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Laser manufacturing of carbide micro milling tools

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Abstract

Pulsed laser ablation is increasingly being used for the manufacturing of cutting tools, both with undefined and defined cutting edges. The machining of cutting inserts made of ultra-hard material with pulsed lasers is an industrially established process, while the production of more complex geometries, such as fluted tools is being developed. Ultrashort-pulsed laser processes, contrary to conventional tool manufacturing processes, are not based on the mechanical removal of material and are thus free of wear or cutting forces. Especially for the production of micro tools are cutting forces detrimental: the resulting deformations need to be compensated and can lead to tool failure during production. The absence of forces make laser processing an interesting alternative to the grinding of micro tools.
In this paper, processes for manufacturing carbide micro cutting tools with defined cutting edges using an ultra-short-pulsed laser are detailed. Processing strategies to machine a tool using a setup consisting of four mechanical and two optical axes are developed. Tungsten Carbide (WC) single-edge micro milling tools-with Ø 200 µm-are machined using a laser source (τ_p<12 ps, λ= 532 nm) with an average power of P_{max}= 4 Watt. By using self-limiting laser ablation finishing processes, high surface quality and geometrical accuracy are achieved. No significant thermal damage of the material by the laser processes can be observed. Milling experiments in low alloyed copper with the laser produced tools demonstrate the applicability of such technology for the manufacturing of WC micro milling tools.

Keywords: ultrashort-pulse laser ablation; carbide micro milling tools; tungsten carbide; tangential laser processing

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1. Introduction

The demand for miniaturized devices has been rapidly growing. Exclusively needed in the watch industry a couple of centuries ago, miniaturized devices can now be found in a wide variety of fields ranging from electronics to optics or medicine. Micromachining, because of its high efficiency, accuracy and low cost compared to other micro processing technologies, still is one of the main technologies used for the manufacturing of microproducts as described by Liu et al., 2013. According to Masuzawa, 2000, micromachining is defined as the machining of workpiece features comprised between 1 and 500 µm, by extension cutting tools with a diameter <500 µm can be considered as micro cutting tools. In general, such tools are made from WC and machined using grinding wheels with micrometer-sized diamond grains. Although ground tools with diameters as small as 10 µm are commercially available, the processing forces and vibrations are detrimental to the process' robustness as described by Spath et al., 2002. The grinding forces lead to a positioning error and finally inaccurate tools. Zdesbski, 2012, measured Ø200 µm ground and uncoated tools from the same batch to find the average diameter to be Ø183 ± 8 µm. Alternatively, force-free processes, such as Focused Ion Beam (FIB) machining or Electro Discharge Machining (EDM) have been used to machine micro tools. According to Adams et al., 2001, FIB presents the advantage of having a high accuracy and a very small unit removal and is therefore suited for the machining of micro cutting tools. However, because of the small material removal rate, it is not suitable for industrial production. EDM also presents the advantage of small unit removal - with wires as small as 10 µm available - but the removal mechanism is based on the melting and vaporization of the workpiece material which typically leads to a heat-affected zone, as reported by Zdesbski, 2012.

In this paper the potential for machining WC micro milling tools by laser is experimentally evaluated. The single-edge micro milling tools, with Ø 200 µm, are machined using a laser source with pulse lengths $\tau_P \leq 12$ ps and a wavelength of $\lambda = 532$ nm. To evaluate the machining quality, the geometrical accuracy of the tools and the thermal damaging of the material are assessed. Milling experiments in copper with the laser produced tools are performed to evaluate the applicability of such processing for the manufacturing of WC micro milling tools.

2. Laser machining process

2.1. *Laser machining setup*

The tools are produced using a Time Bandwidth Duetto laser emitting at a wavelength of λ= 532 nm. This ultrashort pulsed solid-state laser produces pulses with a width of $\tau_P \leq$ 12 ps, at an average power of up to P_{max}= 4 W and with a frequency ranging from 50 kHz to 8.2 MHz. Retardation plates placed in the laser path ensure a circular polarization. A variable beam expander is used to adjust the beam diameter. The laser beam is guided into a galvanometer scanner deflecting the beam along the U- and V-axis with a speed of up to 2000 mm/s in the working plane. The beam is focused to a spot of a few micrometers using an F-Theta lens with a focal length of 163 mm. The workpiece is positioned via three mechanical axes (X', Y', B') while the linear Z- axis positions the scanner and thus the focal plane. A multi-axis machine controller is used to control the four mechanical and two optical axes synchronously. The schematic representation of the experimental setup can be found in Fig. 1. The micro milling tools are produced from EMT210 blanks from Extramet AG with a diameter of Ø 300 µm. The composition of this submicron grade tungsten carbide can be found in Table 1.

Table 1. Laser parameters and information about the cemented carbide grade used

Laser parameters		Composition EMT 210	
Wavelength [nm]	532	WC [%]	89
Pulse duration [ps]	≤ 12	Co [%]	10
Beam quality M^2	<1.2	Other carbides [%]	1
Fluence [J/cm^2]	6.4	Avg. grain size [µm]	0.8
Polarization	Circular		

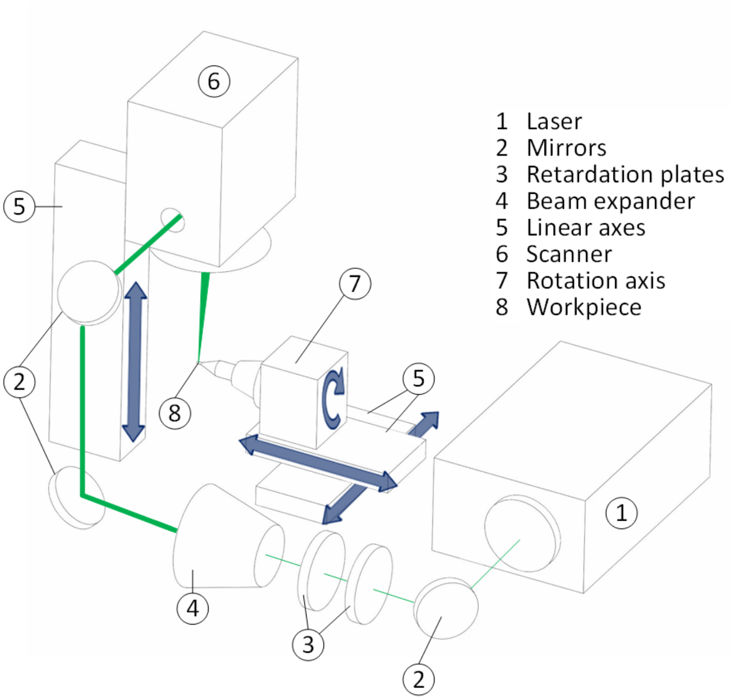

Fig. 1. Laser machining setup

2.2. *Machining of the tools*

The tool, with a rake angle of 0 ° and a clearance angle of 15 °, is designed to be machined using a combination of the two optical axis and only four mechanical axes. The machining is divided in five consecutive processing steps, which can be partially seen in Fig. 2:

1. diameter reduction
2. machining of the rake face
3. machining of the tip
4. machining of radial clearance

5. machining of the flank face

Each of these steps is processed using tangential laser processes, as described by Warhanek et al., 2016. Such laser processing, associated with an ultrashort- pulsed laser leads to very low thermal damage of the material, as shown by Butler-Smith et al., 2016, and a precise machining and high surface quality compared to conventional orthogonal laser processing

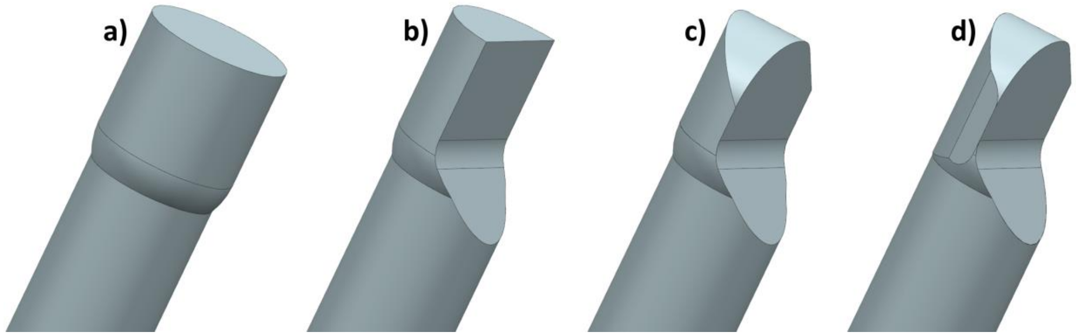

Fig. 2. From left to right, the successive processing steps towards a micromilling tool: (a) After the diameter reduction; (b) After machining the rake face; (c) After machining the tip; (d) The completed tool after creating the radial clearance and the flank face.

The material is removed by a combined movement of the mechanical and optical axes. The optical axes deflect the focal spot in a repetitive motion, called a scanpath. By moving in successive steps the blank into the scanpath with the mechanical axes, the material is removed. This process can be compared to a grinding process with the scanpath reproducing the grinding wheel's profile. For reduction of the tool diameter, as in steps 1 and 4, the focal plane is set on the tool's axis. By successive infeed steps, the tool is moved into the scanpath while rotating, until the tool reaches the set diameter. For the machining of the rake and flank faces, the surface to produce is tilted and a combined X, Y and Z movement of the mechanical axes moves the scanpath parallel to the surface to machine. Through successive infeed steps in Y direction, all excess material is removed. The tip is processed similarly, but the surface cannot be tilted. The clearance angle α at the tip thus cannot be influenced; it is determined by the angle of the cutting kerf.

The optimal tilt angle δ is determined experimentally, by studying the surface quality of surfaces machined under 0 °, 4 °, 7 °, 11 ° and 15 °. The results are analyzed optically using an incident light microscope. As can be seen on Fig. 3, processing with tilt angles < 7 ° lead to poor result, with the bottom part of the surface not being ablated. This is due to the combined effects of the shadowing of the caustic, the higher projection surface of the beam and the higher incidence angle. Higher tilt angles lead to fully-cut surfaces since more of the incident light is coupled into the material. The surface tilted with 7 ° shows the best surface quality. Processing of the rake and flank faces is thus done under 7 ° tilt.

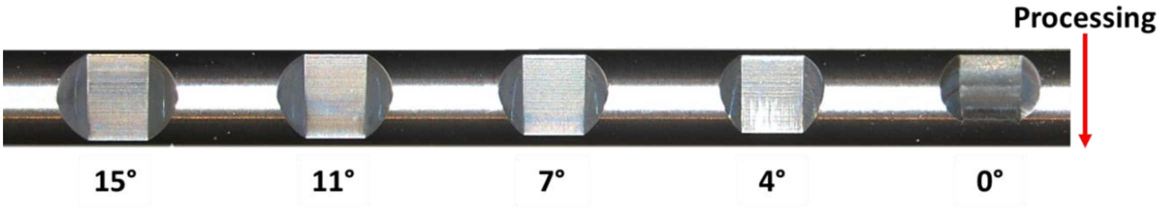

Fig. 3: surfaces machined by laser with incidence angles o 15°, 11°, 7°, 4° and 0°

3. Assessment of the machining

3.1. *Measurement of the tools*

Four identical tools were produced and 3D-surface measurements of the tools were conducted using an Alicona Infinite Focus microscope equipped with a Real 3D rotation unit. The rake face, flank face and cutting edges at the flank and tip are measured with a 100x objective and an estimated vertical resolution of 10 nm. 50 profiles with a length of 80 µm are extracted along the cutting edge, filtered with a cutoff length of λ_c=250 µm and averaged to determine the surface roughness Ra on the rake or flank face respectively. Because of the short measurement length, the surface roughness cannot be determined according to standard ISO 4288. Table 2 sums up the geometrical measurements of the tools. The clearance angle on the flank of the tool is found to be 14.8 ° ± 3 %, while the clearance angle at the tip is 3.78 ° ± 7 %. The cutting edge radii of 1.75 µm and 2.03 µm on the flank and tip respectively are close to the minimum measurable with the Alicona microscope and should be considered with caution. Surfaces machined by tangential laser processing exhibit a surface roughness Ra measured below 100 nm. Such low surface roughness is due to the self-limiting laser ablation finishing regime, caused by the processing under high incidence angle, as described by Tokarev et al., 1995.

Table 2. Results of the geometrical measurement of the tools

	Flank					Tip		
	r_{peak} [µm]	α [°]	γ [°]	$Ra_{clearance}$ [nm]	Ra_{rake} [nm]	r_{peak} [µm]	α [°]	γ [°]
Tool 1	1.65	15.2	0	35	40	2	3.5	0
Tool 2	1.7	14.7	0	58	70	1.7	4	0
Tool 3	1.65	14.4	0	64	40	1.9	4	0
Tool 4	2	15	0	109	20	2.5	3.6	0
Average	1.75	14.83	0	66.5	42.5	2.03	3.78	0

SEM analyses of the cutting tools, see Fig. 4, show no presence of material damaging by the laser process. Neither oxidized nor molten material can be found. Detailed views show no break-outs at the cutting edges. In contrary to grinding were WC grains are pulled out, or to EDM where the Cobalt is preferentially removed, laser processing ablates both Cobalt and WC alike, leading to smooth cutting edges. Cut WC grains can be clearly discerned on the flank face at the tip, in Fig. 4 b).

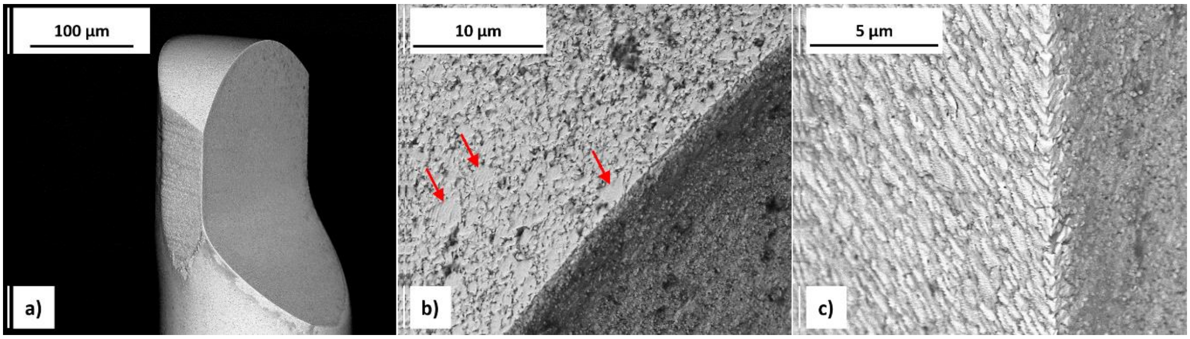

Fig. 4. BSE micrographs of a laser machined Ø 200 µm micro milling tool. (a) Tip of the micro cutting tool; (b) Detail of the cutting edge at the tip; (c) Detail of the cutting edge at the flank. Red arrows indicate some of the discernable cut grains

By scaling down the processes, microcutting tools with Ø 100 µm and Ø 50 µm are produced. SEM micrographs of the tools can be seen in Fig. 5. The cutting edges at both the flank and tip of the Ø 100 µm tool are still well defined, but the rake and clearance faces do not join on the flank of the Ø 50 µm tool and first signs of heat-affected zone can be found. Redeposited molten debris is found at the edges of the Ø 50 µm tool. Such debris could be detrimental for the adhesion of a coating of the tool.

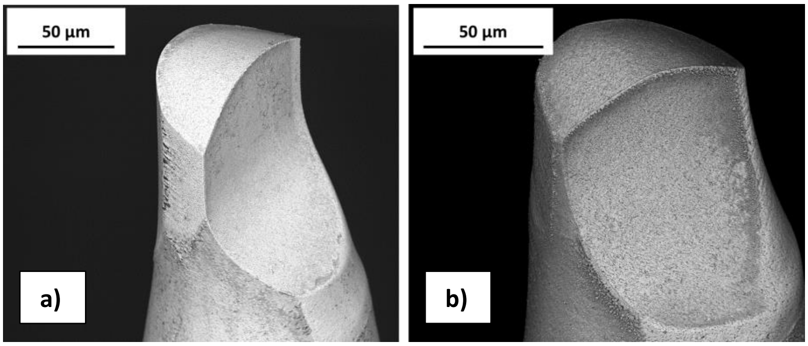

Fig. 5. BSE micrographs of laser machined micro milling tools. (a) Ø 100 µm tool; (b) Ø 50 µm tool

3.2. *Milling trials*

The laser produced tools with Ø 200 µm are tested in a series of up-milling experiments on Cu-ETP copper. The dry milling experiments are done on a modified Mikron HSM 400U five axes milling machine with a high-speed Mach200-00 spindle from Machswiss. Processing forces are measured on an internally developed MicroDyn, a three component process force dynamometer using Kistler Piezos as described by Transchel et al., 2012. The forces are averaged over 10 milling passes. The long term behavior of the tools is studied by measuring the processing forces throughout the lifetime of the tools using the parameter sets listed in Table 3.

Table 3. Milling parameters

Parameter set	P1	P2	P3	P4
Feed rate, v_f [mm/min]	286	382	286	300
Cutting speed v_c [m/min]	120	120	120	126
Depth of cut, a_p [µm]	140	140	140	140
Width of cut, a_e [µm]	5	5	8	5
Length of pass [mm]	15	15	15	15

The processing forces as a function of the number of paths milled are plotted in Fig. 6. The reference parameter set, P1, was used to machine 120 paths. Both normal and feed forces grow rapidly over the 20 first paths milled to reach 0.6 N and 0.2 N respectively. The passive force increases rapidly over the 60 first paths up to 2.3 N. The high passive force indicates that the clearance angle at the tip is not sufficient. The forces of processing parameters P2 and P3 show similar trends, with a rapid growth of the forces up to the breakage of the tools, after 24 and 35 paths respectively. The passive forces of parameter P4 increases steadily over 300 paths to reach 0.7 N. Both normal and feed forces grow rapidly over 20 paths to reach 0.75 N and 0.5 N respectively. After 70 paths, both processing forces drop to 0.1 N, indicating that the tools are not cutting anymore. Parameter sets P1 and P4 show a not expected and yet not understood behavior of dropping normal and feed forces. Further investigations have to be done to determine the causes. Nevertheless, the milling experiments prove that the laser-manufactured carbide micro milling tools are able to cut low alloyed copper.

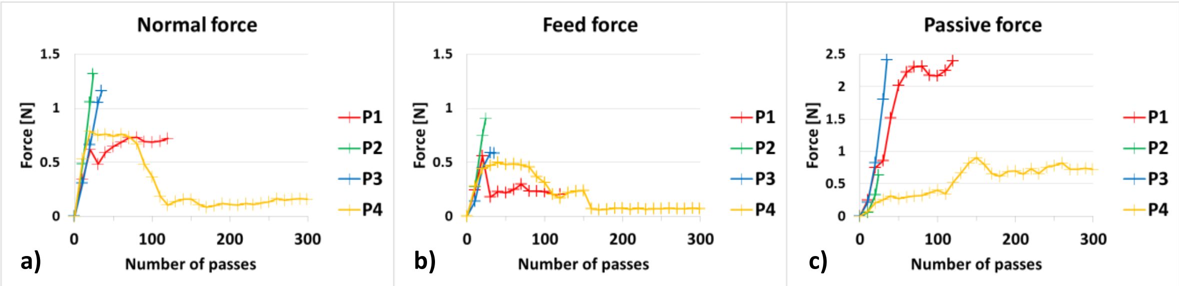

Fig. 6. Averaged processing forces as a function of the number of paths. (a) Normal forces; (b) Feed forces; (c) Passive forces

4. Conclusion

In this paper an alternative micro milling tool manufacturing process using ultrashort pulsed laser ablation is presented and evaluated. By using four mechanical and two optical axes, tools with a diameter Ø 200 µm, Ø 100 µm and Ø 50 µm were produced. The Ø 200 µm tools were produced with good repeatability and accuracy. Sharp cutting edge radii, under 2 µm, and good surface quality, Ra roughness under 70 nm, were achieved. SEM investigations showed no visible heat-affected zone. Milling experiments on Cu-ETP copper demonstrate the applicability of laser processing for the machining of micro cutting tools. A higher clearance angle at the tip could have led to improved machining performance. Laser processing on a 5 axes setup would enable the machining of higher clearance angles at the tip. By scaling down the developed tangential laser processes, tools with diameters of Ø 100 µm and Ø 50 µm were machined. By further reducing the focal spot and optimizing the laser parameters, machining of cutting tools under Ø 100 µm without heat damage should be feasible.

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