Lasers in Manufacturing Conference 2019

CAM solution for quasi-tangential laser ablation of complex 3*D* workpieces

Norbert Ackerl[a*], Johannes Gysel[b], Maximilian Warhanek[a], Konrad Wegener[a]

[a]*ETH Zurich, D-MAVT, IWF, Leonhardstrasse 21, 8092 Zürich, Switzerland*
[b]*inspire AG, Technoparkstrasse 1, 8005 Zürich, Switzerland*

Abstract

A fast forward computation of the laser ablation paths and hatches for complex 3*D* geometries enabled by a computer-aided manufacturing (CAM) toolbox is presented. Specifically, the laser paths for quasi-tangential irradiance condition on a rotary specimen are calculated and the machine code for a laser manufacturing system with up to seven synchronously controllable axes generated. In order to set the parameters for the path determination, an empirical parameter study points to the material specific removal rate in accordance with pulse and line overlap. Therefore, a manifold use of this tool is possible for all laser sources from continuous wave to ultra-short pulses. This leads to a unique flexible way, hitherto not available for fast prototyping applications. Following, laser manufactured specimens with complex contour shapes reveal the high potential of this approach. High-precision laser manufactured dental implants and diamond-grinding tools with tolerances in the micrometer range serve as demonstrators.

Keywords: Computer aided manufacturing, Laser manufacturing, Ultra-short pulsed, Laser turning, Tool path planning;

1. Introduction

Laser manufacturing gains more market shares and in some applications, e.g. cutting of metal sheets, lasers are already state of the art. Depending on the desired workpiece geometry, several laser-scanning strategies are possible. Many processes are carried out on flat substrates and a 2*D* or layered 2.5*D* strategy is sufficient. In both cases, the laser beam irradiates the surface orthogonal and for layered strategies the surface quality and geometric conformity strongly depends on used laser parameters (Neuenschwander et al.

[*] Corresponding author. Tel.: +41 44 633 73 50; fax: +41 44 632 11 25.
E-mail address: ackerln@ethz.ch.

2014). However, if the laser beam is steered quasi-tangentially to the surface a very different incidence condition occurs. This leads to a self-limiting process comparable to laser polishing under glancing incidence, which has less dependence on the fluence (Tokarev et al. 1995). This strategy points to high-precision laser manufacturing and has the advantage of generating a defined contour even on dissimilar materials like tungsten carbide and diamond composites (Warhanek et al. 2016). Moreover, combined processes in case of grinding tool conditioning show a tangential laser process to reach high precision (Dold et al. 2011) followed by a possible orthogonal sharpening step (Chen et al. 2015). The girthed area of grinding tools can be additionally structured to enhance the tools properties (Walter et al. 2012). Nevertheless, both process strategies, orthogonal and tangential, are viable and the combination enables the laser production of complex geometries with high precision. In general, quasi-tangential processing can be carried out with higher laser power and fluence, which would lead to deviations in the orthogonal scenario, due to the self-limiting property. On the contrary, quasi-tangential processing does not use the whole laser beam and, therefore, power efficiency for the ablation process is decreased. Consequently, the part of the Gaussian beam being below the threshold fluence is dissipated in the specimen. In case of heat-sensitive materials this can induce a heat-affected zone, e.g. observed for ceramic composites (Ackerl, Warhanek, et al. 2019b)

The laser-path calculation for flat substrates and orthogonal incidence conditions is state of the art and implemented in different industrial software programs from the galvo-scanhead suppliers. However, in case of rotational workpieces and complex outer contours, an industrial available computer aided manufacturing (CAM) tool for laser ablation is to date not available. The orthogonal 2.5D scenario on rotational workpieces was demonstrated with the optical axes synchronized to the rotational axes in a master-slave configuration (Warhanek, Pfaff, et al. 2017). Therein, one approach for the computation of the laser hatches and paths relative to the specimen's surface for orthogonal ablation is demonstrated. However, if high precision and manufacturing time plays a role, a combination of quasi-tangential and radial processes can be preferential. Recently, the strategies and routes for the laser path calculation of 7-axes synchronous was shown (Ackerl, Warhanek, et al. 2019a) and enables a variety of applications. Here, a selection of realized applications using an open-source CAM solution (Gysel 2017) with adaption for different axis systems with and without an optical scanhead are discussed. Starting with the basic routines of this toolset, a holistic understanding is built up to demonstrate the usability and point to novel applications in future.

2. Laser path calculation program modules

2.1. Overview and program flow

The general routine of the presented CAM toolset is shown in figure 1. Initially, the geometry designed in a computer aided design program (CAD) has to be related to the blank specimen. This gives the part of the geometry, which shall be removed from the feedstock. Subsequently, the design is exported from the adjacent software used to the stereo lithography file format (STL). Some subroutines are discussed in the following section to deal with the challenges of a triangulated complex surface. A parameter study for a certain combination of material, laser system and process strategy in conjunction with the axes system is necessary for the computation of the laser hatches and paths. Specifically, the material removal rate in conjunction with the surface quality leads to the layer depth for slicing the geometry and calculating the laser paths. After the computation, the machine code is generated with the available commands for the laser machine tool. Within the referenced software package the commands can be set freely to control the adjacent axes and laser triggering commands. Following, the numerical code (NC) is run on the manufacturing system.

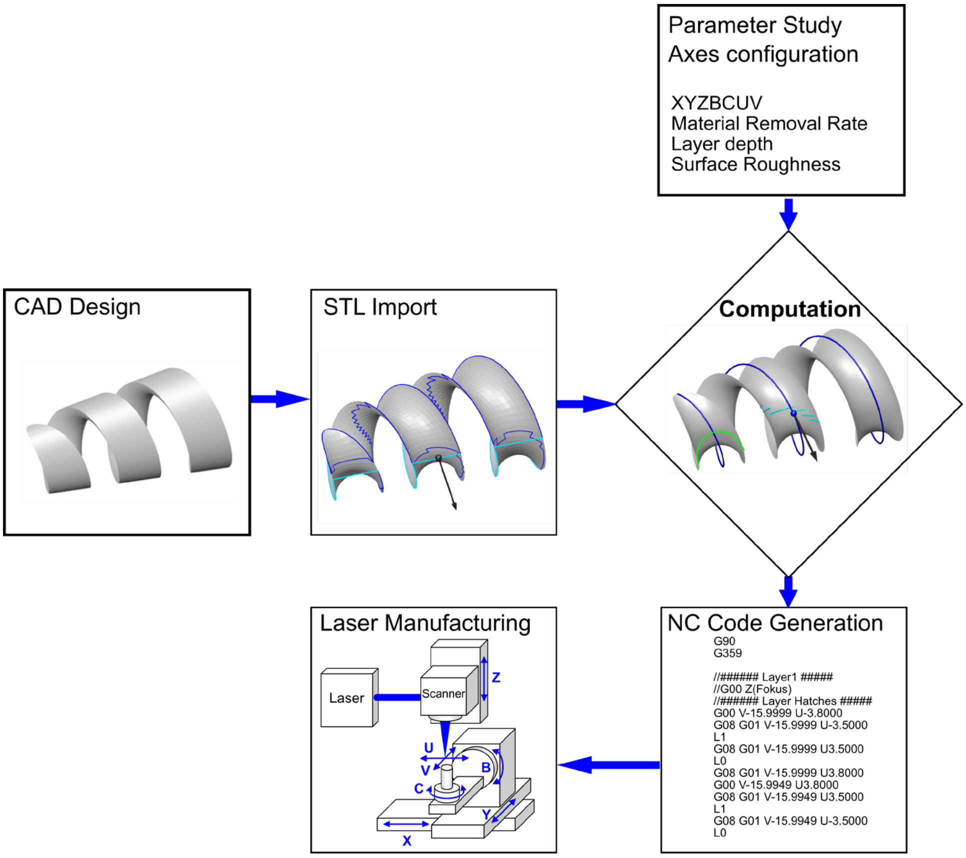

Fig. 1. Block diagram of the CAM toolbox for laser path calculation. After designing the desired geometry, the import is realized via triangulated STL. With the laser parameters as input the laser paths are computed and the axes system specific NC-code generated.

2.2. CAD import

The import of the geometry is realized for files in the stereo lithography (STL) format for complex 3*D* geometries and parametrized geometries with the AutoCAD drawing exchange format (DXF). During the export to STL, the designed geometry in CAD is triangulated and depending on the CAD software different challenges occur. Figure 2 shows possible defects from the export depending on the precision set for the export, which lead to a non-closed surface. Small errors with a gap smaller than the triangle size, depicted in figure 2a, can be detected and closed. However, if the gap is too big or multiple neighboring edges occur (figure 2b, c) a safe interpolation and shift of these edges is not possible and leads to a faulty surface. In rare cases, the adjacent triangles can have multiple edges and following the surface is over-defined. All errors, except of the small ones from rounding during export, lead to non-reparable defects and subsequently stop of the path calculation.

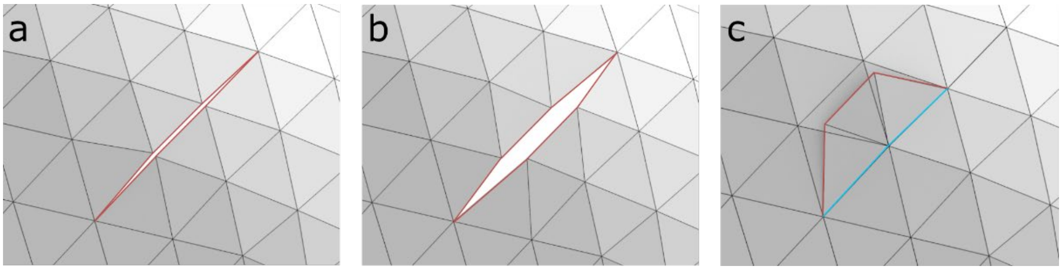

Fig. 2. Common defects in STL files after export from the CAD program (a) no common edge with small gap marked with red; (b) big gap between neighboring edges, and (c) multiple neighboring edges.

2.3. Parameter study and configuration

The prerequisite to compute the laser paths for complex surfaces is to know the material removal rate in conjunction with the demanded surface quality. Strongly dependent on the laser source, be it continuous laser radiation, pulsed or ultra-short pulsed, the ablation characteristic may vary strongly. Therefore, a parameter study must be carried out with the adjacent laser source and material. If orthogonal and quasi-tangential processes are combined for each extreme in terms of irradiation condition, a parameter study is needed. Moreover, the available or planned axes configuration has to be considered to generate the relative paths between laser and workpiece.

The material removal rate, surface quality and dimensional accuracy are inter-dependent and influenced by the laser fluence, pulse overlap, line overlap, and strategy. For a certain combination of the workpiece material and laser machining configuration a database can serve to feed the parameters to the CAM solution and directly compute the paths and hatches.

2.4. Laser path computation

The Boolean difference between the workpiece blank and designed geometry is loaded in the CAM solution. This defines the volume to be removed. A detailed description of the routines and computation with the mathematical representation can be found in literature (Ackerl, Warhanek, et al. 2019a). Figure 3 shows an exemplary geometry, where the helical pitch is not constant and the groove geometry changes.

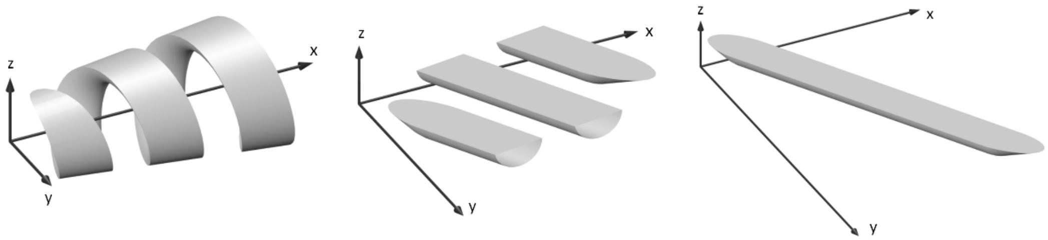

Fig. 3. The imported geometry to be removed from the blank is unrolled considering the helical pitch. Every revolution by 2π is considered and the helix transformed from cylindrical coordinates to pseudo-Cartesian.

After import and possible correction of the design geometry, the helical pitch is detected and the volume separated after each revolution of 2π. The cylindrical coordinates are transformed to Cartesian ones for a more convenient slicing and computation. Following, the geometry is stitched together in the transformed system to calculation.

2.5. Process strategies

Depending on the strategy, the imported geometry is sliced in a different way. In case of radial incidence condition, the paths are computed similar to 2.5*D* slicing approaches. However, for quasi-tangential processing the path is generated from a tangential vector position. The possible strategies of scanhead and scanhead-free laser machine configurations lead to different approaches (Warhanek, Pfaff, et al. 2017). In the next section, two realizations are discussed, where the adjacent strategy is realized. In case of a scanhead-free axes configuration the pulse-to-pulse separation is done with a spindle axis. Subject to the workpiece radius and laser repetition frequency for pulsed system the rotation speed is set to reach a constant overlap. The laser beam is steered on the girthed area of the specimen in helical paths with defined line overlap. After each full path in x-direction, compare figure 3, either the rotational direction has to be changed or the workpiece set back in x. In strong contrast, using a scanhead opens the possibility to scan fast parallel to the x-axis and having a slow rotation. However, in both scenarios a synchronized axes control system is necessary for high-precision results.

3. Application examples and discussion

Within this contribution, two different application examples are adressed. First, the conditioning process of diamond grinding tools is presented followed by the laser machining of a ceramic dental implant. The processes concerning the grinding tools are carried out in a scanhead-free configuration and realizing the relative movement solely with mechanical axes. Figure 4a depicts the quasi-tangential finishing strategy on a diamond-grinding wheel. The diamond grains are distributed in the bulk metallic binding material and therefore forms a composite. Starting with a cylindrical blank the defined geometry is laser machined with a combination of radial and quasi-tangential strategies.

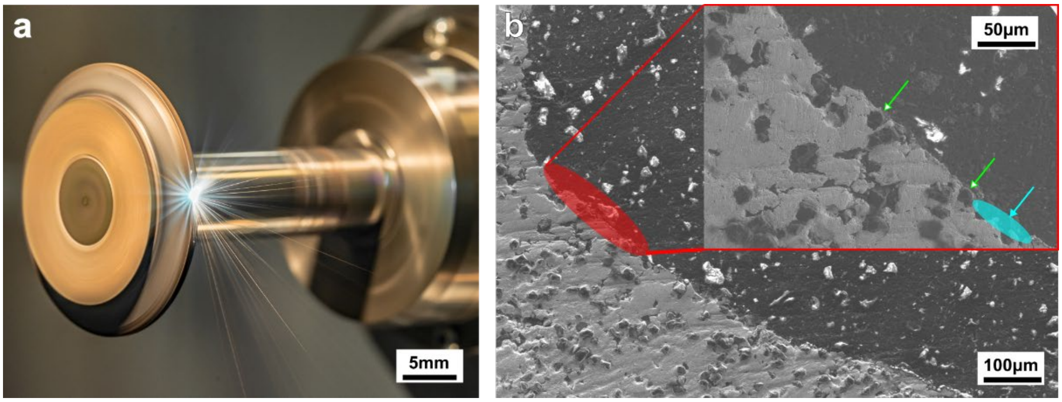

Fig. 4. Processing of diamond grinding wheels with a high-power ultra-short pulsed laser system. (a) Photograph of the quasi-tangential scanhead-free finishing process on the workpiece. (b) a SEM micrograph shows the cross-section of the grinding tool with cut diamonds marked with the arrows and voids from the grinding and polishing preparation with the magenta oval.

Figure 4b shows the distinct edge of the quasi-tangentially manufactured grinding wheel in a cross-sectional scanning electron graph. A zoom on the red region of interest reveals cut diamond grains at the edge with some diamonds washed out during the sample preparation. A subsequent radial sharpening process removes the metallic binder selectively and sets diamond protrusions. These are beneficial for the mechanical grinding process. A precision better than 3µm over the whole contour is reached, compare table 1. Following, the more complex geometry of a threaded grinding tool was laser manufactured. Starting with a cylindrical tool blank, see figure 5a, a defined contour is ablated on a helical path with constant pitch.

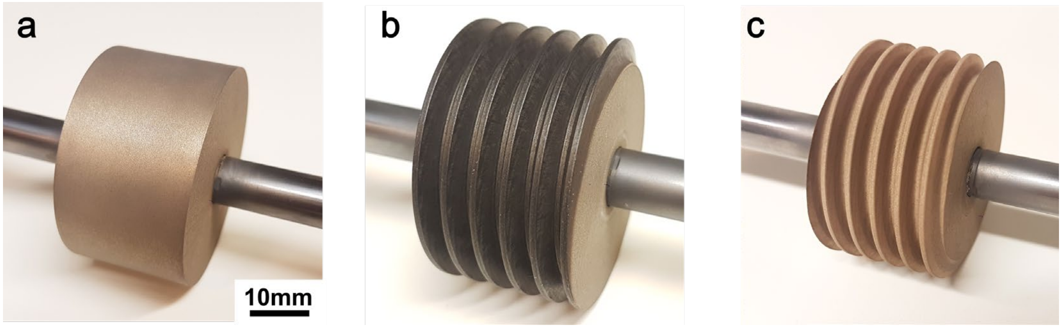

Fig. 5. Processing steps for a threaded grinding tool. Starting with the tool blank (a) the precise helical contour is laser machined (b). A radial sharpening process removes parts of the ablation debris and sets diamond grains free to sharpen the tool (c).

A quasi-tangential roughing process leads to the result shown in figure 5a, where 100W of average power are used. Subsequently, a radial sharpening step removes about 5 µm of material and the small parts of carbon on the diamond grains (Ackerl, Gysel, et al. 2019). This picture is corroborated by Raman spectroscopy studies, where no phase transformed carbon was detected after the adjacent processing steps. However, at present the processing times of these tools on the laboratory scale axes configuration is long compared to conventional production routines. This is a matter of optimization and the processes can be scaled with mechanical axes having higher acceleration and maximal speeds. Moreover, the rotational speed in conjunction with the laser repetition rate points to faster processing if both are increased. The process parameters are summed up in table 1 to give an overview concerning the presented strategies.

In contrast to the grinding tools, the laser manufacturing of dental implants is more complex. The geometry consists of different features and the groove contour changes on a varying helical path. Hence, a seven axes laser machining test bed was necessary with five mechanical and two optical galvo axes. Moreover, the control has to be synchronized between the mechanical and optical system to steer the hatched laser beam quasi-tangentially over the whole path. Figure 6 depicts the step-wise manufacturing of an implant. The outer contour of the implant is manufactured from the cylindrical raw material with a quasi-tangential strategy. For the final implant two routes are possible, either a production with radial incidence directly from the blank, or a stepwise combination of both strategies. The comparison of radial and quasi-tangential manufacturing can be seen in figure 6 b and c, with adjacent process parameters in table 1. Furthermore, a distinct surface structuring of the implant with a subsequent radial step can introduce certain roughness in favor for interaction with soft tissue after implantation. As a proof-of-concept an implant was machined stepwise, starting with quasi-tangential roughing, finishing to manufacture the defined geometry with smaller 4µm of mean deviation. Figure 6d shows the result of the radial finishing removing some micrometers of material and introducing roughness on the surface. The edges are marked with the red arrows and the optical reflectivity clearly changes.

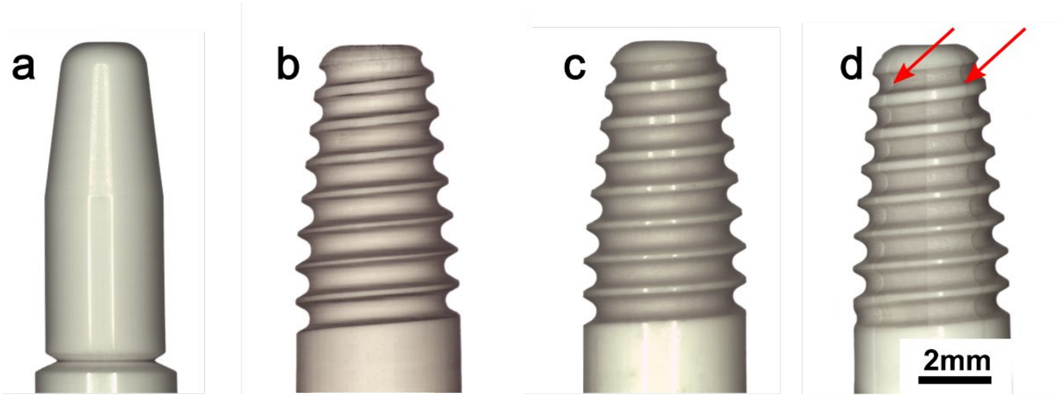

Fig. 6 Stepwise laser manufacturing of dental ceramic implant. First, the defined outer contour is created quasi-tangentially (a). Radial (b) and quasi-tangential (c) roughing leads to different surface qualities. The tangentially finished implant can be surface finished radially to introduce roughness or defined structures on the surface (d), here four section are radially machined marked with the arrow.

The discussed manufacturing routine makes fast iteration cycles for research and development possible for hard-to-machine materials. Industrially, these implants are diamond ground having the drawback to redesign the grinding tool for each geometric change on the workpiece. Hence, laser manufacturing is a competitive route for rapid prototyping.

Table 1. Process parameters for quasi-tangential laser machining. The first value represents the tangential or radial (marked with *) roughing process followed by a finishing step. The fluence in case of tangential processes is not projected along the surface.

Specimen	Grinding Wheel	Grinding Worm	Dental Implant
Maximal Average Power P [W]	60* / 100	60* / 100	2* / 8
Pulse duration [ps], wavelength [nm]	10 / 1030	10 / 1030	0.4 / 520
Repetition rate f_{rep} [kHz]	800	800	200
Fluence F [J/cm^2]	45.3* / 75	45.3* / 75	10.4* / 41.8
Surface Speed v_s [m/s]	4.7	4.7	0.5* / 0.1
Feedrate v_F [mm/s]	0.04* / 0.1	0.05-0.1	1.5°/radius/scan
Layers thickness l_Z [µm]	5.7* / 10	4.9* / 10	7.2* / 15 / 7.5
Process time t_P [h]	1.5* / 2.2	39* / 33	2
Mean deviation $\bar{\xi}$ [µm]	20* / 1	100* / 23	18* / 4
Maximal deviation $\hat{\xi}$ [µm]	33* / 3	160* / 40	50* / 15

The presented CAM toolbox makes the laser machining of complex 3*D* workpieces possible in a fast manner. The laser paths are computed on short time scales of minutes to hours, depending on size and desired precision of the paths. A combination of radial and quasi-tangential processes makes the manufacturing in short time feasible. The radial processes are in general more power efficient, considering the coupling of the laser energy to the specimen. However, if layered ablation is carried out small stochastic deviations in each layer can accumulate and influence the final precision. In case of rotational specimen, a combination with glancing incidence enables superior surface quality and precision. Nevertheless, if processes are combined the geometry must be measured for efficient manufacturing. A stepwise manufacturing and measurement loop with active compensation would enable the route to industrialization of this approach (Warhanek, Mayr, et al. 2017).

4. Conclusion and outlook

This contribution introduces a tool for laser path and hatch computation to generate complex geometries on various workpieces. Depending on the axis configuration of the laser machine tool the laser paths are calculated with and without optical axes. This approach is highly flexible and the subroutines of the presented CAM solution can be adapted to specific needs. Two different strategies are implemented for radial and quasi-tangential laser machining. Hitherto, a combination of both processes makes high precision laser machining in viable time possible.

For high precision demands, an orthogonal roughing followed by quasi-tangential finishing with active compensation strategies will be developed pointing to a stepwise manufacturing, measuring and compensation strategy. In future, a material specific database for ultra-short pulsed laser machining makes the manufacturing of complex parts in a fast-prototyping manner possible. Moreover, the implemented routines can be enhanced and due to the limitations of the STL file format a new importing function will be developed. One further strategy for higher geometric conformity via taper angle correction is assessed in ongoing work.

Acknowledgements

The funding by the Swiss Commission of technology and Innovation and the Swiss National Science Fund (no. 169654) is acknowledged. N.A., M.W. and J.G want to thank Josquin Pfaff for his valuable input during the conception of the CAM toolbox and the support on design plus implementation of the scanhead-free experimental setup.

References

Ackerl, Norbert, Johannes Gysel, Maximilian Warhanek, and Konrad Wegener. 2019. “Ultrashort Pulsed High Power Laser Conditioning of Super-Abrasive Grinding Worms.” in *High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VIII*. Vol. 1091105. SPIE.

Ackerl, Norbert, Maximilian Warhanek, Johannes Gysel, and Konrad Wegener. 2019a. “Path Calculation of 7-Axes Synchronous Quasi-Tangential Laser Manufacturing.” *The International Journal of Advanced Manufacturing Technology* 21.

Ackerl, Norbert, Maximilian Warhanek, Johannes Gysel, and Konrad Wegener. 2019b. “Ultrashort-Pulsed Laser Machining of Dental Ceramic Implants.” *Journal of the European Ceramic Society* 39(4):1635–41.

Chen, Genyu, Hui Deng, Xingcai Zhou, Cong Zhou, Jie He, and Song Cai. 2015. “Online Tangential Laser Profiling of Coarse-Grained Bronze-Bonded Diamond Wheels.” *The International Journal of Advanced Manufacturing Technology* 79(9–12):1477–82.

Dold, C., R. Transchel, M. Rabiey, P. Langenstein, C. Jaeger, F. Pude, F. Kuster, and K. Wegener. 2011. “A Study on Laser Touch Dressing of Electroplated Diamond Wheels Using Pulsed Picosecond Laser Sources.” *CIRP Annals - Manufacturing Technology* 60(1):363–66.

Gysel, Johannes. 2017. “CAM 2.5D Laser Ablation V2.0.” Retrieved (https://zenodo.org/record/1048515).

Neuenschwander, B., B. Jaeggi, M. Schmid, and G. Hennig. 2014. “Surface Structuring with Ultra-Short Laser Pulses: Basics, Limitations and Needs for High Throughput.” *Physics Procedia* 56:1047–58.

Tokarev, V. N., J. I. B. Wilson, M. G. Jubber, P. John, and D. K. Milne. 1995. “Modeling of Self-Limiting Laser-Ablation of Rough Surfaces - Application To the Polishing of Diamond Films.” *Diamond and Related Materials* 4(3):169–76.

Walter, Christian, Mohammad Rabiey, Maximilian Warhanek, Nicolas Jochum, and Konrad Wegener. 2012. “Dressing and Truing of

Hybrid Bonded CBN Grinding Tools Using a Short-Pulsed Fibre Laser." *CIRP Annals - Manufacturing Technology* 61(1):279–82.

Warhanek, M., C. Walter, M. Hirschi, J. Boos, J. F. Bucourt, and K. Wegener. 2016. "Comparative Analysis of Tangentially Laser-Processed Fluted Polycrystalline Diamond Drilling Tools." *Journal of Manufacturing Processes* 23:157–64.

Warhanek, Maximilian, Josef Mayr, Christian Dörig, and Konrad Wegener. 2017. "Accurate Micro-Tool Manufacturing by Iterative Pulsed-Laser Ablation." *Lasers in Manufacturing and Materials Processing* 4(4):193–204.

Warhanek, Maximilian, Josquin Pfaff, Johannes Gysel, and Konrad Wegener. 2017. "Rotary 2 . 5D Pulsed Laser Ablation." Pp. 1–8 in *WLT Laser in Manufacturing*.