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Advances in manufacturing spinal cord implant using 3D selective laser induced etching of fused silica

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Abstract: Spinal cord injury (SCI) results in its dysfunction and can lead to permanent paralysis. We developed a mechanical microconnector system (mMS) to support regeneration after the SCI. This paper describes a new fabrication process of the mMS using selective laser induced etching (SLE). This technique enables the 3D microstructuring of fused silica and promises rapid and highly individualizable mMS. We show that the SLE process enhances the fabrication with regard to complexity, speed and quality. An individual mMS is produced in less than 48h hours with structures from 4µm to 1mm.

I. Introduction

A biocompatible mechanical microconnector system (mMS) for supporting the regeneration after spinal cord injury (SCI) was developed. Estrada et al. published the effectiveness of the mMS in a rodent animal study [1].

Besides the biocompability of the mMS it is crucial to easily individualize and rapidly prototype the system with varying geometry. SCI can exist in different shapes, as hemi- or complete transection. Using a 3D patterning technique facilitates easy customization the mMS to the individual anatomy of the SCI. A further benefit of 3D patterning is the rapid prototyping of systems. Acute SCI comprise of a primary injury followed by secondary injury due to a sequence of tissue destructions occurring seconds to weeks after the primary injury [2]. Therefore, a possible treatment of the SCI with the mMS and hence the fabrication of the system needs to ensue in time. Rengier et al. have presented the potentiality to manufacture a personalized 3D printed model from medical imaging data [3]. Thus, the possibility to create a process flow from medical imaging to the fabricated mMS is given.

As published recently, a fabrication process of the mMS made of biodegradable materials was demonstrated [4,5]. The system was manufactured using two half shells with a subsequent binding step in order to obtain 3D cavities. Gottmann et al. have shown selective laser induced etching (SLE) for 3D microstructuring of fused silica [6]. This subtractive 3D patterning technique offers the opportunity to highly individualize and rapidly prototype mMS. 3D microchannels and cavities can be created leading to the feasibility to fabricate the mMS in one part. This paper deals with manufacturing the mMS using the SLE process. The possibility to fabricate complex 3D structures with simultaneously high accuracy in the micrometer range advances the development of a system for SCI.

II. Material and methods

The material used for the fabrication is a 1mm thick quartz glass wafer (fused silica). Its inertness and transparency make it a suitable material for the mMS. Fig.1 displays the mMS in a size comparison, which is designed for a porcine model. Detailed structure descriptions can be found in [4].

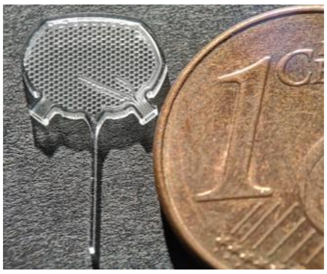

Figure 1: Fused silica mMS compared in size to Euro cent coin.

The SLE process is divided into two steps. The first step is the modification of the fused silica through a femtosecond laser. Here a machine from LightFab GmbH with a 1030nm femtosecond laser is used. The 3D structure is translated beforehand into lines in separate layers with a well-defined distance (parameter line distance) which can be written by the laser focus layer by layer. Table 1 shows the parameters used for this writing process. The duration of writing one mMS is 25 minutes. The second step is about the etching of the exposed parts of the fused silica in potassium hydroxide (KOH). The etchant (8 mol/L) is placed together with the written structure at 82°C in an ultrasonic bath for 42 hours. Within this work, mainly the structure of the mMS, line distance and laser energy are adapted for manufacturing the device with SLE. Critical structures of the mMS are the detailed honeycomb geometry (structure size <15µm), the big cavity in the center and the in comparison to the device thickness (1mm) long (>1cm) non-straight microchannels.

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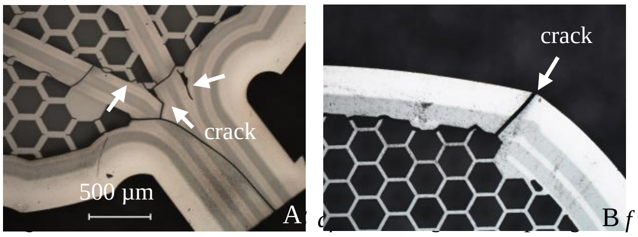
The honeycomb structures are at the outer part of the structure and etched first, followed by the central cavity. The microchannels etch much longer. Thus, the stress field induced by the writing process intensifies during etching while simultaneously the mechanical stability decreases, what might result in cracks [6]. Fig. 2A shows cracks after the etching step at sharp edges. To prevent that, sharp edges of the structure are smoothed with a radius of 5µm. Fig. 2B displays a crack in the frame after etching. The central cavity and microchannels are realized by a fully written area with an enlarged line distance of 15µm to reduce energy and stress input. To accelerate the etching of the microchannels, the course of written lines of material modification is adapted to the form of the microchannels.



honeycomb structure (A) and at slow etching microchannels (B).

Moreover, the sidewalls of the honeycombs are created with a precisely calculated offset considering the undercut due to the lengthy etching of the microchannels, thus this limits the design freedom. Resulting structures are shown and analyzed in the next section. The general influence of parameters to the SLE process can be found in detail in [6].

Table 1: Parameters of the writing process

Laser Energy	300 nJ
Depth Correction Factor	130 nJ/mm
Marking Speed	200 mm/s
Writing Field Size	0.7 mm
Laser Frequency	1531 kHz
Pulse Duration	2 ps
Line Distance (standard)	5µm

III. Results and discussion

Evaluation of the fabricated mMS were executed by microscopic analysis. A laser energy of 300nJ with a linear depth correction factor of about 130nJ/mm are suitable. Higher energies and/ or factors led to several cracks while writing and/ or etching.

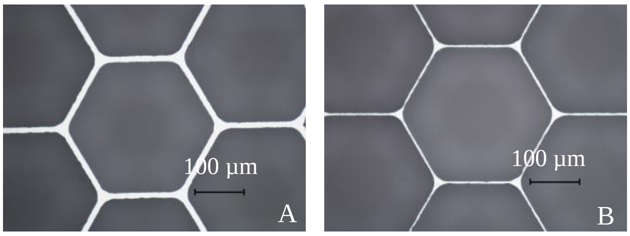


Figure 3: Top view of the honeycomb structure with sidewall thickness of 13µm (A) and 4µm (B).

Fig. 3 shows honeycomb structures with different sidewall thicknesses achieved by different offsets. Structure sizes down to 4µm ±1µm sidewall thickness (Fig. 3B) were demonstrated. The etching time for fully etching of the longest microchannel was 42 hours. To obtain a sidewall thickness of 13µm (Fig. 3A), the offset was set to 25µm. The cross-section of the mMS is displayed in Fig. 4. Microchannels can be seen on the left and the central cavity centered between the honeycomb structures. With structure height of 200µm and wall thickness of 13µm, an aspect ratio of about 1:15 is shown. However, this process is limited to fused silica, which is in contrast to the used polymer in [4] a fragile and non-biodegradable material.

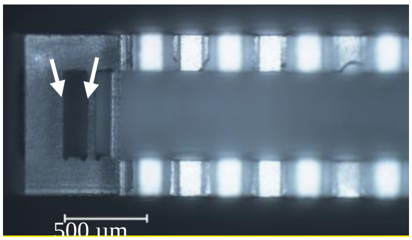


Figure 4: Cross section of the mMS with honeycomb structure, central cavity and microchannels (indicated by white arrows).

IV. Conclusions and Outlook

This work demonstrated the successful application of the SLE process to the fabrication of the mMS in one piece. The model structure and the process parameters were adapted to achieve a highly customizable, rapid producible mMS made of fused silica. Compared to the former published fabrication process [4,5], the new process has reduced effort, more design freedom and enables smaller structure sizes. This pushes forward the individual treatment of spinal cord injuries. Furthermore, this process opens up the possibility to integrate 3D waveguides for potential sensor integration in the future. For biodegradable polymers the femtosecond laser with frequency doubling for 2 photon polymerization will be investigated.

AUTHOR'S STATEMENT

Authors state no conflict of interest. Informed consent has been obtained from all individuals included in this study. The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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