheel roughness, suggesting that a more plateau-like wheel topography leads to comparatively higher normal forces and less efficient material separation. In contrast, the surface roughness of the finished cemented carbide (Fig. 4b) is lowest for the smoother wheel conditions. This indicates that the attainable surface finish is primarily governed by the grinding wheel topography, with the workpiece roughness following the trend of the grinding wheel roughness. These observed interactions for resin bonded wheels are therefore similar to conventional grinding, but contrary to finishing of cemented carbides with elastically bonded diamond grinding wheels [3]. The revealed dressing-topography-process relationships can serve as basis for process design in fine finishing and prove the importance of the grinding wheel topography.

3.3. Material separation mechanisms in finishing of cemented carbides with fine diamond grinding wheels

Whereas the above analyses quantify the macroscopic process behaviour of the resin bonded fine diamond grinding wheels, they do not specifically explain the workpiece surface generation in finishing of cemented carbides. To examine the underlying material separation mechanisms, the finished surfaces were analysed by SEM. The pre-ground surfaces exhibit pronounced scratches, fragmentation and smearing, as is typical for grinding cemented carbides [13,14]. In contrast, the fine finished surfaces appear more homogenous, showing only slight grooves and scratches in the feed and cutting speed directions, Fig. 5.

However, detailed surface analysis reveals that even after finishing with the resin bonded fine diamond grinding wheels, fine scratches are present on the workpiece surface, which exhibit slight bulging and micro burrs along their sides. This may be due to ductile side flow of the Co-binder at the surface [15,16]. Thus, mechanisms known from grinding of cemented carbides can be partly transferred

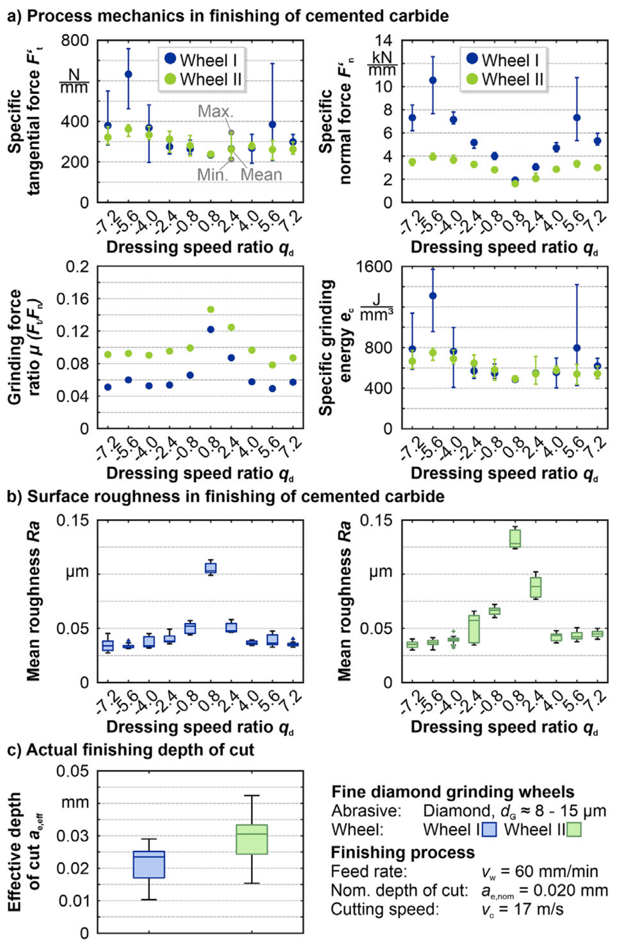

Fig. 4. Process behaviour depending on the dressing conditions.

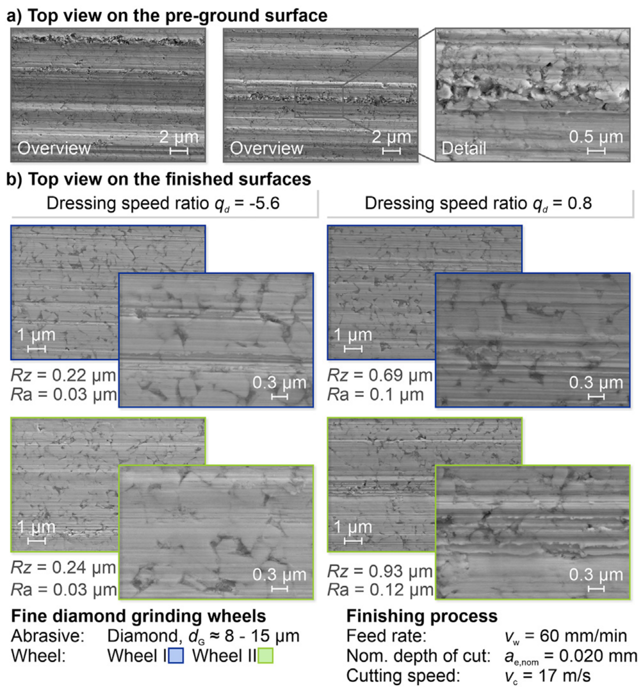

Fig. 5. SEM images of the pre-ground and finished surfaces, EHT = 10 kV.

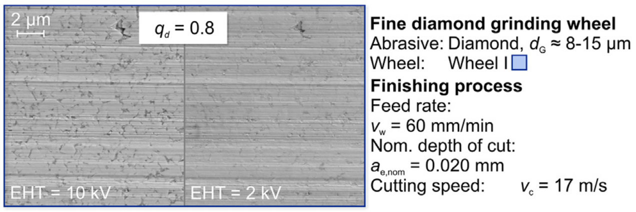

Fig. 6. Detailed SEM analysis of a finished surface.

to finishing with resin bonded fine diamond grinding wheels, although it addresses a different scale of surface finish. Moreover, even the very smooth surfaces (see Fig. 5, q_d = −5.6) show fine grooves, indicating scratching of tungsten carbide (WC) grains. Nonetheless, despite differences in surface roughness, no distinct break outs or severe grain pull outs were observed for the varying dressing conditions.

In order to deepen the understanding of surface generation in finishing of cemented carbides, additional SEM analyses were performed at different accelerating voltages, thereby probing different near-surface interaction depths [17]. Fig. 6 shows SEM images of the same surface area acquired with different settings. At higher accelerating voltage, the WC grains are clearly resolved (Fig. 6 left). At lower accelerating voltage, a thin layer on the workpiece surface becomes apparent (Fig. 6 right). It can be assumed that this layer is attributed to smeared cobalt from the binder phase [15].

Complementary cross sectional observations further clarify the material separation mechanisms. Fig. 7 shows fracture surfaces of finished cemented carbide specimens for different dressing conditions. The finished surfaces exhibit roughness levels consistent with finishing requirements for cutting tools, whereas the grinding wheel topography differs in roughness and in the *Spk/Svk* ratio.

Cross sectional analysis was performed by notching followed by controlled fracturing in order to overcome the limitations of conventional sectioning and polishing, e.g., rounding or fracturing of WC grains and to preserve the microstructural features in the direct vicinity of the finished surface. In addition, selective etching to remove Co-binder from the finished surface was applied to enable visualising the true topography of WC grains. The subsequent SEM imaging was realised in a highly tilted configuration (Fig. 7). The etched finished surfaces show flattened WC grains, while the fine grinding scratches remain visible. This indicates that the WC grains are cut and flattened due to the interaction with the fine diamond grinding wheel. The observed cross section is similar to that reported for polished cemented carbides [18]. The flattening and levelling of WC grains contribute to the low surface roughness achieved in finishing, whereas the overall roughness level is determined by the grinding wheel topography set by the dressing process.

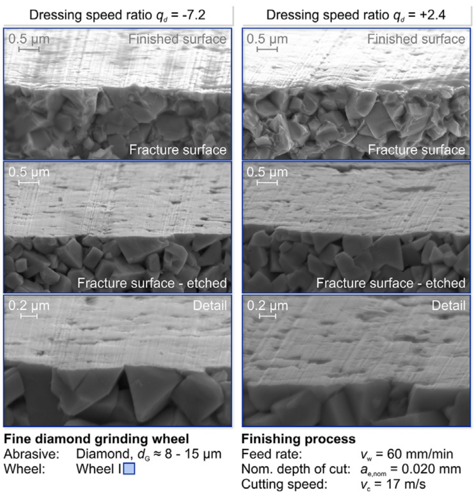

Fig. 7. Side view on fracture surfaces of finished cemented carbide surfaces.

4. Conclusion and outlook

The investigations were conducted with the objective of obtaining a fundamental understanding of the mechanisms in finishing of cemented carbides with resin bonded fine diamond grinding wheels. Particular emphasis was placed on the influence of dressing conditions.

Dressing tests using silicon carbide dressing wheels demonstrated how the topography of the diamond wheels can be adjusted. Depending on the dressing speed ratio in up and down dressing, the topography varied from a smooth plateau-like surface to a rough and fissured grinding wheel topography. Workpiece surface analysis revealed that the surface roughness of the finished cemented carbide specimens correlates directly with the roughness of the dressed grinding wheels. This indicates that the underlying abrasive interactions are similar to those of conventional grinding wheels, albeit at a smaller scale.

With respect to process mechanics, the dressing conditions had a substantial influence on grinding forces and specific grinding energy during finishing. A smooth grinding wheel topography led to higher forces but lower grinding force ratios. Regarding the material separation mechanisms, it can be concluded that, in addition to a thin binder-related surface layer, flattened WC grains contribute to the obtained surface finish. Nonetheless, the surface roughness level is mainly governed by the grinding wheel roughness set by the dressing process.

Building on the present findings, analysis of abrasive swarf formed during dressing would provide additional insight into the mechanisms responsible for the observed grinding wheel topography variations. With respect to surface integrity, it is also of interest to further analyse the impact of finishing on the WC grains under varying dressing conditions, as high-resolution analysis reveals a change of dislocations directly at the surface of fine finished cemented carbides [19]. Supplementary analysis of surface residual stresses would provide further insight into surface integrity depending on the grinding wheel conditions. Moreover, from an application perspective, it would be of interest to evaluate how cutting tools finished under different grinding wheel conditions, set by dressing, perform in machining, for example in terms of wear behaviour and tool life.

Declaration of competing interest

The author declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Monika Kipp: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Philipp Hoier:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Peter Krajnik (1):** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Dirk Biermann (1):** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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