

High-Precision Laser Conditioning of Diamond Grinding Wheels

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Abstract

A novel approach for machining of cylindrical ultra-hard materials with a highly defined contour is presented. Diamond grinding tools with complex geometry are manufactured with picosecond orthogonal and quasi-tangential laser ablation. Hitherto, laser manufacturing required a special axis configuration and often optical beam deflection devices are utilized. Here, strategies and processes on a scanhead-free configuration are discussed enabling straight-forward implementation in industry. This rapid and flexible approach for small-scale production of master tools for industrial grinding processes reveals benefits compared to conventional approaches. The manufacturing time is comparable to standard processes, however increased grain protrusion is attained with the presented laser strategy. A combined laser manufacturing strategy enables an ablation rate of $35 \text{ mm}^3 \text{ min}^{-1}$ and a maximal geometric deviation of $3 \mu\text{m}$ after finishing. The final grinding tools are sharpened by a radial laser process removing the metal-based binding material. Following, this isolates the stochastically distributed diamond grains from the binder. Hence, high-precision diamond grinding wheels with a mean error of smaller $1 \mu\text{m}$ over the complete contour can be manufactured. The meta-stable diamond structure persists and is assessed via Raman spectroscopy.

Keywords: diamond grinding tool, laser conditioning, laser manufacturing, ultra-short pulses, Raman spectroscopy, precision machining

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1. Introduction

The demand for high precision gears to reduce wear and acoustic emission points to the necessity of tight manufacturing tool tolerances. Super-abrasives, like diamond and cubic boron nitrides (cBN) master tools, are therefore required to produce hard hobs with long endurance and precision. These master tools are conventionally manufactured by wire electric discharge machining (EDM) or single-grain diamond turning. One main drawback of the wire-EDM concerns the non-conductive super-abrasives. The grains are not cut by the wire, but the conductive binder is removed and grains are washed out from the surface leaving a void. Nevertheless, a defined outer geometry can be produced reaching high precision with a lack of abrasives on the surface. Hence, the grinding tool must be used for some time to set the undefined cutting edges free allowing a high-speed grinding process. Laser conditioning has proven to be a viable alternative to the conventional processes, however the manufacturing time is for most applications not competitive.

Timmer (2001) investigated the applicability of laser manufacturing to profile rotary tools. Subsequently, Zhang and Shin (2002) reported in the early 2000s a technique for laser-assisted truing and dressing. A vitrified cBN grinding wheel was produced with a diamond dressing tool in conjunction with a laser.

This should increase the life time of the expensive dresser and enable a homogeneous condition during the production of the grinding wheel. Subsequently, the next step of dropping the diamond dresser was reported using directly the laser radiation for truing and dressing. Jackson et al. (2003) introduced an orthogonal dressing process for chromium-doped alumina with a high-power Nd:YAG laser. Explicitly, it is stated to use proper laser parameters in terms of power and scan strategy to avoid massive damage and phase transformations. Following, chemical analysis pointed to a re-solidified surface with alumina dissolution and multi-valent chromium oxides. Xie et al. (2004) reported dressing of resin-bonded diamond wheels, where the ablation threshold difference enables an effective sharpening process. However, high precision was not reached due to evaporation of the resin and following loss of the diamond grains. Bronze bonded diamond tools were studied by Hosokawa et al. (2006) and a sharpening process with a ms Q-switched laser investigated. They used an air jet nozzle to blow away the metallic binder before re-solidification and convection cooling, which leads to high ablation rates. In case of low power no damage of the diamond grains was detected. However, the established processes were not fast enough to be economical and subsequent increase of average power lead to high thermal impact.

Chen et al. (2010) reported laser assisted truing and dressing of bronze-bonded diamond grinding wheels and measured the process forces of such tools. The study revealed a strong dependence on laser parameters, surface quality and following grinding performance. A numerical model revealed the influence of

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power density and adjacent heat impact leading to a specific removal rate. A non-negligible amount of graphite at the diamond grains points to a thermal process and a heat-affected zone, if a density of above 100 MW cm^{-2} is used. Shortly after, von Witzendorff et al. (2012) investigated sharpening and dressing of grinding tools with different pulsed laser sources. The sources ranged from a pulse duration of 12 ps to 20 ns in the near-infrared (1064 nm) and with green wavelength (532 nm). The ablation rate and selectivity was studied between binder and diamond grains. Short pulses turned out to be beneficial and the stochastically distributed diamond grains could be dressed without any detectable phase transition. In similar manner (Dold et al., 2011) studied touch dressing of single-layer large diamond grains with ultra-short pulses of 10 ps. Cut diamond grains were generated, which are favorable for high surface quality grinding with small surface roughness. Furthermore, the grinding efficiency could be increased with lower processing forces, if structuring a defined clearance angle on the grains. This angle dependency was investigated in detail by Transchel et al. (2013) on single diamond grains. A defined modification of the flank angle proves to be beneficial and altered the cutting characteristics of the tool in terms of smaller forces during the process and higher surface quality.

Walter et al. (2012) reported laser dressing and truing of cBN grinding tools with high geometric accuracy using tangential irradiation conditions, which enabled an edge radius smaller $20 \mu\text{m}$. A material removal rate of up to 46 mm min^{-3} was reached at 48 W average power with a NIR 200 ns fiber laser at 75 % pulse and 25 % line overlap. These parameters pointed to a layer thickness of $50 \mu\text{m}$ and therefore a high material removal rate leading to short manufacturing time. Subsequently, the tools were tested in grinding experiments up to a specific material removal rate of $7000 \text{ mm}^3 \text{ mm}^{-1}$ and showed good durability. Following, Chen et al. (2015) investigated the profiling of diamond tools with a pulsed fiber laser and tangential processing. Processing of the grinding wheel was reported with laser power up to 40 W and 210 ns of pulse duration. However, the graphitization of the diamond grain persisted for all parameters with the broad characteristic Raman peak at 1582 cm^{-1} . A follow-up study from the same group (Zhou et al., 2016) investigated the graphite layer evolving under ambient, argon and grinding fluid condition. Nonetheless, a graphite layer was clearly detectable in the Raman spectra at all ablation conditions after laser manufacturing.

Walter et al. (2014) presented laser dressing and truing, which is profiling and sharpening, of industrially used grinding tools. Cleaning and surface structuring techniques were applied to modify the tool behavior. Laser-induced defined profiles were studied and point to an increased specific material removal rate of the grinding process. However, the wear of the sharpened edges was higher and lead to shorter lifetime and, therefore, higher tool change costs. A similar study was recently presented by Zhang et al. (2018), where reduced cutting forces for structured tools have been reported. The wear started at the laser induced sharp edges leading to round off, which changes the cutting characteristics and influences the surface quality.

A study by Warhanek et al. (2015) pointed out the applicability of ultra-short pulsed laser processing with a laser touch dressing process. Combining fast deflection with a galvo scanner and slow rotation on a high-precision XY-table lead to accurate laser machining and positive clearance angles. Hence, the cutting forces during grinding diminished, showing the potential of ultra-short pulsed laser ablation. The quasi-tangential process is inherently self limited and enables the production of high precision geometries. Moreover, if an iterative measurement step is introduced, the total manufacturing time can be decreases (Warhanek et al., 2017) allowing high precision and fast laser manufacturing.

Within this study, combined processes for conditioning of super-abrasive diamond tools are presented. Orthogonal laser ablation is combined with a subsequent quasi-tangential incidence manufacturing step. Hence, a high material removal rate strategy is combined with the self-limiting finishing for highest precision. Ultimately, a radial sharpening process sets the cutting edges of the super-abrasive grain free from the binding material for an optimized grinding performance.

2. Materials and Methods

2.1. Experimental Configuration

The ablation setup consisted of five mechanical axes, illustrated in figure 1. A Trumpf TruMicro 5070 regenerative-amplified picosecond laser acted as source and was guided via modifying optics into the pivot point of a swivel B axis. Different anti-reflective coated focusing lenses were used to adapt the focal beam diameter. For this study, a 150 mm lens leading to a focal radii of $23 \mu\text{m}$ was applied. Furthermore, $\lambda/4$ and $\lambda/2$ wave plates allowed to control the polarization state and direction. The X,Y,Z and A axes were driven with controllers from

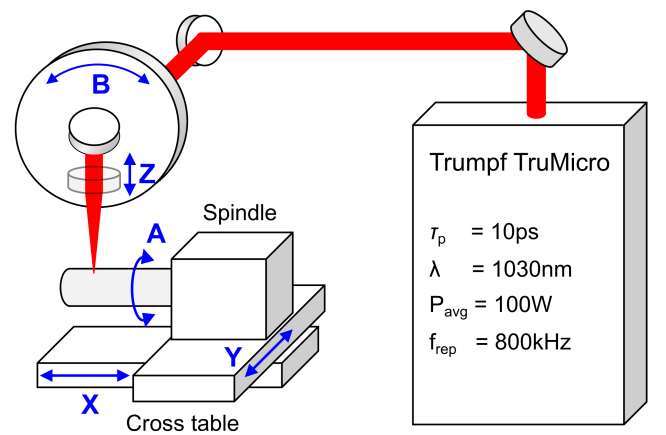


Figure 1: Experimental setup for synchronous laser ablation utilizing an ultrashort-pulsed Trumpf laser source. The axes are three linear stages for XYZ movement, a fast rotating spindle axis A and manual swivel axis B.

Aerotech Inc. and controlled with Aerotech's A3200 software. The swivel axis B is manually adjusted and not used for the production of grinding wheels, but necessary for threaded grinding

tools. This approach enabled synchronous movement of the X,Y,Z and A axes for combined feedback controlled motion. Fast relative surface motion of the laser beam and workpiece was realized with the spindle axis, which operated up to 100 s^{-1} to adjust the surface speed and pulse overlap, accordingly. A suction unit with a two stage particle filter (G4, H15) was used to collect the ablation debris and generated nano-particles. Additionally, a pressurized air operated nozzle at 2 bar was used for convection cooling mounted on the opposite side of the suction unit.

For the laser path computation on the target geometry a CAM tool (Gysel, 2017) was developed for orthogonal and quasi-tangential laser manufacturing. The details on the calculation routines were recently reported by Ackerl et al. (2019). Here, solely a brief overview of the program flow is discussed. A CAD file is exported to the stereo lithography (STL) file format, which can be imported into the CAM software tool. Following, the axes movement, laser paths, and hatches are calculated for an adjacent set of laser parameters. Therefore, the settings leading to a certain layer thickness and quality have to be established by a parameter study with the used laser source on the target material. Specifically, the layer thickness, beam distance, and spindle rotational speed have to be determined for orthogonal and quasi-tangential processing strategies. An additionally implemented feature allows to consider hardware limitations for the axes movements, like maximal velocity and acceleration. These constraints lead to idle rotations for positioning and accelerating rotations to consider inertia of the workpiece and axes.

2.2. Process Strategies

Laser processes have a trade-off between maximal ablation rate, surface quality and dimensional accuracy. Each characteristic can be optimized with an associated laser parameter set, but in many cases a combination of these characteristics is necessary. For this reason, three distinct processes are introduced for the laser manufacturing of high-precision grinding wheels. An orthogonal roughing processing step is followed by quasi-tangential roughing and finishing. Subsequently, a sharpening step is applied to generate the protrusion of diamond grains and clean the surface. Orthogonal laser processes are utilized for high ablation rate and the concept is depicted in figure 2a. The workpiece is rotated with the spindle axis and positioned with the X-axis and Z-axis at the focal position for each layer. Starting with a blank cylinder, the layers with a depth of l_r are ablated with a beam distance of l_b on helical paths. The surface speed is controlled by the rotational speed v_r and constantly accelerated for layered ablation to keep the pulse overlap constant at smaller radii. Moreover, the generated flanks project the laser beam, which leads to a decreased power density and a part of the beam is reflected. Therefore, a deviation to the designed geometry evolves, which has to be compensated for. In figure 2b a basic principle of empirical beam path compensation is shown. The laser paths are compensated already in the CAM, where a reduced ablation rate at the flanks is considered by the axial shift of x_c . Additionally, the ablation at the

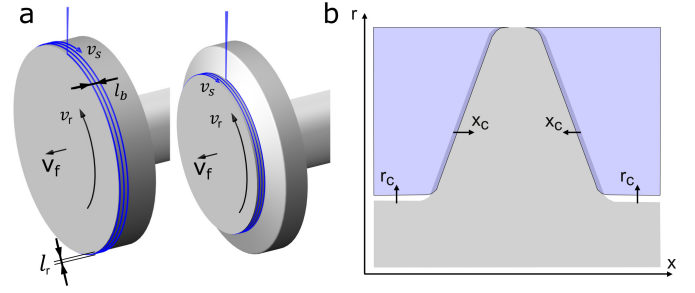


Figure 2: Radial strategy for high ablation rate roughing (a). The laser beam is steered with constant surface speed v_s on helical paths with distance l_b ablating a layer of thickness l_r . In (b) an empirical compensation strategy for radial massive laser ablation process is depicted. The flanks are shifted by x_c and the section with orthogonal incidence moved by r_c .

bottom of the contour is shifted radially by r_c to consider accumulated errors. Both values are attained experimentally. In an iterative manner, a quasi-optimum can be found to reach practical dimensional accuracy for the subsequent quasi-tangential manufacturing steps.

As discussed, the orthogonal roughing process shows a high ablation rate accompanied by low dimensional accuracy. Therefore, a self-limiting quasi-tangential process is subsequently utilized for high precision manufacturing. The laser beam irradiates the surfaces under grazing incidence, depicted in figure 3a. Surface speed is held constant by controlling the ro-

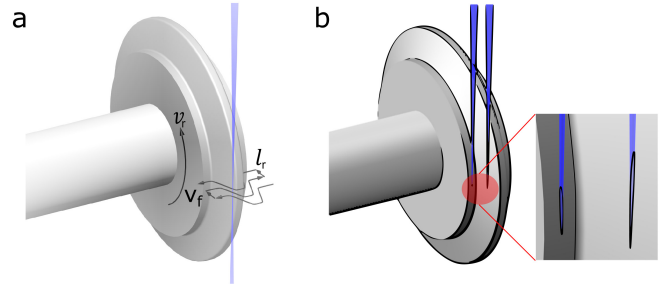


Figure 3: (a) Sketch of the self-limiting quasi-tangential ablation condition and projected laser spot on the flank and bottom. This projection leads to a difference in fluence and is compensated in the laser path calculation. The Laser beam is steered along the contour with v_r , and constant surface speed adjusted by the rotational speed v_r .

tational speed v_r and the laser steered synchronized in X and Y with a feed rate of v_f . Similar to the orthogonal process, the projection of the laser beam on the double curved surface is a challenge for stable ablation conditions, shown in figure 3b. This discrepancy is compensated in the CAM path calculation by lowering the feed rate at the flanks keeping the ablation rate constant.

The last step of the production routine involves an orthogonal sharpening process. This is attained by a similar motion as the final layer of the orthogonal roughing process. However, the process is carried out with a fast rotation to remove only a small portion of the binding material, which has a lower fluence compared to the super-abrasive. A combination of these three processes enables the production of high-precision grinding tools

in viable time. The distinct calculation of the laser paths without a parameter study is not implemented yet and would lead to computational complex models. Out of that reason a parameter study is carried out to attain the process settings for certain material removal rate and accompanying surface quality. Prospectively, a database will be established for different materials and geometries relying on the empirical parameter studies.

2.3. Material and Measurement Methods

The grinding tool blanks were supplied by Ultrawheels with 25 μm natural diamond grains statistically distributed in a metallic binding material. During the production a granular mix of binder constituents and diamond grains is heated under pressure to obtain the dense raw material. 30 mm cylindrical blanks mounted on a precision-grinded cemented carbide shaft is used throughout this study.

Optical stereo microscopy was utilized for first inspection after laser manufacturing. A confocal Leica DCM3D 3D microscope served as measurement device to determine the depth, ablation volume and surface roughness. Additionally, an Alicona G5 enabled the inspection of the whole grinding wheel before and after the grinding tests. Small features and diamond grains were analyzed with a Hitachi SU-70 scanning electron microscope.

Raman spectra were attained with a WITec alpha300R spectroscopy and green wavelength of 532 nm. At the used 50x magnification the focal diameter is about 5 μm . The grating was set to 900 cm^{-1} with the spectral center at 1200 nm to measure the Rayleigh peak for calibration. This leads to a measurement range of -210 cm^{-1} to 2450 cm^{-1} with reasonable signal-to-noise ratio. Each spectrum was measured five times at the same spot and integrated over 4 s. The measurement data was filtered to remove cosmic rays and smoothed by the Savitzky-Golay windowing algorithm.

The geometric precision was determined with a Zoller Venturion 450 measurement device. The specimen is illuminated with collimated light and the shadow of the sample is detected by a large scale CCD detector. Two precise linear axes allow the positioning of the sample and a rotational axis enables the measurement over the whole circumference. The Zoller pilot software was used for evaluation of the measurement and export to a vector file format. The measurement accuracy specified by the manufacturer is 1 μm . A Diavite tactile measurement device allowed to measure the geometry and surface roughness of the hob after grinding it with the laser-processed tools.

3. Results and Discussion

3.1. Parameter Study

A set of parameter studies for the two processing strategies has been carried out. Due to the inhomogeneous condition of the blank body with metallic binder and distributed diamond grains, single pulse ablation characteristics are not considered. Square pockets with 2 mm side lengths have been ablated on the lateral area of cylinders and on flat specimen of the same material. Hence, a broad parameter range has been experimentally

investigated due to limited references on this kind of composite material. A first study considered the necessary beam overlap l_b for good surface quality, which subsequently was set to 8 μm for both strategies. This leads to a center point overlap of 83% at a spot size of $d_f = 46 \mu\text{m}$. Figure 4 sums up the study condensed in a two dimensional contour plot, where the surface quality acts as side constraint.

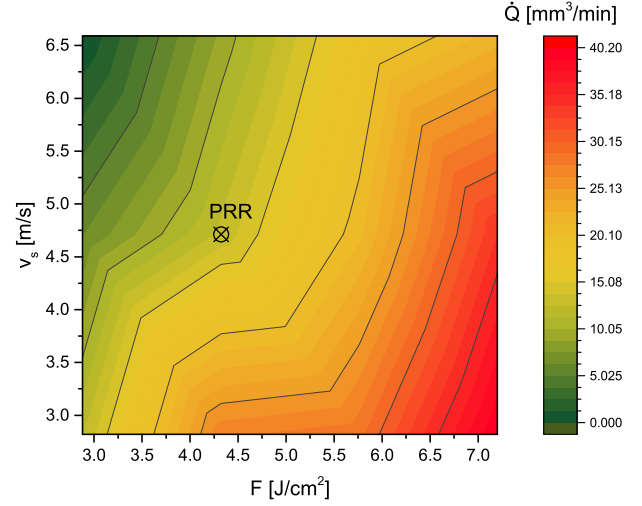


Figure 4: Contour plot of the orthogonal ablation rate depending on the fluence and surface speed, correlated to the pulse overlap. The used parameter set for radial roughing PRR is shown in the graph. The lines are guide to the eye for iso-contours.

A trend is revealed with an increase in the ablation rate for higher fluence and lower surface speed. The pulse-to-pulse distance was varied between 3.5 μm and 8.375 μm . Generally, the specific ablation rate depends on a multitude of laser parameters, process strategies, and material properties. In this case the used experimental setup and laser source limited the possible parameter space, considering maximal ablation rate and surface speed. A laser wavelength of $\lambda = 1030 \text{ nm}$, repetition rate $f_{\text{rep}} = 800 \text{ kHz}$, pulse duration of $\tau_p = 10 \text{ ps}$ and spot size of $d_f = 46 \mu\text{m}$ was used. Leaving the average power P and surface speed v_s as adjustable control. Following, the necessary parameters for laser machining are denoted with the adjacent dependencies:

$$\begin{aligned} F &= \frac{4P}{d_f^2 \pi f_{\text{rep}}} \\ l_p &= \frac{v_s}{f_{\text{rep}}} \\ X_p &= 1 - \frac{v_f}{d_f f_{\text{rep}}} \\ X_b &= 1 - \frac{l_b}{d_f} \end{aligned} \quad (1)$$

Here the pulse X_p and line overlap X_b are given, which result for the studied surface speed between 80% and 95%. An analytic expression for the ablation rate $\dot{Q}$ cannot be derived straight forward due to the inherent non-linearity of the multi-pulse laser ablation process. However, a proportionality incorporating the angle of incidence θ relative to the surface can be stated to:

$$\dot{Q} \propto (P, f_{\text{rep}}, d_f, v_s, v_f, \theta) \quad (2)$$

Clearly, the ablation rate strongly differs between the orthogonal and quasi-tangential incidence of the laser radiation. An

empirical study revealed the ablation rate and the orthogonal study cannot directly be translated to quasi-tangential processing parameters. Therefore, a separate study has been carried out for this process. From the parameters tested a set in conjunction with maximal ablation rate, surface quality and dimensional accuracy has been selected. Table 1 summarizes the settings for the laser ablation utilized for the laser manufacturing of the diamond grinding tool.

Table 1: Ablation parameters for the different process strategies. Radial roughing PRR, quasi-tangential roughing PTR and finishing PTF and an orthogonal sharpening process PS. The non-projected fluence in the quasi-tangential processes is marked with a $\star$.

Parameter	PRR	PTR	PTF	PS
P [W]	60	100	100	4
F [J cm^{-2}]	4.5	7.52 $\star$	7.52 $\star$	0.3
l_r [μm]	5.7	10	1	1
v_s [m s^{-1}]	4.712	0.188	0.942	2.827
v_r [s^{-1}]	50	2	10	30
v_f [$\mu\text{m s}^{-1}$]	400	400	100	500

All parameters reported have been cross checked with the ablation of pockets with defined depth acting as a control. In case of the orthogonal process small deviations in each layer accumulate and point to a higher dimensional deviation.

3.2. Diamond Grinding Wheel

Starting from the blank workpiece, diamond grinding wheels were laser manufactured without compensation with the described processing strategies and parameters from table 1. In order to evaluate the processes, one grinding tool was manufactured with the orthogonal and quasi-tangential roughing parameters. Following, the interface layer and the diamond grains were studied. The cross section of this specimen was embedded in a conducting polymer and grinded with diamond grinding pads up to grit 4000. The samples have not been polished, preventing the wash out of diamond grains and imaged qualitatively with the SEM, shown in figure 5. The diamond grains appear black and the metallic binder in light grey. Inspection of the cross-section points to well-distributed diamond grains and no accumulation even after laser ablation with high average power. The red horizontal line separates the regions of orthogonal and quasi-tangential ablation without compensation strategies. The bottom part of the graph reveals the accumulated deviation of the orthogonal process at the flank and more clearly on the straight parts of the contour. During the process, parts of the beam are deflected at the flank and generate a higher ablated volume. This has been considered for following manufacturing with the compensation strategy presented, compare figure 2b. A magnified SEM graph of two red marked areas reveals the surface condition after ablation. The quasi-tangentially processed region shows cut diamonds on the edges and the curvature. On the other hand, the quality of the orthogonal processed region is lower with higher roughness and deviation. In the SEM analysis no heat-affected zone could be observed and the marked diamond grains in figure 5 have been additionally inspected by Raman spectroscopy.

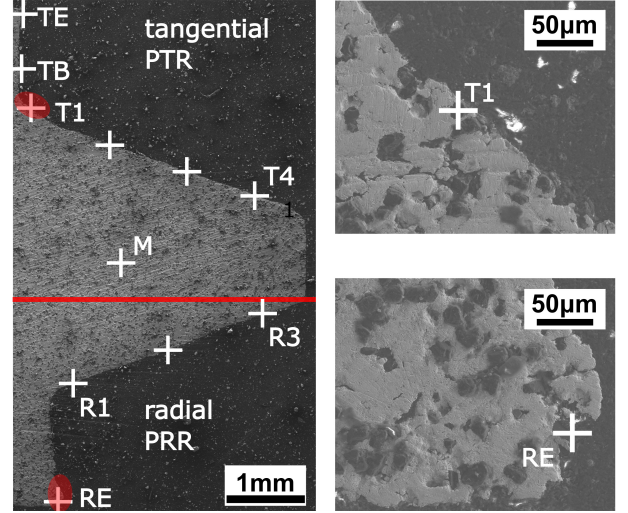


Figure 5: SEM graph of the cross-section after quasi-tangential and radial roughing from a cylindrical blank. The red line separates these two regions. Raman spectra have been taken at each marked grain to assess possible graphitization. A magnified inset shows the diamond grains in black distributed in the greyish metallic binder.

3.2.1. Raman Spectroscopy Study

The Raman spectrum of diamond is well known, having solely one active optical phonon mode. Therefore, the sharp single peak at 1332 cm^{-1} is easy to detect and can be clearly distinguished by any amorphous or crystalline allotrope of carbon. Crystalline graphite shows a first order single peak at 1575 cm^{-1} and the amorphous configuration has a broad peak due to the hybridized energy levels centered around the same crystalline peak. Here, the data was analyzed at each of the spots labeled in figure 5 by a least-square fit to the spectral data and a Lorentz peak shape was applied:

$$I = I_0 + \frac{1}{\pi} \frac{2Aw}{4(k - k_c)^2 + w^2}. \quad (3)$$

A constant offset I_0 was taken into account and the peak height A , width w and location k_c fitted. The peak position can give insights into possible laser induced internal stress. However, no peak shift has been detected, which points to no modification of the grains from the laser processing. Figure 6 depicts the measured spectra and the attained Lorentz peak positions for the Rayleigh and diamond first order Raman peaks. The Rayleigh peak is taken for the calibration of the Bragg grating, separating the elastic and inelastic scattered parts. The fluorescence background in some of the spectra is attributed to the metallic binding material showing some excitation at 1431 cm^{-1} . However, the sharp diamond Raman spectra are clearly distinguishable and no sign of graphite is observed. It can be stated, that high power ultra-short pulsed laser manufacturing up to 100 W does not introduce Raman-detectable graphitization. The diamond phase persists for both processing strategies in contrast to longer laser pulses in the nanosecond regime as reported previously (Chen et al., 2015).

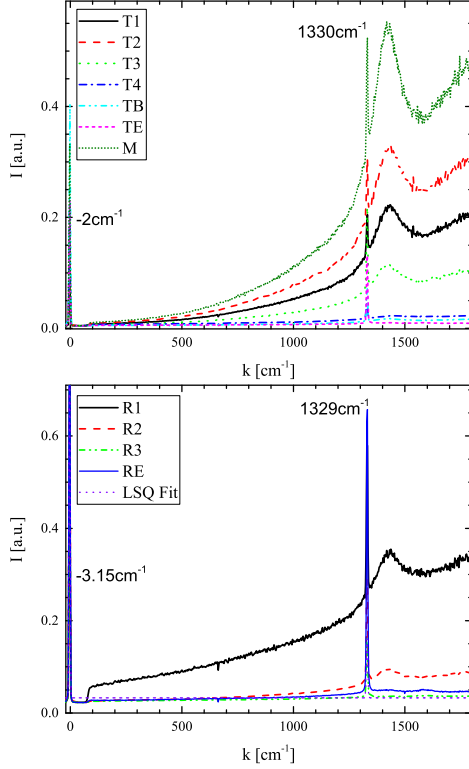


Figure 6: Raman spectra after laser machining revealing the diamond structure with measurement points denoted after figure 5. The characteristic peak at 1332 cm^{-1} is clearly distinguishable for all measurements, even with fluorescence background from the metallic binder.

3.2.2. Dimensional Accuracy and Process Time

The high-precision conditioning process involves the fast orthogonal roughing, quasi-tangential roughing and finishing. These three processes allow an accuracy of below $10 \mu\text{m}$ over the complete contour to design. Final finishing is in principle possible, if lower fluence is utilized combined with a zero radial feed. In this case the final deviation is solely limited by the precision of the mechanical axes system. Moreover, the quasi-tangential process enables the production of higher precision compared to the focal spot diameter by only coupling a small fraction of the laser beam into the workpiece. However, only scanning the contour takes several tens of passes to reach a quasi-equilibrium ablation state and approaching the final contour. Out of that reason an active compensation is proposed for the quasi-tangential finishing step to reach highest precision in feasible time.

The principal idea of laser path compensation is based on an empirical study, measurement and a contour shift operation. Step-wise the quasi-tangential laser processing strategy from figure 7a allows to manufacture a precise outer contour. However, the challenge of varying energy density, compare Figure 3b, leading to changing irradiation conditions and ablation, persists. Therefore, the geometry is measured with the Zoller and the deviation evaluated computationally. The segments to be removed are overcompensated and the new laser path shifted normal to the measured contour. A sketch in figure 7b shows the design contour in green and

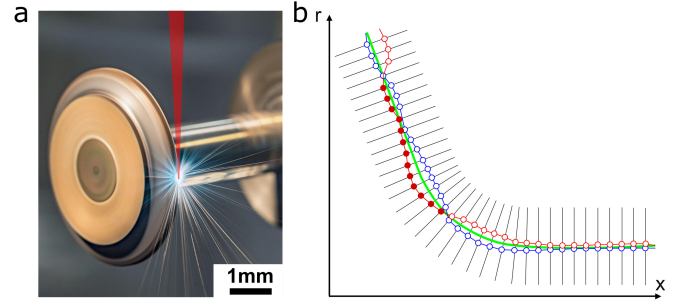


Figure 7: (a) The laser is steered quasi-tangentially to the afore radially processed surface. (b) Compensation strategy for high precision with the design contour in green and measurement in blue. The red curve shows the orthogonal shifted new laser path.

the discretized measurement in blue. Subsequently, the new compensated laser contour is generated for the path calculation. Depending on the slope and laser incidence condition, the contour is compensated with empirically attained values. At regions already in tolerance the feed rate is increased to save processing time and no radial feed used. Table 2 shows the processes with the adjacent parameters, number of sliced layers and processing times. After each laser manufactured grinding tools the parameters and compensation values are refined to reach highest precision.

The conditioning process with compensation revealed a maximal deviation of $3 \mu\text{m}$ over the whole contour. Moreover, a mean deviation below $1 \mu\text{m}$ was measured, which indicates a stable manufacturing process and is at the resolution limit of the used measurement device. During the manufacturing, the metallic binder is preferentially ablated taking into account the lower ablation threshold of metals compared to diamond. Therefore, the final sharpening production step only removes little binder material to set the diamond grains free, but keep enough to have the grains mechanically well bonded, which is $5 \mu\text{m}$.

Table 2: Number of layers and non-optimized production time for the processes from table 1 with feed rate v_f . Radial roughing PRR, quasi-tangential roughing PTR and finishing PTF, active compensation PTC and sharpening PS is shown with adjacent mean $\bar{\xi}_{\text{proc}}$ and maximal deviation $\hat{\xi}_{\text{proc}}$. The processing time per layer t_l and total time t_{proc} for each process are given.

Parameter	PRR	PTR	PTF	PTC	PS
$v_f [\mu\text{m s}^{-1}]$	400	400	100	100-1000	500
N_{layer} with feed	613	20	30	8	12
N_{layer} no feed	-	5	5	-	-
$t_l [\text{s}]$	9.4	280	111	60	23
$t_{\text{proc}} [\text{min}]$	96	100	65	40	5
$\bar{\xi}_{\text{proc}} [\mu\text{m}]$	238	33	24	3	-
$\hat{\xi}_{\text{proc}} [\mu\text{m}]$	63	17	11	<1	-

The process time of the five introduced processes is shown in table 2 for each layer and the process step itself. These times incorporate the axes movement, positioning and laser ablation. Ultimately, the processes have not been optimized for speed

and the manufacturing time can be reduced significantly. One strong limitation identified is the presented experimental setup, see 1, where the mechanical XY-axes have small acceleration 10 mm s^{-2} and maximal velocity of only 350 mm s^{-1} . These side constraints make it necessary to introduce an acceleration time and in between two adjacent layers the rotational spindle axis must revolve several time to keep the synchronous movement.

In comparison to conventional production techniques, e.g. diamond dressing and wire-EDM conditioning, the laser manufacturing of diamond grinding wheels is competitive. The production time in the presented conditioning process is comparable to industrial used techniques and manufacturing times for precise master tools. Moreover, ultra-short pulsed laser conditioning revealed the big advantage of being selective on the material and, hence, the diamond grains show a protrusion.

Higher precision and faster manufacturing times are feasible, if an additional in-line measurement system is used, as shown by Warhanek et al. (2017). An orthogonal laser ablation step with higher power could be used and the accumulated errors measured, compensated, and high-precision reached with quasi-tangential processing. In principle, the measurement can be carried out tactile or optically contact-free. However, the measurement has to be fast to keep the acquisition time of the whole profile low. A viable approach would be a laser touch probe with a discretized measurement strategy, projection devices, or a fast confocal microscope. Furthermore, optical coherence tomography would be a feasible option, however to date, the lateral resolution is not high enough and the measurement time long. For production processes an in-process process control is desirable to get a fast feedback, where acoustic emission or a fast area power meter could give a valuable measure. Nevertheless, to date there is no straight forward measurement device available and therefore an inherent measurement approach has to be developed.

3.2.3. Performance Considerations

The laser-conditioned grinding wheels have been tested in an industrial production chain. Following, the tool wear and quality of two laser manufactured master tool was assessed after high speed precision grinding of a cemented carbide hob. A two-step process with 0.8 mm roughing in one layer and two layers of 0.8 mm finishing was carried out. The surface speed was kept at 18 m s^{-1} with a feed rate v_f of 50 mm min^{-1} for both steps. A total volume of 3303 mm^3 was removed with each laser-conditioned grinding wheel and the hob showed high precision and surface quality. The tactile assessment on 1.5 mm revealed a superb quality, however, a small variation between the flanks of the hob was detected. The left flank showed an R_a of $0.13 \mu\text{m}$ ($R_z = 0.82 \mu\text{m}$) and the right flank showed an R_a of $0.19 \mu\text{m}$ ($R_z = 1.1 \mu\text{m}$). This deviation seems to come from uncut diamond grains on the contour of the master tool. Subsequent measurement of a cut in a metal sheet made with the grinding wheel corroborates this assumption. Hence, the compensated laser process with step-wise measurement must be adapted for highest demands to guarantee a fully defined girthed area of the master tool.

Confocal microscopy on the same region of interest on the diamond master tool before and after grinding points to high durability. Figure 8a shows the measured surface before grinding and b after grinding with negligible wear on the diamond grains. The line profile in Figure 8c reveals the protrusion of the diamond grains, which persist at approximately $12 \mu\text{m}$. In strong

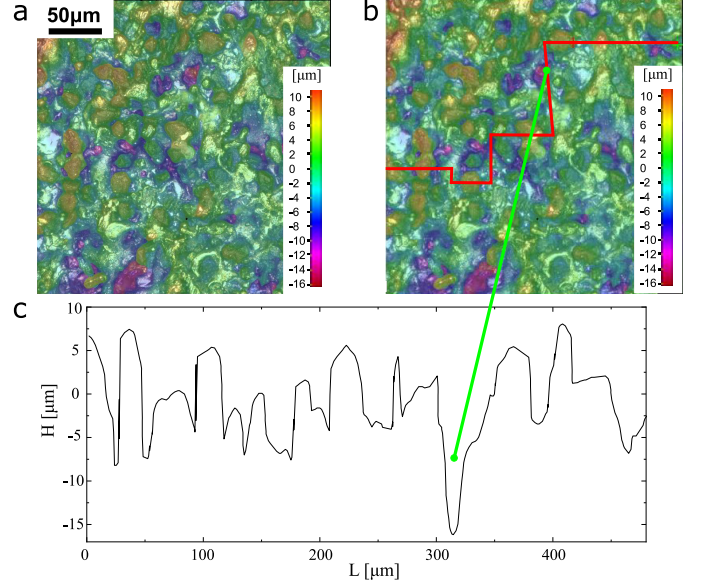


Figure 8: Confocal 3D micrographs of the grinding wheel before (a) and after (b) grinding of 3000 cm^3 at the same region of interest. (c) Shows the typical height of diamond grains from the red line in (b). The protrusions are $5 \mu\text{m}$ with a height of $12 \mu\text{m}$ to the binder.

contrast to conventional production techniques, laser conditioning inherently enables a sharpening of the grinding tool. Albeit, the precision contour can be manufactured by wire-EDM, laser-conditioned surfaces contain cut diamond grains with protrusion. Exactly this sharpening process enables a faster and more defined grinding processes and is preferred by industry. The reduced initial grinding time to set the grains free of the binder and establishing a cutting edge is an additional benefit of the introduced production steps. Moreover, the little wear points to longer tool life time and higher attainable precision, which reduces the total costs of precision hob manufacturing.

4. Conclusions

A new laser machine tool setup solely built with mechanical axes has been introduced. The necessary fast surface speed for laser manufacturing is reached with a spindle axis. Following, industrial competitive manufacturing of diamond bonded grinding wheel has been reported. High-power ultra-short laser ablation reveals a high potential for the production of master tools to produce precision tools. The three introduced processing steps of roughing, finishing and sharpening allow high precision production within a tolerance band of $\pm 3 \mu\text{m}$. In comparison to conventional wire-EDM the processing time is competitive and additionally sharpening is possible.

The manufactured grinding wheels were tested in a real world application and hobs produced. Moreover, the sharpened diamond grinding wheel have a long tool life time and after the production of two hobs no wear has been detected. An in-process measurement configuration would allow to speed up the production time and even higher average laser power than 100 W could be utilized. Moreover, the ablation rate could be significantly increased if the pulse and line overlap are optimized and the spot diameter enlarged for the roughing step.

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