Florestan Schindler[1]
Laboratory for Machine Tools
and Production Engineering (WZL)
of RWTH Aachen University,
Steinbachstr. 19,
Aachen D52074, Germany
e-mail: f.schindler@wzl.rwth-aachen.de

Richard Brocker
Laboratory for Machine Tools
and Production Engineering (WZL)
of RWTH Aachen University,
Steinbachstr. 19,
Aachen D52074, Germany
e-mail: r.brocker@wzl.rwth-aachen.de

Fritz Klocke
Mem. ASME
Laboratory for Machine Tools
and Production Engineering (WZL)
of RWTH Aachen University,
Steinbachstr. 19,
Aachen D52074, Germany
e-mail: f.klocke@wzl.rwth-aachen.de

Patrick Mattfeld
Laboratory for Machine Tools
and Production Engineering (WZL)
of RWTH Aachen University,
Steinbachstr. 19,
Aachen D52074, Germany
e-mail: p.mattfeld@wzl.rwth-aachen.de

A Discussion on Removal Mechanisms in Grinding Polycrystalline Diamond

Polycrystalline diamond (PCD) grinding takes an important role in the field of tool manufacture. Regardless, there is still lack of process knowledge about the occurring material removal mechanisms in PCD grinding. In order to get a better understanding of the process characteristics, the surface integrity zone of PCD inserts has been analyzed in detail after grinding for the first time. The drawn conclusion questions solely ductile or brittle behavior as removal mechanisms. Both thermal and mechanical process loads during the grinding process lead to thermophysical and chemical effects on a micro- and mesoscopic-scale and might thus have a significant impact on the material removal mechanism.
[DOI: 10.1115/1.4029804]

Keywords: grinding, polycrystalline diamond, removal mechanisms

Introduction

Steady material innovations for automotive and aerospace components in particular have driven the innovation of tooling technology. A tendency toward diamond cutting tools could be shown for tool materials. Many cutting tools are equipped with PCD inserts due to its outstanding performance [1,2]. However, the challenge comes with the machining of PCD. After sintering, PCD round blanks are cut into tips either with laser ablation or electro discharge machining [3]. Subsequently, the tips are brazed onto carbide inserts. The most common finishing technology for these tools is grinding, which provides a high surface quality and thus a long tool lifetime especially at the cutting edge. However, the impacting grains ought to be harder than the material that needs to be ground. Diamond is the hardest natural material known on earth, which is just outperformed by synthetic fullerenes. The knoop hardness of PCD is given with 50 Gpa and thereby reaches almost the range of diamond with 57–104 Gpa. Hence, only diamond grinding wheels are applied in PCD grinding [4]. Low material removal rates and high tool wear are the consequences that influence the cost factor in PCD tool manufacturing negatively, especially from the sustainable perspective [5]. Especially, in grinding diamond, the material removal mechanisms are not completely understood. Thus, reliable process models for a better understanding of the PCD grinding process are missing. This still limits the improvement of the process and economical machining. Process design has mostly been done empirically for the last 500 years [4,6,7].

State of the Art in PCD Grinding

In 1920, Vervoort stated the importance of diamond as the "hardest, most transparent and most reflective material ever known" in his book about the "art of diamond grinding." First try outs in grinding diamond with diamond grains lead back to the year 1476 AD when van Bercken cemented the powder of diamonds, which he rubbed against each other, to a metallic wheel and used it for grinding diamonds. He supplied olive oil as lubrication and set up a grinding process at remarkably high number of revolutions of the grinding wheel with more than $n_{gw} = 1800\,\mathrm{min}^{-1}$ [8]. Even at that time diamond grinders made use of the fact that diamond is anisotropic due to its crystal structure. Hence, the machining steps were divided into cleaving, sawing, rubbing, grinding, and polishing. But since then, the importance of diamond has shifted not only from its occurrence as jewelry to its application as tool material but also in its production process, where nowadays diamonds are not just mined but also synthesized at high pressures and high temperatures [9].

Even today, grinding diamond materials in case of PCD means a challenge for all parts, the grinding wheel, the machine and the process control. PCD shows an isotropic behavior as a result of the sintering process. Therefore, one cannot make use of the fact that crystal diamond cleaves easily along the octahedral planes [10]. These facts lead to low material removal rates and extremely high values of the grinding wheel wear. Industrial applications address values for the grinding ratio G from 0.01 to 0.05 [6,11]. Some work has also been done for the combination of laser

[1]Corresponding author.
Contributed by the Manufacturing Engineering Division of ASME for publication in the Journal of Manufacturing Science and Engineering. Manuscript received August 29, 2014; final manuscript received February 9, 2015; published online September 9, 2015. Assoc. Editor: Guillaume Fromentin.

ablation with grinding [12]. Other researchers investigate the hybrid process of abrasive electrical discharge grinding (AEDG), but this technology is still not applied in industry [13,14]. However, most studies focus on the cutting edge formation and neglect the material removal mechanisms [15]. A better understanding of the latter might help advancing the manufacturing process.

Removal Mechanisms

In grinding hard and brittle materials, the behavior is significantly different from machining ductile materials. Existing models were developed for ductile or brittle regime grinding but mostly in grinding much softer single-phase materials [16]. In PCD grinding, little work has been done in using metallic bonded diamond grinding wheels [6]. According to Kenter, the removal mechanisms depend on the process kinematics and on the tribological system. He found attrition wear to be the dominant factor for material removal. However, the ground PCD surface and swarf were analyzed in his work:

- Neither grooves on the ground PCD surface nor could material adhesion be found. Crack formation was observed in both, diamond grains of the wheel and in the PCD substrate, which led to micro breakage and hence influences the directionality of the surface roughness.
- Within the swarf only fragments were found, without indication for plastic deformation.
- Ductile behavior could not be observed.

Kenter came to the conclusion that the process conditions in PCD grinding are similar to a polishing process due to the observed removal mechanisms. However, following the grinding process the subsurface of PCD has never been analyzed.

In polishing PCD, some work has been done in order to improve material removal rates [17]. Finally Pastewka et al. might have discovered why it is possible to grind diamond with diamond [18]. A simulation model for polishing diamond with diamond grains was elaborated. It showed a good accordance of the estimated material removal values with removal rates after polishing experiments. According to the model, the interacting diamonds enforce attrition and internal compressive and shear stresses at the interacting surface zone. That burden leads to mechanical and thermal loads at values that might influence the carbon modification. Hence, a hypothesis was crafted that these circumstances enforce local transitions on atomic scale from the carbon modification diamond to graphite. Furthermore, the dominating removal mechanisms were:

- Diamond transitions to the carbon modification of graphite, diamond grains scratch continuously graphite particles off the substrate.
- The process loads temperature and pressure force carbon to react with oxygen to carbon dioxide.

Subsequently, an "amorphous diamond like carbon (DLC) phase" was supposed to exist, which must occur during the polishing process. However, up to now those DLC layers could not be observed in situ, because releasing the process loads converts the layer into graphite or diamond. All discussed material removal mechanisms in PCD grinding are summarized in Fig. 1.

Experimental Setup

For the investigations on the material behavior of PCD in grinding, a conventional tool grinding machine S22P Turbo has been modified. In order to ensure a firm and vibration resistant hold, the clamping unit was designed directly onto the SK50 mandrel of the machine. In face grinding of the PCD inserts, a vitrified cup wheel D15 was used with oil supplied as lubricant. The rotation of the grinding wheel was directed toward the cutting edge. Hence, the diamond grains of the wheel impact the substrate at the edge. The PCD insert is characterized by a 500 μm thick diamond layer having a mean diamond grain size of $d = 10\,\mu$m. The PCD layer is seated on a cemented carbide substrate having a cobalt percentage of 5.8% by volume. The total insert thickness in finish grinding was $s = 4$ mm. The grinding parameters where derived from industry values and identified during former investigations and are listed below, the tool path is illustrated in Fig. 2, top right [4,6,12,19].

- Cutting speed: $v_c = 15$ m/s.
- Depth of cut: $a_e = 6\,\mu$m.
- Feed rate: $v_{wp} = 200$ mm/min.

Before grinding, the wheel was dressed by a vitrified bonded SiC-dressing wheel with mesh 80 mean grain size. Continuous sharpening was not applied during the grinding process. In grinding, a total stock of $a_{e,ges} = 100\,\mu$m was removed.

Analytical SEM Investigation

Following a platinum coating process, surface characterization was investigated with a scanning electron microscope (SEM). The characterization (Fig. 2) revealed only little directionality of the ground surface. This could be proven by roughness measurements orthogonal, parallel, and diagonal to the grinding direction:

- Mean parallel roughness: Ra = 0.041 μm, range Ra = 0.038–0.049 μm.
- Mean diagonal roughness: Ra = 0.046 μm, range Ra = 0.039–0.060 μm.
- Mean orthogonal roughness: Ra = 0.040 μm, range Ra = 0.028–0.043 μm.

For surface characterization a tactile measuring instrument Hommel T8000 with a cone pin ($r_t = 2\,\mu$m, $\alpha_t = 60$ deg) and a measuring length of $L_t = 300\,\mu$m were used at a repetition rate of three. However, the surface analysis identified preferential lateral crack propagation referred to the grinding direction for the use of a worn out grinding wheel topography. An example of such a ground PCD surface is given in Fig.2, bottom right (II and III). Considering alternating loads during the grinding process, mainly imposed by the impacting grains, lateral cracks are a consistent material reaction due to its overload. Grooves due to plastic deformation could only be found at the transition zone from PCD to

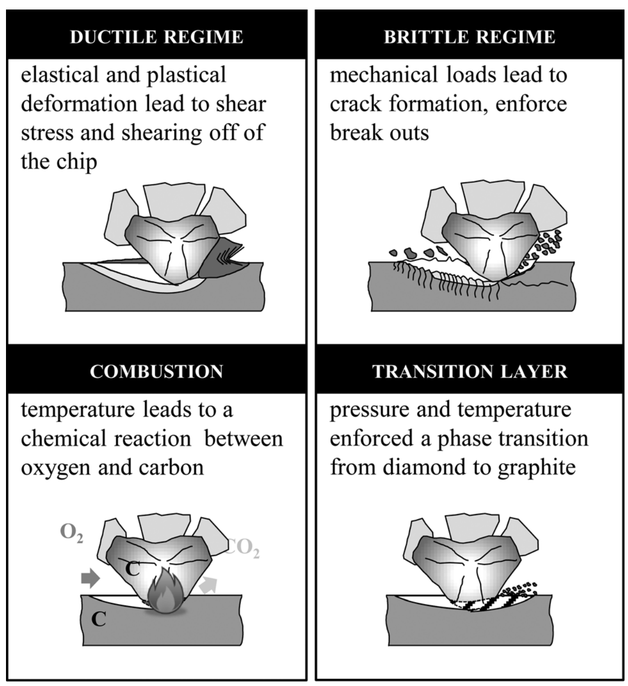

Fig. 1 Material removal mechanisms in PCD grinding

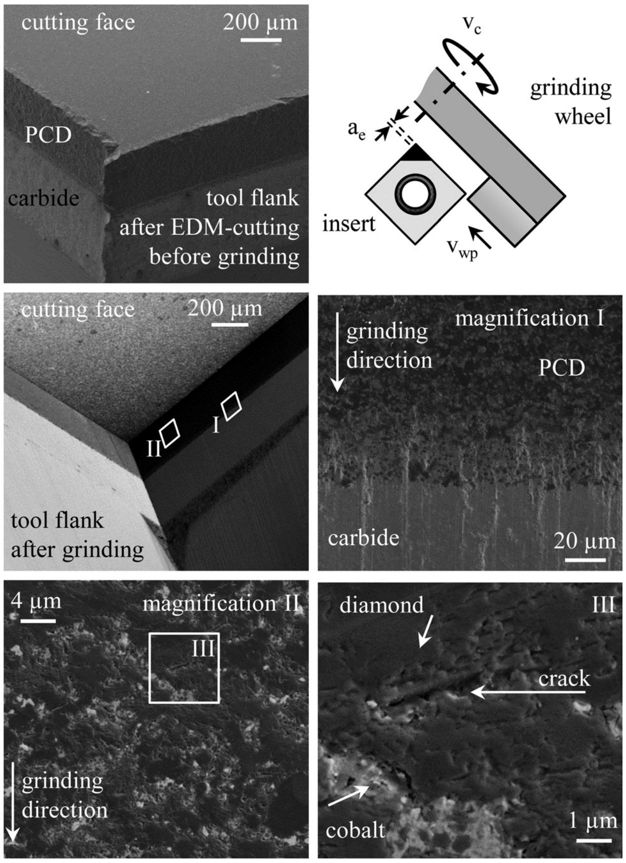

Fig. 2 SEM analyses of PCD flank before and after grinding

carbide (I). In contrary, the ground carbide surface showed visible groves, which indicates a ductile removal behavior.

Analytical Transmission Electron Microscope (TEM) Investigation

In order to get an insight into the surface integrity zone, the method of focused ion beam (FIB) preparation was applied. By using a gallium ion beam, single layers of the surface could be evaporated at atomic scale and cross sections in form of lamellae were cut out (Fig. 3). Before and after the grinding experiments, a lamella with a thickness of $l = 300\,\text{nm}$ and a depth of $t = 6\,\mu\text{m}$ was taken from the tool flank of one PCD sample. Prior to the

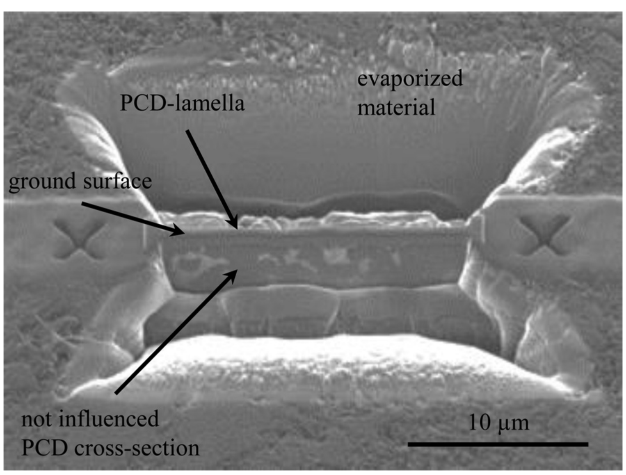

Fig. 3 PCD lamella after FIB-preparation

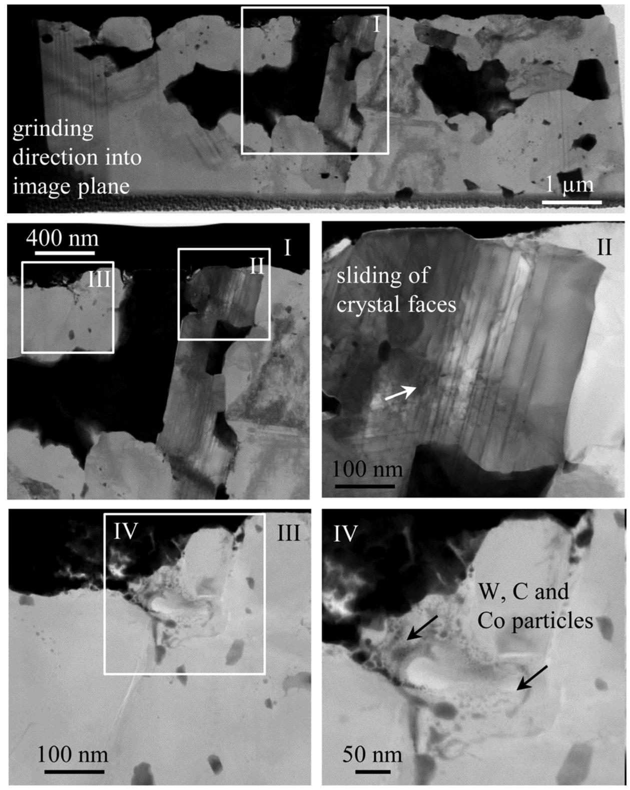

Fig. 4 STEM pictures of the PCD subsurface for lamella O, after grinding

FIB-preparation, the PCD surface was coated with a tungsten layer in order to protect the PCD subsurface from premature vaporization through the impacting beam. Lamella P was separated parallel to the grinding direction, lamella O was separated orthogonally in order to analyze the influence of the cutting speed direction on the subsurface. Afterward, the lamellae were analyzed within the scanning TEM (STEM) (Figs. 4–6).

An overview of the PCD subsurface of lamella O is shown at the top of Fig. 4. Within the PCD zone at the rim of the ground area several observations could be made:

- Regarding the orthogonal grinding direction, the surface tends to be rougher than into grinding direction.
- The grinding normal force might have provoked an internal sliding of diamond faces orthogonally from the surface into the subsurface (II).
- The subsurface can be characterized by many particles that are pressed between diamond grains from the PCD substrate into the cobalt catalyzer (III and IV).

For a comparison of the material behavior depending on the grinding direction and sideways to it, some STEM pictures of lamella P are illustrated in Figs. 5 and 6.

For lamella P, the following conclusions could be drawn:

- The surface of ground diamonds within the PCD subsurface is extremely flat. Within the diamond no internal cracks could be observed. No interim layer of a DLC zone could be found within the diamond on the observed scales (I).
- At certain areas in vicinity of two diamonds, internal stresses of the diamond could be identified which may be caused by the sintering process or by the mechanical process loads in grinding. However, they show a slight directionality toward the grinding direction (II).
- Furthermore, some swarf consisting of tungsten carbide from the insert face was found (III).
- At highest magnifications, small cracks within the diamonds could be found as well as some indication for internal stresses

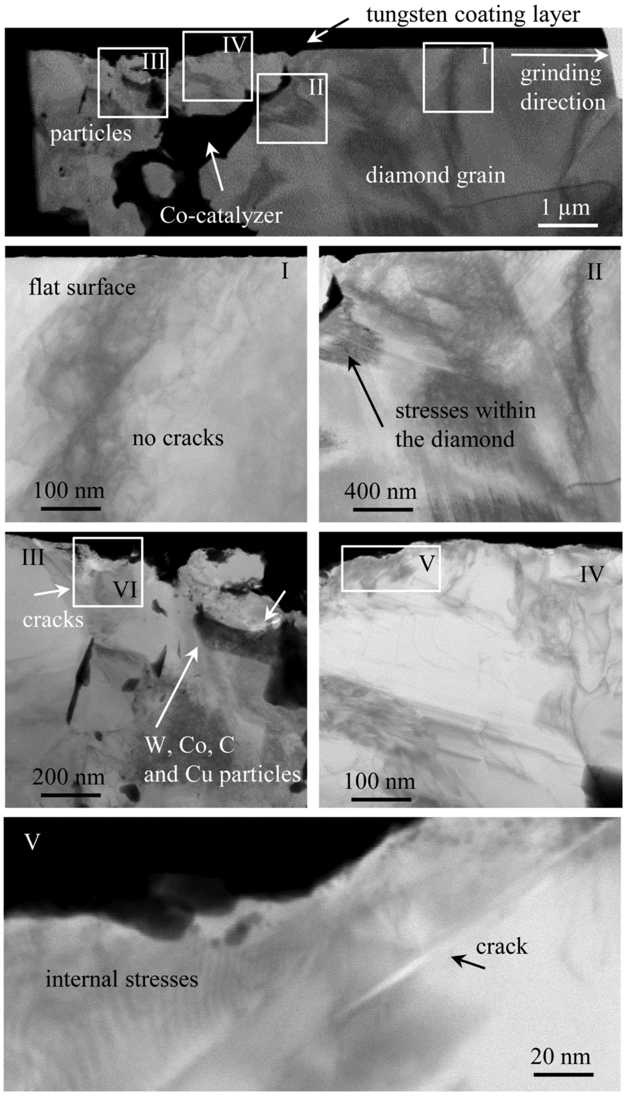

Fig. 5 STEM picture of the PCD subsurface for lamella P, after grinding

which might originate from plastic deformation on a nanoscopic scale (V).

- The gaps between diamonds at the surface area got indented with diamond particles. These clogging microparticles could be from the impingement of worn diamonds from the diamond wheel or the micron sized inclusions originate from removed PCD material.
- Magnification VII in Fig. 6 shows a HRTEM picture (high resolution TEM (HRTEM)) of the carbon and swarf particles above a PCD diamond close to the surface. HRTEM enables analyses of crystallographic structures of single phases on

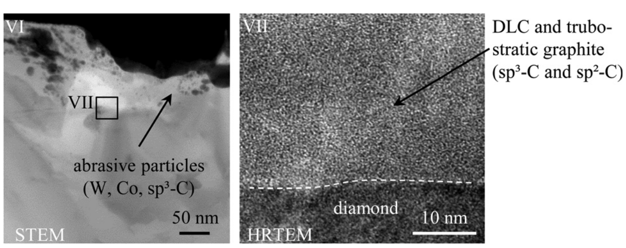

Fig. 6 HRTEM magnification of the transition zone at the PCD subsurface

atomic scale. This indicates certainly a phase transition from diamond to other carbon modifications. Other researchers have found DLC and turbostratic graphite to build similar wave like carbon structures [20–25]. Turbostratic graphite is a disordered mixture of diamond (sp^3) and graphite (sp) clusters.

Conclusions

The mechanisms which were identified by Kenter could be confirmed to some extent [6]. Traces for plastic deformation within the PCD subsurface only occurred on a nanoscopic scale. Ductile regime grinding could not be proven to occur on the microscopic scale of the mean diamond grit size of the PCD material during the process. However, diamond grains within the PCD substrate were ground and an extremely fine surface roughness was created. Evidence for cracks within the diamonds could hardly be found. These effects lead to the question how comparatively big diamond grains at the surface layer could have been shaped in the described manner. A possible drawn conclusion supports Pastewka's hypothesis of physical and chemical effects that precede transitions of the carbon modification on atomic scale [18]. Between diamond grains of the PCD subsurface a DLC zone and turbostratic graphite was found. This might be a proof for ongoing carbon phase transitions during PCD grinding. If thermophysical effects enforce atomic graphitization on both sides, at the grinding wheel and at the PCD substrate, specifically designed processes that push the thermal and mechanical process loads from the wheel toward the substrate might improve the efficiency of the process. Nevertheless, crack formation at the subsurface must be avoided. According to Pierson, diamond and graphite are allotropic modification phases of carbon. Thus, both structures may exist for the same condition of aggregation [9]. Diamond is metastable for normal conditions anyway. The transition needs just activation energy for proceeding. However, the strategy of transforming diamond into graphite has just never been followed because it was never of an economic interest. If it could be controlled precisely, it might be interesting in future. In further investigations the influence of different grinding parameters will be analyzed focusing also on carbon phase transitions.

Acknowledgment

Parts of the work are being funded within the framework of the Federal Ministry of Education and Research of Germany, program VIP.

Nomenclature

a_e = depth of cut
$a_{e,ges}$ = total stock removed
d = mean grain size
DLC = diamond like carbon
FIB = focused ion beam
G = ratio between ground material volume and worn grinding wheel volume
HRTEM = high resolution transmission electron microscopy
l = lamella thickness
L_t = measuring length
n_{gw} = number of revolutions of the grinding wheel
PCD = polycrystalline diamond
r_t = cone pin radius of the surface measuring device
Ra = mean surface roughness
s = insert thickness
sp^2 = graphite carbon hybridization
sp^3 = diamond carbon hybridization
STEM = scanning transmission electron microscope
t = depth
TEM = transmission electron microscope
v_c = cutting speed

v_{wp} = feed rate

α_t = cone pin angle of the surface measuring device

References

[1] Abele, E., and Schramm, B., 2008, "Using PCD for Machining CGI With CO_2 Coolant System," Prod. Eng. Res. Dev., **2**(2), pp. 165–169.

[2] Heath, P. J., 2011, "Developments in Applications of PCD Tooling," J. Mater. Process. Technol., **116**(1), pp. 31–38.

[3] Kozak, J., Rajurkar, K. P., and Wang, S. Z., 1994, "Material Removal in WEDM of PCD Blanks," ASME J. Manuf. Sci. Eng., **116**(3), pp. 363–369.

[4] Tso, P.-L., and Liu, Y.-G., 2002, "Study on PCD Machining," Int. J. Mach. Tools Manuf., **42**(3), pp. 331–334.

[5] Linke, B. S., "Review on Grinding Tool Wear With Regard to Sustainability," ASME J. Manuf. Sci. Eng. (to be published).

[6] Kenter, M., 1990, *Schleifen von polykristallinem Diamant*, Dissertation, Bremen University, Bremen, Germany.

[7] Fineberg, J., 2011, "Tribology: Diamonds Are Forever—Or Are They?," Nat. Mater., **10**(3–4), pp. 3–4.

[8] Vervoort, L., 1910, *Diamond Its Properties and Its Machining*, State Library Munich, Antwerp, Belgium.

[9] Pierson, H., 1993, *Handbook of Carbon, Graphite, Diamond and Fullerenes; Properties, Processing and Applications*, Noyes Publications, Albuquerque, NM.

[10] Lachmund, U., and Spur, G., 1997, "Verschleißverhalten von polykristallinem Diamant bei instationärer Beanspruchung," Ph.D. dissertation, Technical University of Berlin, Berlin.

[11] Friemuth, T., 2002, *Herstellung spanender Werkzeuge*, Habilitation, Hannover University, Hannover, Germany.

[12] Brecher, C., Klocke, F., Schindler, F., Janssen, A., Fischer, B., and Hermani, J.-P., 2013, "Finishing of Polycrystalline Diamond Tools by Combining Laser Ablation With Grinding," Prod. Eng. Res. Dev., **7**(4), pp. 361–371.

[13] Koshy, P., Jain, V. K., and Lal, G. K., 1996, "Mechanism of Material Removal in Electrical Discharge Diamond Grinding," Int. J. Mach. Tools Manuf., **36**(10), pp. 1173–1185.

[14] Kozak, J., 2002, "Abrasive Electrodischarge Grinding (AEDG) of Advanced Materials," Arch. Civ. Mech. Eng., **2**(1–2), pp. 83–101.

[15] Liu, X. L., Yan, F. G., Wang, Y., Hu, J. S., and Wang, Y. J., 2006, "Study on Precision Grinding Technique of PCD Tool's Cutting Edge," Key Eng. Mater., **305**, pp. 186–190.

[16] Bifano, T. G., Dow, T. A., and Scattergood, R. O., 1991, "Ductile-Regime Grinding: A New Technology for Machining Brittle Materials," J. Eng. Ind., **113**(2), pp. 186–189.

[17] Chen, Y., Zhang, L. C., Arsecularatne, J. A., and Montross, C., 2006, "Polishing of Polycrystalline Diamond by the Technique of Dynamic Friction Part I-V," Int. J. Mach. Tools Manuf., **46**(6), pp. 580–587.

[18] Pastewka, L., Moser, S., Gumbsch, P., and Moseler, M., 2010, "Anisotropic Mechanical Amorphization Drives Wear in Diamond," Nat. Mater., **10**(1), pp. 34–38.

[19] Element Six Ltd., 2014, "Diamond Materials for Metalworking," (last accessed Sept. 25, 2014), http://www.e6.com

[20] De Fonton, S., Oberlin, A., and Inagaki, M., 1980, "Characterization by Electron Microscopy of Carbon Phases (Intermediate Turbostratic Phase Graphite) in Hard Carbons When Heat-Treated Under Pressure," J. Mater. Sci., **15**(4), pp. 909–917.

[21] Kuznetsov, V. L., Zilberg, I. L., Butenko, Y. V., Chuvilin, A. L., and Segal, B., 1999, "Theoretical Study of the Formation of Closed Curved Graphite Like Structures During Annealing of Diamond Surface," J. Appl. Phys., **86**(2), pp. 863–870.

[22] Oya, A., and Marsh, H., 1982, "Phenomena of Catalytic Graphitization," J. Mater. Sci., **17**(2), pp. 309–322.

[23] Pawlyta, M., 2013, "Transmission Electron Microscope Studies on Carbon Nanostructured Materials," Arch. Mater. Sci. Eng., **63**(2), pp. 58–67.

[24] Ralchenko, V., Nistor, L., Pleuler, E., Khomich, A., Vlasov, I., and Khmelnitskii, R., 2003, "Structure and Properties of High-Temperature Annealed CVD Diamond," Diamond Relat. Mater., **12**(10–11), pp. 1–8.

[25] Tomita, S., Hikita, M., Fujii, M., Hayashi, S., Akamatsu, K., Deki, S., and Yasuda, H., 2000, "Formation of Co Filled Carbon Nanotubes by Metal-template Graphitization of Diamond Nanoparticles," J. Appl. Phys., **88**(9), pp. 5452–5456.