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Laser micromachining of biomimetic structures with ultrashort laser pulses for passive transport of lubricants in milling tools

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Abstract

During the milling of metals, a minimum quantity of lubricant has to be guided to the cutting edge of the tool. In the framework of this work, this fluid transport is passively implemented by the capillary effect like it is present in the open microfluidic systems of various natural materials. One promising approach for the fabrication of microchannels is micromachining with ultrashort laser pulses. In the present work, using ultrashort laser pulses, such biomimetic microchannels for passive transport were micromachined on cemented tungsten carbide. The biomimetic microchannels provide a hierarchical structure consisting of a wide channel with a width of 450 µm and subchannels with a width of 50 µm. To evaluate the lubricant transport, flow velocity measurements of structures of different depths were performed. The biomimetic structure with a total depth of 200 µm shows very promising results with a maximum flow rate of 0.35 mm³/s.

Keywords: Laser micromachining; grooves; microchannels, ultrashort laser pulses; fluid transport

1. Introduction

The pitcher plant Sarracenia attracts insects to slide down their smooth funnels and digest them inside. According to Chen et al. 2018 hairs called peristomes, located on the border of the pitcher or tube, have micro-channels that transport water, creating a slippery film for insects to slide on. The continuous water transport from the inner to the outer border of the pitcher on the peristome causes the formation of the liquid film.

The wetting of the cutting edge of a milling tool with lubricants during the mechanical milling process is essential for obtaining workpieces of high quality. For economic and ecological reasons, minimum quantity lubrication is often sought in mechanical manufacturing processes. Furthermore, in addition to conventional lubricants based on fatty alcohols, water-based lubricants are also used in the production of fluidic transport systems. Such fluidic systems can be implemented into the milling tool by laser micromachining to support minimum quantity lubrication of water-based lubricants. Channels with trapezoidal and V-shaped cross-sections can be realized by reducing the number of parallel lines with an increasing number of scans. As shown in Holder et. al. 2022 laser micromachined grooves typically exhibit a V-shape in the cross-section and no ideal vertical walls of a capillary can be created. Therefore, generating cavities with a defined width by using a certain number of parallel lines leads to a trapezoid shape in the cross-section. As the depth of the cavity increases, it eventually forms a V-shaped cross-section.

Additionally, micromachining with ultrashort laser pulses is a useful method to produce surface structures in the micro- and laser-induced surface structures in the nanometer range, as presented by Furmanski et. al. 2007 and by Placzek et. al. 2022, respectively. Laser-induced (periodic) surface structures, such as LIPSS, Grooves, and Bumps, are known for their influence on the wettability of a surface. Such characteristics may additionally favor the transport of liquids in microchannels, which were manufactured by means of ablation with ultra-short laser pulses

This technology to manufacture surface structures allows the biomimetic approach to produce fluid transport structures following the Sarracina plant on the surface of materials used for machining tools.

The aim of this work is to create such biomimetic structures, which enhance the transport of lubrication liquids in minimum quantities.

2. Methods

The experiments were conducted with the ultrafast laser system Duetto from Time-Bandwidth, which emits laser pulses with a wavelength of 1064 nm and a pulse duration of 10 ps. The laser beam provided a Gaussian intensity distribution with circular polarization and a beam quality factor of $M^2 < 1.3$. The beam was scanned over the sample surface with a Galvanometer-Scanner and focused by an F-Theta lens with a focal length of 80 mm. The resulting diameter of the beam waist was $d_0 = 30 \pm 2$ µm. For all experiments, the beam waist was set on the surface of the sample.

The TC-Co sample (DK460UF from Gühring) consists of 90 % tungsten carbide and 10 % cobalt. The tungsten carbide grains have a grain size of 0.65 µm. The samples had a length of 60 mm, a width of 14 mm, and a thickness of 14 mm. The sample surface was mechanically polished to a surface roughness of $R_a = 0.1$ µm before structuring.

The cross-section of the biomimetic transport structure (green) according to the model of the Sarracenia plant is shown schematically in Figure 1. The biomimetic transport structure consists of a wide channel (light green) and five subchannels (dark green).

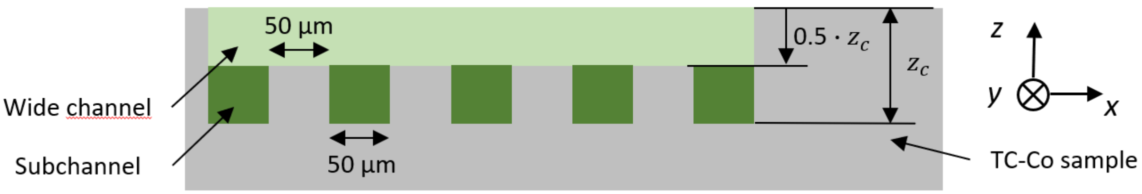

Fig. 1. Schematic representation of the hierarchic structures according to the model of the Sarracenia plant.

Channels with a length of 35 mm were generated on the samples by means of laser ablation with ultra short pulses. The scaling of the channels, meaning the adjustment of the width and the depth of the channels, was adjusted by varying the number of scanned lines in x-direction, and the depth of the channels was adjusted by the number of scans, respectively. The distance between each line, the hatch distance in x-direction, was set to 6 µm. Additionally, cavities were micromachined on both ends of each channel as an inlet and an outlet to simplify the placement of a droplet of lubricant and to evaluate the flow velocity of the channels.

The channels were machined ablated with a pulse energy of 21.5 µJ and a scan velocity of v_s = 1500 mm/s. With a constant repetition rate of f_{rep} = 500 kHz and a focal diameter of d_0 = 30 ± 2 µm this leads to a pulse overlap in x direction of about $O_{p,x}$ = 90 %.

In order to quantify the functionality of the transport structures, flow velocity measurements were performed. For this, a 5 µL drop of the fluid was deposited at the inlet, and the fluid flow from the inlet area via the different transport structures to the outlet area is recorded by a camera. The flow velocity of the individual transport structures can be determined using programs for image analysis.

3. Results

Figure 2 shows the resulting flow velocity for the lubricant based on fatty alcohol (FA, purple) and for the water-based lubricant (WBL, blue) as a function of the travel distance in the biomimetic channels with different depths. A measurement uncertainty of 10 % is considered and illustrated by error bars. A decrease in the flow velocity can be observed with increasing travel distance for each of the channels.

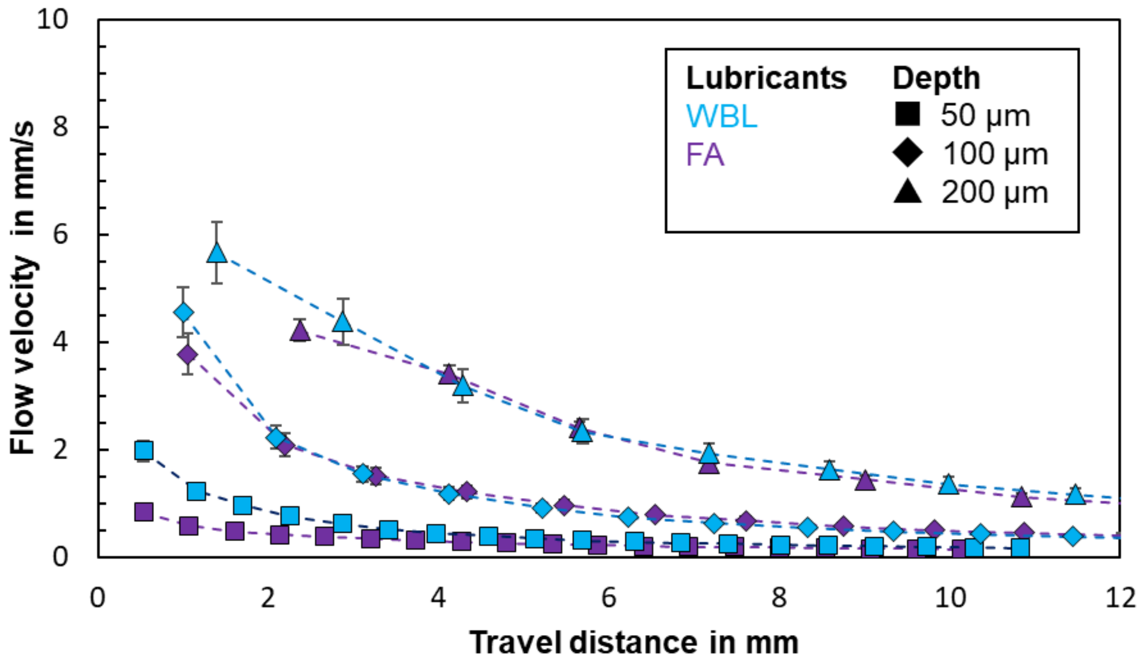

Fig. 2. Flow velocity of biomimetic structures of different depths as a function of the travel distance for a lubricant based on fatty alcohol (purple) and a water-based lubricant (blue).

Both, the fatty alcohol (FA, purple) and the water-based lubricant (WB, blue), show the highest total flow velocity for the deepest structures with a depth of 200 µm. Both types of lubricants showed similar velocity profiles for structures with the same depth. Only for travel distances up to about 3 mm slightly higher flow velocities were determined for the water-based lubricant. This minimal difference shows the potential that such complicated machining tools are not limited to a single lubricant, but also allow the wide application of different lubricants if required for different machining processes.

The cross-sectional area of the transport structure as well as implemented flow rate increases with increasing depth of the structure. From this one can conclude, that increasing the depth of the structure leads to even higher volume flow rates.

4. Conclusion

In summary, it is possible to micromachine biomimetic hierarchical transport structures for fluid transport. No significant difference was found between the two types of lubricants in terms of flow velocity behavior. By increasing the depth of the structure at a travel distance of 1.2 mm a flow rate of 0.3 mm^3/s of a water-based lubricant could be achieved in a single biomimetic structure, which proves the high potential of such structures to improve the minimum quantity lubrication approaches in mechanical machining.

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