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Innovative micro-tool manufacturing using ultra-short pulse laser ablation

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\section*{ABSTRACT}

The continuously growing demand for micro-electro-mechanical systems (MEMS) with decreasing feature sizes necessitates adjusted manufacturing solutions. Micro-milling fulfills the high requirements for precision and reliability placed on the final product. The employed tools have diameters in the range of 50–300 μm and are commonly manufactured by grinding. However, a reduction in tool diameter leads to a decrease in stiffness in the fourth power and the introduced load in grinding causes a high scrap rate. Furthermore, the flexibility in tool design is limited to the attributes of the grinding wheel. These restrictions in micro-tool manufacturing can be avoided by using ultra-short pulse (USP) laser ablation. This process allows a force-free 2-D and 3-D machining across a broad range of materials without wear formation. By using a USP laser, a wide range of customer-oriented applications in the micrometer scale can be addressed. Also, it leads to precise ablation with minimal thermal and mechanical damage. This paper provides knowledge on the manufacturing of micro-tools made of tungsten carbide with small diameters and high aspect ratio. For the desired tool geometries, necessary process parameters are evaluated and their physical limits are shown and discussed. An innovative CAM-system has been programmed to allow the manufacturing of advanced geometries using a 4-axis laser machine test bench developed by ETH Zürich. A 515 nm wavelength laser beam is capable of providing flawless tools with diameters as low as 50 μm and aspect ratios up to 6. Due to precise calibration, the tool run-out is decreased to < 5 μm. Providing multiple teeth at smaller diameters and individually shaping of each tooth is feasible using a beam radius < 10 μm and a pulse duration of 1 ps. A form deviation to the target geometry below 5 μm evidences high repeatability. The cutting edge is exposed after being struck by a focused ion beam. In the cross-section, the cutting edge radius is determined to be < 3 μm. By mastering the multi-axis laser ablation process, micro-tools for machining ductile and brittle workpieces are presented. The performance of the micro-tools is analyzed in subsequent milling experiments. Enabling optimization of the tool geometry leads to higher flexibility compared to ground micro-tools. The laser-processed tools enhance the range of micro-structuring. Pitch distances of structures in the range of the tool diameter with extreme aspect ratios are realized in ductile and brittle materials.

\section{Introduction}

Due to the constant development and improvement in the field of laser machining, precise structures in the micrometer scale can be machined. The ability to generate micro-structures is desirable for many applications ranging from miniaturization to functionalization of surfaces. Therefore a premise is the capability to reliably machine micro-tools with defined geometries like chip flutes, cutting edges, and so on. To this purpose, micromachining tungsten carbide (WC) by means of ultra-short pulse (USP) lasers is discussed in this paper. No sufficient guidance currently exists on how to reliably obtain excellent process results for producing micro-tools using USP-laser ablation. To guarantee high replicability and superb tool quality, a multi-axis CAM-system is introduced. A parametric analysis was carried out to gain further knowledge about the physical interaction of laser with WC. A freeform target shape is machined using different laser process parameters to maximize quality and form accuracy and minimize surface roughness. In this paper, it is shown that laser beam machining (LBM) reveals a worthy alternative to grinding when producing micro-milling tools. By optimizing the laser machining and using an innovative CAM-system, the limitations in tool geometry design can be shifted and the run-out error can be reduced significantly. The conventional tool
manufacturing processes are based on mechanical removal of material by grinding. This process leads to cutting forces, which can be high enough to damage a micro-tool. Besides, the wear of grinding tools leads to inaccuracies of the manufactured micro-tool. Due to the high flexibility when using a 4-axis laser machining setup in combination with tangential and radial laser ablation, multi-cutting edges can be arranged on a micro-tool having a diameter below $\Theta < 200 \mu m$. Thermal damage is negligible when using a laser with a beam focus radius $\varnothing_0 < 10 \mu m$ and a pulse duration smaller than $\tau_p < 1 \text{ ps}$. Accurate machining conditions are crucial, as the tool shape quality determines to a great extent the tool performance. Klocke et al. (2002) recognize the impact of the cutting edge radius $\omega$ dimension of a tool. As the feed per tooth $f_w$ depends on the cutting edge dimension in the case of micro-milling, the influence of the radius $\omega$ must not be neglected. If the uncut chip thickness $h$ adopts comparable values as the cutting edge radius $r_w$, the effective rake angle $\gamma_{\text{eff}}$ assumes a negative value and thus the chip formation undergoes ploughing, as defined by Bissacco et al. (2008). According to Heisel et al. (2014), the ploughing effect is present if the uncut chip thickness $h$ is below the minimum uncut chip thickness $h_{\text{min}}$.

In subsequent milling experiments, the high performance of the laser-processed tools is shown. Due to negligible small process forces of laser machining compared to grinding, extreme aspect ratios up to 6 are achievable. Besides this, the process forces in grinding bend the tool during manufacturing and the stiffness of a tool is drastically reduced by lowering the tool diameter. Moreover, the introduced notching effect at the formation of the chip flutes contributes to the stiffness reduction. Thus, it can be shown that the run-out error of a laser-process tool is significantly smaller compared to ground tools. Büttner et al. (2019) describe the run-out of a ground tool having a diameter $\Theta = 200 \mu m$. The run-out can adopt values higher than the feed per tooth $f_w$, which results in an unequal engagement of each cutting edge. It is shown that under unfavorable conditions, some cutting edges are not at all involved in the material removal process. To realize a desired shape with accurate micro-structures, low inner edge radii and structure distances in the micrometer range, micro-tools with diameters in the range of tens to hundreds of micrometers must be employed.

2. Micro-tool manufacturing

2.1. Techniques

The quality and reliability of the workpiece are determined to a great extent by the condition of the deployed micro-tool. Thus, high requirements are placed on a micro-tool, such as sharp cutting edges, high form accuracy, low run-out error, distinct cutting edge angles, high stiffness, and other factors. Uhlmann and Schauer (2003) ascertain that run-out introduced from geometrical inaccuracies can adopt values larger than the feed per tooth $f_w$ and are thus more likely to cause tool failure. Customarily, a downsizing of macro-milling tools is performed to produce micro-milling tools. However, this procedure leads to high tool breakage rates. The micro-tool manufacturing techniques are limited. Li et al. (2011) suggest unpretentious tool geometries so that accurate and economical manufacturing is feasible.

To meet these requirements, various manufacturing techniques are available. Due to the high degree of automation and thus ensuring large quantities, the majority of tool manufacturers use grinding for micro-tool manufacturing. However, grinding implies process forces and vibrations, which cause a high scrap rate when machining filigree structures. Besides grinding, non-conventional manufacturing technologies are available, which are suitable for micro-tool fabrication. These include wire electro-discharge machining (EDM), focused ion beam (FIB) machining and laser beam machining (LBM). The main advantages of these technologies are negligible small process forces, high geometrical flexibility, no influence of wear formation and high repeatability. As these technologies exhibit a low material removal rate (MRR) for finishing strategies and a high machining duration has to be expected in comparison to grinding. If replication of a conventionally micro-tool having multiple teeth, distinctive cutting angles, and chip flutes is desired, multi-axis machine tools are necessary. Additionally, no CAM-systems are commercially available for non-conventional machining. Thus high knowledge on path programming is required.

Applying incorrect machining parameters promotes the formation of a heat-affected zone (HAZ), leading to surface defects such as cracks or the occurrence of brittle white layers. When machining tungsten carbide (WC), the two phases WC and Cobalt (Co) show a different physical behavior: the threshold fluence $F_{\text{th}}$ is higher for WC in comparison to the Co-binder. This results in unsteady material removal, which promotes the formation of a relatively high roughness. The non-thermic ablation of material by induced collisions of ions using a FIB results in superb ablation quality, but economically unfeasible manufacturing times.

Many researchers describe micro-tool manufacturing methods. However, only a few are equipped with multi-axis machines and CAM-systems. Hence, the presented micro-tools are often limited to simple geometries. Micro-tools having diameters as low as $\Theta < 30 \mu m$ are discussed in the literature; however, these are restricted to one cutting edge and do not exhibit chip flutes or minor cutting edges. Merely Aurich et al. (2012), Eberle et al. (2018), Hajri et al. (2018) and Pfaff et al. (2017) show the capabilities of precise micro-tool manufacturing of WC by using multi-axis LBM and grinding. Table 1 displays an overview of research, based on micro-tool manufacturing using the most common technologies: grinding, wire-EDM, FIB and LBM. The overview is limited to micro-cutting tools made of WC or steel with defined cutting edges.

In particular, FIB provides a worthy opportunity for manufacturing. However, this process requires demanding environmental conditions, as machining is performed in a vacuum. Additionally, the MRR is limited, and thus an industrial application is not economically justifiable. Due to the Gaussian energy distribution of the ion beam, a rounding of sharp edges is discussed by Picard et al. (2003). It is shown that micro-tools manufactured by FIB machining and wire-EDM are geometrically limited, as a generation of a chip flute angle $\lambda_{\text{CF}} \neq 0$ and freeform shapes are not achievable. The presented micro-tools exhibit major cutting edges, whereas minor cutting edges are not possible to generate. Summarizing the manufacturing techniques leads to the conclusion that LBM exhibits the greatest potential. Thermal damage is negligible when working with USP laser ablation. Furthermore, due to a small laser beam radius $\varnothing_0$, high geometrical accuracy, small cutting edge radii $\omega$, and a low roughness $R_a$ are realizable.

To supplement the overview, Eberle et al. (2015) and Warhanek et al. (2016) discuss the manufacturing of tools made of polycrystalline diamond in macro- and micro-scale. By comparison, LBM is so far the only process to accomplish the manufacturing of high-quality micro-tools with complex cutting edge features with a high MRR.

2.2. CAM-system for micro-tool manufacturing

Due to synchronized multi-axis LBM, complex micro-tools are feasible to produce. For realization, a CAM-system for 2.5-D and 3-D laser processing is developed and discussed. This system post-processes the trajectories derived from a CAD model of the desired micro-tool. Due to adaptive laser beam control and innovate calculation methods of the trajectories, a low roughness $R_a$ and a high form accuracy is guaranteed on each feature. A graphical user interface displays the calculated trajectories for easy error detection and adjustments. Based on this, major and minor cutting edges, chip flutes with any chip flute angles $\lambda_{\text{CF}}$, and low cutting edge radius $\omega$ are feasible to generate having a 4-axis machine setup. For machining a cylindrical workpiece, tangential and radial laser machining is implemented.

Both strategies exhibit fundamental advantages that complement each other. Axial machining is not considered, as the laser beam caustic
interferes unwittingly with the workpiece. While performing radial machining, the energy is conducted efficiently into the surface of the workpiece. This leads to a high energy density and maximal heat accumulation due to the fast consecutive pulses resulting in a high MRR.

The coding of the CAM-system for radial laser machining is performed with a parallel orientation of grinding wheels and achieves high accuracy with deviations below 3 μm. Compared to conventional mechanical processes, LBM machining offers a high variation of geometric possibilities and allows micro-structuring of highly abrasive materials.

The coding of the CAM-system for radial laser machining is performed in MATLAB. This enables the processing of complex geometries like a chip flute with a variable chip flute angle \( \lambda_{CF} \) and the shaping of the major and minor cutting edges. The first step is to design the geometry of the desired tool geometry, see Fig. 1a. With this geometry and Boolean operations, a negative shape is created which defines the volume that has to be removed by ablation, see Fig. 1b.

The material is ablated layer by layer, starting from the top surface until the desired depth is reached. A slicing operation calculates the contour of each layer for a given ablation depth, see Fig. 1c. For material removal, the laser beam travels along with a set of parallel trajectories with constant distance, see Fig. 1d. To ensure precise ablation and accuracy, skywriting trajectories are added at the beginning and end of each laser ablation trajectory. On these, the laser is turned off. They allow the beam delivery system to accelerate and decelerate the mirrors in the scanner and the focal point of the laser. Thus a constant speed and constant ablation rate on the ablation trajectories is reached. Through the variation of the trajectory angle between each layer, a better surface finishing is possible. Without considering the trajectory angle variation, the direction of the laser trajectories would line up, resulting in grooves on the bottom of the ablated volume. With the laser trajectories of each layer, an NC-Code is generated, which can be executed on the laser setup, see Fig. 1e.

The micro-tool manufacturing procedure is presented in Fig. 2. The tool blank can be prepared either by grinding or laser ablation. The ablation of the chip flute is conducted in the radial orientation of the laser beam, as seen in Fig. 2a. The laser beam is indicated in green and is deflected by two highly dynamic galvo motors in the scanning head.

At the scan head, an F-Theta lens is mounted. Thus, independent of the orientation of the mirrors in the scanner, the focus of the laser always stays in the working plane. The scanning head is mounted on a mechanical Z-axis, which allows the focusing of the laser beam on the workpiece. The cylinder blank is clamped in the rotation A-axis. This, in turn, is mounted on a mechanical X and Y axis mechanical stage.

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**Table 1** Summary of micro-tool manufacturing techniques.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter Ø [μm]</th>
<th>Radius ( r_z ) [μm]</th>
<th>Teeth</th>
<th>Geometry</th>
<th>Workpiece material</th>
<th>Author</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire-EDM –</td>
<td>100 –</td>
<td>1</td>
<td>( l_z = 30°, \alpha = 10°, \lambda_{CF} &gt; 0° )</td>
<td>Brass</td>
<td>Fleischer et al. (2019)</td>
<td>2019</td>
<td></td>
</tr>
<tr>
<td>WC – 400</td>
<td>1.5...5</td>
<td>1</td>
<td>( l_z = 10°, \gamma = 0°, \alpha = 7° &amp; 14°, \lambda_{CF} = 0° )</td>
<td>TiAl4V</td>
<td>Osad (2016)</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>WC 3</td>
<td>–</td>
<td>1</td>
<td>( l_z = 5μm, \gamma = 0°, \alpha = 90°, \lambda_{CF} = 0° )</td>
<td>Brass</td>
<td>Egashira et al. (2011)</td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>WC 50</td>
<td>&lt; 1</td>
<td>1</td>
<td>( l_z = 70 μm, \gamma = 0°, \alpha = 30°, \lambda_{CF} = 0° )</td>
<td>Nickel</td>
<td>Yan et al. (2009)</td>
<td>2009</td>
<td></td>
</tr>
<tr>
<td>WC 100</td>
<td>–</td>
<td>1</td>
<td>( l_z = 10°, \gamma = 0°, \alpha = 10°, \lambda_{CF} = 0° )</td>
<td>–</td>
<td>Fleischer et al. (2004)</td>
<td>2004</td>
<td></td>
</tr>
<tr>
<td>Grinding WC 500</td>
<td>1.63...2.08</td>
<td>2</td>
<td>( l_z = 10°, \gamma = 0°, \alpha &gt; 0°, \lambda_{CF} = 30° )</td>
<td>TC4 alloy</td>
<td>Wang et al. (2018)</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>WC 10...50</td>
<td>&lt; 0.1</td>
<td>1</td>
<td>( l_z = 10°, \gamma = 0°, \alpha = 6°, \lambda_{CF} = 30°...50° )</td>
<td>Ti &amp; PMMA</td>
<td>Aurich et al. (2012)</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>WC 500</td>
<td>–</td>
<td>2</td>
<td>( l_z = 50 μm, \gamma = 45°, \alpha = 10°, \lambda_{CF} = 20° )</td>
<td>Tool steel</td>
<td>Li et al. (2011)</td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>WC 100</td>
<td>–</td>
<td>2</td>
<td>( l_z = 10°, \lambda_{CF} = 15° )</td>
<td>Tool steel</td>
<td>Ulhamann and Schauer (2005)</td>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>WC 100</td>
<td>–</td>
<td>1</td>
<td>D-type</td>
<td>Brass</td>
<td>Fang et al. (2003)</td>
<td>2003</td>
<td></td>
</tr>
<tr>
<td>WC 50</td>
<td>1...2</td>
<td>1</td>
<td>( l_z = 20°, \gamma = 0°, \alpha = 6°, \lambda_{CF} = 0° )</td>
<td>Stainless steel, brass</td>
<td>Schaller et al. (1999)</td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>FIB –</td>
<td>30</td>
<td>0.3</td>
<td>1</td>
<td>–</td>
<td>6061 Al</td>
<td>Xu et al. (2010)</td>
<td>2010</td>
</tr>
<tr>
<td>hard alloy</td>
<td>35</td>
<td>–</td>
<td>1</td>
<td>( l_z &lt; 2 μm, \gamma = 0°, \alpha &gt; 9.6°, \lambda_{CF} = 0° )</td>
<td>6061 Al</td>
<td>Zhang et al. (2009)</td>
<td>2009</td>
</tr>
<tr>
<td>HSS, WC</td>
<td>25</td>
<td>&lt; 0.1</td>
<td>2...5</td>
<td>( l_z = 90 μm, \gamma &lt; 0°, \alpha = 7°, \lambda_{CF} = 0° )</td>
<td>6061-T4, brass, steel, PMMA</td>
<td>Adams et al. (2001)</td>
<td>2001</td>
</tr>
<tr>
<td>WC 13</td>
<td>0.4</td>
<td>1</td>
<td>( l_z = 4 μm, \gamma &lt; 0°, \alpha &gt; 0°, \lambda_{CF} = 0° )</td>
<td>PMMA, 6061 Al</td>
<td>Adams et al. (2000)</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>HSS 25</td>
<td>–</td>
<td>2...5</td>
<td>( l_z = 2.2 mm, \gamma &lt; 0°, \alpha &gt; 0°, \lambda_{CF} = 0° )</td>
<td>PMMA</td>
<td>Vanile et al. (1996)</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>LBM</td>
<td>500...3000</td>
<td>&lt; 5</td>
<td>2</td>
<td>( l_z = 2...10 mm, \alpha = 20°...34°, \lambda_{CF} = 20°...32° )</td>
<td>–</td>
<td>Eberle et al. (2018)</td>
<td>2018</td>
</tr>
<tr>
<td>WC 100</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>( \alpha = 14.8° )</td>
<td>Cu</td>
<td>Hajiri et al. (2018)</td>
<td>2018</td>
</tr>
<tr>
<td>WC 50, 100</td>
<td>1.75...2.03</td>
<td>1</td>
<td>( \alpha = 14.8° )</td>
<td>Cu</td>
<td>Phiff et al. (2017)</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>WC 50...150</td>
<td>1...4</td>
<td>2.4</td>
<td>( l_z = 50 μm, \gamma = +, \lambda_{CF} = 30° )</td>
<td>Cu, WCu Current</td>
<td>2020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– information n/a</td>
<td>( \lambda_{CF} )</td>
<td>= clearance angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma )</td>
<td>= rake angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Tool trajectory calculation procedure; a) CAD model of desired tool shape; b) defining of material to remove; c) slicing operation; d) calculation of path trajectories; e) generation of NC-Code.
Bauerle (2000) observes that the HAZ can be signi
fl
tron subsystem to lattice cannot happen immediately. It depends on the
two-temperature model, in USP the energy transfer from the elec-
dissolved. Finally, the materials are liberated from the surface in the
form of plasma, as described by Campbell et al. (2005). According to
ablation allows the subsequent reduction of the tool blank diameter
below Ø < 200 μm.

3. Physical background

3.1. Ultrashort pulse laser ablation

Ultrashort-pulse laser ablation (USP) had proved to be a powerful
technique for the high accuracy and high-resolution micro-machining
of thermally conductive materials as well as dielectric materials. USP
mechanism involves nonlinear laser-matter interaction, electron ava-
lanche, and multiphoton ionization process, which enhances the loca-
ized material removal and improves the material processing possi-
bilities. The HAZ in a laser processed material is dependent not only on
the material parameters but also on laser fluence and pulse duration.
Bauerle (2000) observes that the HAZ can be significantly reduced by
using ultrashort pulses for machining. According to Cheng et al. (2013)
the shorter the pulse duration is, the smaller is the thermal effect. Also,
ultrashort pulses are capable of a melt free ablation while working at the
ablation fluence $F_{th}$.

Due to the extreme intensities of ultrashort laser pulses, the materi-
als absorb the incident laser light by multiphoton absorption and the
free electrons are excited into the conduction band. This excitation
generates a hot electron gas. The thermalization of this energy $\tau_e$
occurs between 10 fs to 1 ps. Bauerle (2000) describes that this energy
is delivered to lattice at a slower pace, typically of the order of 1–100 ps. This
causes ionization and the bonds between the atoms are dissolved. Finally, the materials are liberated from the surface in the
form of plasma, as described by Campbell et al. (2005). According to
the two-temperature model, in USP the energy transfer from the
electron subsystem to lattice cannot happen immediately. It depends on the
electron-phonon coupling strength. If the laser pulse duration $\tau_p$ is short
when compared to the duration of the thermalization of electron energy $\tau_e$, the hot electron gas causes the fracture and ablation by phase ex-
losion, while the lattice stays at low temperature, as explained by Leitz
et al. (2011). Campbell et al. (2005) further investigated that if the
ablated material redeposits on the surface, the surface will be cold
even enough to avoid bonding. This assures clean ablation with almost no
HAZ and a burr-free surface. For the machining of the micro-tools as-
associated with this paper, a pulse duration as low as $\tau_p = 1$ ps is used.
According to Neuenschwander et al. (2012), the optimal pulse duration
for precise machining is the sub-picoseconds. However, further reduc-
tion in the pulse duration can lead to reduced precision and unwanted
plasma effects. Furthermore, a better workpiece quality while using the
sub-picosecond pulse duration for machining is observed. Also. as
shown by Büttner et al. (2018), the depth $d$ of an ablated structure in
USP laser machining saturates after multiple pulses to a lower bound.

4. Tool manufacturing

4.1. Laser machine setup

An AMPHOS 200 laser is used for tool manufacturing, and the laser
setup is shown in Fig. 3a. This solid-state laser system generates wa-
velengths of $\lambda_1 = 1030\ nm$ and $\lambda_2 = 515\ nm$. The pulse duration
ranges from $\tau_p = 1\ ps$ to $\tau_p = 10\ ps$ at an average power of
$P_{max} = 200\ W$ for $\lambda_1$ and 150 W for $\lambda_2$. The pulse frequency $f_p$
ranges from 1 kHz up to 400 MHz. Retardation plates installed in the laser
beam path ensure a circular polarization. A variable beam expander is
used to adjust the beam diameter $d_{th}$. The laser beam is guided into an
Intelliscan 14 scan head, which deflects the beam along the U- and V-
axis with a speed of up to $v = 2000\ mm/s$ in the working plane. The
laser beam is focused to a spot diameter $d_{th} < 10\ \mu m$ using F-Theta
lenses with a focal length of 65 mm. The workpiece is positioned via the
mechanical X- and Y-axis while the linear Z-axis places the scanner and
thus the focal plane. As shown in Fig. 3b, the tool blank is clamped in the
rotational A-axis, of the type APR150 from Aerotech. A RENISHAW
NC4 laser probe and a Dino-Lite Edge microscope camera are applied to
analyze the tool blank during the process. The tool blanks are ground
and have a diameter $\Omega = 2.5\ mm$ at the cutting region. Tangential laser
ablation allows the subsequent reduction of the tool blank diameter
below $\Omega < 200\ \mu m$. 

![Fig. 2. micro-tool manufacturing procedure; a) radial ablation of chip flute; b) rotation along A-axis; c) tangential shaping of minor cutting edges; d) tangential shaping of major cutting edges; e) tangential reduction of diameter.](image1)

![Fig. 3. Laser setup; a) laser beam guidance; b) machining space.](image2)
4.2. Parameter study

USP laser processing of brittle materials requires an accurate and agile experimental investigation. The laser process is defined by many process parameters, such as pulse frequency $f_p$, pulse energy $E_p$, scanning speed $v_s$, pulse overlap $U_p$, line overlap $U_l$, and layer thickness $L_T$. These parameters influence independently from each other the resultant quality. The purpose of the investigation is to evaluate the effect of the parameters on the resultant form accuracy, cutting edge geometry, cutting edge radii $r_e$ and roughness $R_a$. The tool blank is made of tungsten carbide (WC) and has a composition of 12 % Cobalt (Co) and 88 % tungsten carbide (WC) with a grain size of $d_g = 0.1 \mu m$. The wavelength is set to $\lambda = 515 \text{ nm}$. A parameter study is conducted on the tool blank to select the optimum parameters for tool manufacturing. The study is executed by ablating a structure, consisting of two geometries: a V-notch to analyze the achieved depth of ablation $d$ and a chip flute to evaluate the machining quality, as shown in Fig. 4a. In Fig. 4b and c, the ablated portions on the blank with two different parameter sets are shown. Fig. 4c has good geometrical surface quality when compared to Fig. 4b. The time taken for laser processing is appreciable.

The study revealed that the parameters scanning speed $v_s$, pulse energy $E_p$ and line overlap $U_l$ have a significant influence on the resultant quality. By reducing the scanning speed $v_s$ and increasing the line overlap $U_l$, while decreasing the pulse energy $E_p$, an improvement of the machining resolution is observed. Due to the decrease of the pulse energy $E_p$, thermal damage introduced by heat accumulation at higher line overlap $U_l$ can be avoided.

4.3. Manufactured micro-tools

By using the optimized laser process parameters, the manufacturing of a tool having a diameter as low as $\theta = 50 \mu m$ is feasible to manufacture. Fig. 5a-f presents representative tools with diameters $\theta = 150...50 \mu m$ holding up two respectively four cutting edges. The diameter along the protruding length $l_p$ is divided into two sections. The diameter $D_e$ at the cutting region of the tools is larger than the diameter $D_0$ at the region between cutting edges and the neck of the tool, as described in Fig. 5g. All tools are cleaned after manufacturing; however, pollution of the tools is visible, as shown in Fig. 5a and c.

4.4. Validation

4.4.1. Heat affected zone

A significant reduction in the quality and the lifetime of the cutting tool is expected to be caused by the generation of the heat-affected zone (HAZ) during laser processing. To characterize the HAZ, a cross-section of the cutting edge of the tool is generated using Focused Ion Beam (FIB). Edge preparation using other methods, like grinding, polishing, or wire-EDM, causes edge rounding and diffusion. Besides, the exposed surface may be adversely affected by the introduced heat and residual stresses by the preparation process. For FIB, an exemplary tool produced with optimized process parameters is located in an SEM in such a way that one cutting edge is oriented upright. To support the exposing of the cutting edge, a diamond-like carbon (DLC) layer is deposited on the surface. Fig. 6a shows a ground micro-tool having a diameter of $\theta = 200 \mu m$. The two cutting edges exhibit a positive rake angle $\gamma$. Due to the grinding process, a texture is visible along the grinding direction, as shown in Fig. 6a and b. A smooth surface with a low roughness $R_a$ can be expected. In Fig. 6b, the cutting edge exposed by FIB is presented. In the cross-section, the WC appears as bright grains, and dark regions in between the grains indicate Co-binder. No visible HAZ can be detected. Fig. 6c illustrates a laser-ablated micro-tool having a diameter of $\theta = 200 \mu m$. The four cutting edges exhibit a negative rake angle $\gamma$. The curved surface area (region I) is ablated in a tangential direction and defines the clearance face. In contrary, the chip flute (region II) is ablated in a radial direction and defines the rake face. The surfaces of laser-processed micro-tools exhibit a rather rougher surface compared to ground tools, as shown in Fig. 6d. Besides, a difference between the surface when ablated in tangential and radial direction can be identified. Unlike the clearance face, the rake face reveals a stepped structure in the sub-micrometer scale. However, both surface structures are unambiguously affected by the laser. As the binder requires a lower threshold fluence $F_{th}$ for ablation compared to WC, it is removed primarily. Furthermore, it is observed, that at the surface, the binder is completely removed. This indicates that the surface only consists of WC grains and reveals enlargement of the roughness $R_a$. Additionally, when machining in radial orientation, the heat accumulates to a greater extent, as the energy is absorbed almost completely by the material along the direction of propagation of the laser beam. In comparison, the energy in tangential machining is directed into the removing material. Hence, a higher surface quality can be expected. However, for both cases, it can be inferred that the thickness of the HAZ is below $t_{HAZ} < 100 \text{ nm}$.

4.4.2. Form deviations

An Alicona microscope is used for the measurements of the laser-processed micro-tools. The rotational 3-D scan is performed with an automated external rotatory and swiveling axis. The microscope allows highly precise non-contact measurements. Also, it is capable of obtaining 3-D measurements of the cutting tools and cutting edges for quality control purposes. Features below 3 $\mu m$ can be displayed with high resolution. In addition to the 3-D data, the measurement device also delivers false-color information for each measurement position, which is linked to the height data. For verification of form deviation, a difference measurement is used to compare the laser-processed tool and the CAD model. Fig. 7 presents the form accuracy of three selected cases. The false-color indicates deviations to the desired micro-tool geometry.

In Fig. 7a, the cutting portion of a tool having a diameter $\theta = 150 \mu m$ and two teeth is seen. By overlapping the 3-D scan with the
CAD model, form deviations are visible. However, the deviations adopt values smaller than 10 μm along the cutting edges, as this region is machined by tangential ablation. The most considerable form deviations are located in the chip flute region and adopt values up to 10 μm, due to the radial ablation. However, as the chip flute does not contribute to the cutting process, the deviations are considered negligible. The cutting edges are in great concordance to the desired geometry. It is feasible to reproduce a distinct and positive rake and clearance angle. Due to the USP-laser process, flawless cutting edge radii $r_c$ are realizable to replicate. In Fig. 7b, the cutting portion of a tool having a diameter $\Theta = 200 \mu$m and four teeth is seen. In concordance with the other tools, the main deviations are located in the chip flute. The comparison proves that the CAM-system is capable of replicating micro-tools featuring multiple major and minor cutting edges. In Fig. 7c, the overlap of two cross-sections of a laser-processed tool and a CAD model is shown, which allows a more detailed analysis of the cutting edges. Based on this, the cutting edge dimensions, such as rake angle $\gamma$ and clearance angle $\alpha$, match with the desired geometry. Furthermore, a
good agreement was found when comparing the contours and diameters.

4.4.3. Roughness and cutting edge radius

As the removed material is transported along with the chip flute during machining, the roughness Ra in the flute is a crucial factor and significantly depends on the laser process parameters. The higher the pulse energy $E_p$ and the longer the process duration is, the higher the roughness Ra becomes. The radial ablated chip flute surface is evaluated for tools with the diameters $\Theta = 150, 100,$ and $50 \mu m$ and the results are summarized in Table 2. The optical measurement of the roughness Ra and cutting edge radius $r_c$ is performed using the Alicona microscope. Due to the relatively low material removal and thus low machining duration when reducing the tool diameter, the tool having a diameter as low as $\Theta = 50 \mu m$ reveals the lowest roughness Ra. Due to the superb surface quality in the grinding process, the roughness Ra of a tool diameter as low as $\Theta = 50 \mu m$ is analyzed by $50 \mu m$ to $2.7 \pm 0.5 \mu m$. These can adopt values up to $F = 1.5 N$ when choosing a depth and with of cut $a_p = a_d = 30 \mu m$ in combination with a cutting speed $v_c = 50 m/min$ and a feed rate $v_t = 540 mm/min$. To avoid tool breakage, process parameters are selected according to Table 3. For Cu and WCu and for laser-processed and ground tools, the same parameter combinations are chosen. Before each milling experiment, the tool run-out was measured. This can be performed by a measurement procedure using the laser micrometer bridge of the machine, while the tool is rotating. Due to the negligible forces in laser ablation, the run-out error adopts values for tools with $\Theta = 150 \mu m$ to $2.7 \pm 1 \mu m$, for $\Theta = 100 \mu m$ to $1.7 \pm 1 \mu m$ and for $\Theta = 50 \mu m$ to $0.7 \pm 0.5 \mu m$; however, the ground tools have an error to $8 \pm 1 \mu m$.

The milling experiments are conducted on a 5-axis-machining center of the type HSM 200 U LP from Georg Fischer Machining Solutions (GFMS). A Levicron spindle provides a rotation speed up to $n_{max} = 90,000$ rpm. The spindle is designed with an air bearing and cooled with liquid coolant to maintain a constant temperature and reduce expansion. The HSK-25 interface is capable of clamping tools with a tool shank of $\Theta = 3 \ mm$. The experiments are supported by a minimum quantity lubrication (MQL) system. Tool diameter and length are detected by an M&H laser micrometer bridge, which allows the measurement of tools with a diameter down to $25 \mu m$ with a measurement uncertainty of $0.2 \mu m$.

Micro-bars with a width $W_b = 50 \mu m$, height up to $H_b = 270 \mu m$ and length $l_b$ to $6$ are realizable. In consequence, micro-structures having a small pitch distance $P$ and a large height $H$ are feasible to machine. Micro-structures with high aspect ratios are commonly needed in micro-die-sinking EDM. Hence, Cu and WCu are chosen as workpiece materials, as these are used for electrodes. In micro-milling, process forces and tool run-out are crucial factors, as these may lead to tool damage. Böttner et al. (2019) measured process cutting forces $F$ when micro-milling Cu and WCu using ground tools with a diameter down to $\Theta = 200 \mu m$. These can adopt values up to $F = 1.5 N$ when choosing a depth and with of cut $a_p = a_d = 30 \mu m$ in combination with a cutting speed $v_c = 50 m/min$ and a feed rate $v_t = 540 mm/min$.

5. Micro-milling experiments

To demonstrate the performance of the laser-processed tools, micro-milling experiments are conducted. Due to small tool diameters having a large protruding length $l_p$, extreme aspect ratios of tool diameter to length $l_p$ up to $6$ are realizable. In consequence, micro-structures having a small pitch distance $P$ and a large height $H$ are feasible to machine. Micro-structures with high aspect ratios are commonly needed in micro-die-sinking EDM. Hence, Cu and WCu are chosen as workpiece materials, as these are used for electrodes. In micro-milling, process forces and tool run-out are crucial factors, as these may lead to tool damage. Böttner et al. (2019) measured process cutting forces $F$ when micro-milling Cu and WCu using ground tools with a diameter down to $\Theta = 200 \mu m$. These can adopt values up to $F = 1.5 N$ when choosing a depth and with of cut $a_p = a_d = 30 \mu m$ in combination with a cutting speed $v_c = 50 m/min$ and a feed rate $v_t = 540 mm/min$.

### Table 2

Comparison of roughness Ra in the chip flute for different micro-tools.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Properties</th>
<th>Removed material per flute</th>
<th>Machining time per flute</th>
<th>Roughness Ra</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>$\Theta = 50 \mu m$, Teeth = 4</td>
<td>$2.95 \times 10^{-5} [mm^3]$</td>
<td>$16.07 s$</td>
<td>$0.18 \pm 0.03 \mu m$</td>
</tr>
<tr>
<td>#2</td>
<td>$\Theta = 100 \mu m$, Teeth = 4</td>
<td>$2.0 \times 10^{-5} [mm^3]$</td>
<td>$123.8 s$</td>
<td>$0.24 \pm 0.02 \mu m$</td>
</tr>
<tr>
<td>#3</td>
<td>$\Theta = 150 \mu m$, Teeth = 2</td>
<td>$1.0 \times 10^{-5} [mm^3]$</td>
<td>$619.26 s$</td>
<td>$0.75 \pm 0.18 \mu m$</td>
</tr>
<tr>
<td>#4</td>
<td>$\Theta = 150 \mu m$, Teeth = 2</td>
<td>–</td>
<td>–</td>
<td>$0.13 \pm 0.04 \mu m$</td>
</tr>
</tbody>
</table>

### Table 3

Parameters when conducting micro-milling experiments with laser-ablated and ground tools.

<table>
<thead>
<tr>
<th>Feed per tooth $f_t$</th>
<th>3 $\mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate $v_t$</td>
<td>540 mm/min</td>
</tr>
<tr>
<td>Cutting speed $v_c$</td>
<td>40 m/min ...15 m/min</td>
</tr>
<tr>
<td>Spindle Speed $n$</td>
<td>90,000 rpm</td>
</tr>
<tr>
<td>Width of cut $a_w$</td>
<td>5 $\mu m$</td>
</tr>
<tr>
<td>Depth of cut $a_d$</td>
<td>5 $\mu m$</td>
</tr>
</tbody>
</table>

Fig. 8. Comparison of cutting edge radii $r_c$ for different tool diameters for laser-processed and ground tools.

![Fig. 8](image-url)
negligible low run-out, steep flanks, and a constant width of bars and pillars $W_{P,B}$ is guaranteed. The high aspect ratio of the tools allows tight pitches of bars and pillars $P_{P,B}$. The tools are capable of machine ductile materials, such as Cu, and brittle materials, such as WCu.

6. Conclusions

The fabrication of flawless micro-milling tools using USP-laser ablation in combination with a multi-axis CAM system is discussed. It is found that the choice of laser parameters profoundly influences the tool quality. The most crucial factors besides others are: pulse duration $\tau_p$, scanning speed $v_s$, pulse energy $E_p$, and line distance $d_l$. Tools made of WC with diameters down to $\varnothing = 50 \mu m$ and a protruding length $l_p = 300 \mu m$ are possible to machine. Additionally, due to negligible process forces during tool manufacturing, mechanical damage can be avoided leading to a high form accuracy and low run-out error. Besides, extreme aspect ratios of protruding length $l_p$ to diameter are feasible. Using a CAM-system enables the realization of multiple teeth, defined rake angles $\gamma$, and tools with different chip flute angles $\lambda_{CF}$. The laser setup and CAM-system enables a reliable alternative tool manufacturing compared to grinding. Following conclusions can be summarized:

- Laser machining of micro-tools introduces negligible process forces, thus mechanical damage can be avoided, and tool run-out error reduced. For this reason, form accuracy of the tool and thus on the resultant workpiece structures are more accurate in comparison to ground tools.
- By a combination of radial and tangential laser ablation, the same tool geometry as ground tools is realizable to machine by having a laser machine setup consisting of 4 mechanical and 2 optical axes.
- USP-laser ablation leads to non-measurable thermal damage. Therefore, no HAZ is detectable.
- The quality of a laser-processed tool does not only depend on the laser parameters and machining strategy but also significantly on the tool diameter $D_c$. As less material is removed when manufacturing a small tool after tool blank roughing, compared to a larger tool, the machining duration is lower. Hence, less interaction between tool and laser is required.
- Micro-milling experiments proved the high performance of laser-processed tools. Due to the high aspect ratio of the tools, micro-structures with low pitch distances and larger heights can be produced. The tools are capable of machining ductile material, such as Cu, and brittle material, such as WCu.

CRediT authorship contribution statement


Declaration of Competing Interest

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

References

Aperture Micro Scanning System. SPIE.