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Femtosecond laser-assisted mould fabrication for metal casting at the micro-scale

Enrico Casamenti[a,*], Luciano Borasi[b], Sacha Pollonghini[a], Adeline Durand[b], Samuel Rey[a], Raphaël Charvet[b], Cyril Dénéréaz[b], Andreas Mortensen[b], and Yves Bellouard[a]

[a] *Galatea Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), CH-2002 Neuchâtel, Switzerland*
[b] *Laboratory of Mechanical Metallurgy (LMM), École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*

Abstract

Existing technologies for the production of metallic 3D micro-components are, in their current state, either too slow to be economically viable, restricted to augmented two-dimensional shapes, or produce structures of porous metal. Here we overcome those barriers by bringing metal casting into the realm of microfabrication. We present a process that enables the production of freeform, dense, 3D metal architectures at printing speeds well above alternative approaches for metal 3D printing at the same resolution. Using femtosecond laser micro-machining combined with chemical etching, arbitrarily shaped 3D-cavities are carved out of fused quartz substrates and subsequently pressure-infiltrated with high melting point metals, such as pure silver, copper or gold, and their alloys. The resulting glass/metal combinations contain interconnected dense metal 3D structures that are shaped freely with micrometric resolution to enable new types of micro-devices and composite structures.

Keywords: micro-manufacturing; freeform fabrication; microcasting; femtosecond laser

1. Introduction

The manufacturing of freeform 3D shapes at the microscale has been an ongoing quest for the last decades. Some pioneering work was achieved on polymers through *stereolithography*, [1–3] while femtosecond laser micromachining demonstrated 3D capability and microscale resolution in fabricating glass components with a combination of laser irradiation and selective chemical etching. [4–6] Comparatively, the fabrication of metals

* Corresponding author. Tel.: +41-21-695-42-71.
E-mail address: enrico.casamenti@epfl.ch.

with similar geometrical flexibility and precision remains a challenge. More specifically, on one hand powder-based techniques are limited by the powder size to a resolution of about 20 µm. [7] On the other hand, despite their large throughput and precision, lithography-based processes, such as LIGA, remain limited to the so-called 2.5D geometries. [8,9] Finally, during the last years, many innovative additive manufacturing techniques have been developed for producing truly 3D metallic micro-components [10,11]; however, with the exception of local electro-deposition methods, those processes produce parts of porous or irregularly shaped metal.

We present here a new process that enables the fabrication of sound noble metal micro-components with micrometric precision and full design freedom in all 3-dimensions, which affords higher production rates than current existing solutions. The first main step consists in carving the negative of the desired geometry in a fused quartz substrate by femtosecond laser microfabrication followed by selective etching in hydrofluoric acid (HF) at 2.5 vol% for few hours. During the second main step, the fabricated hollows in the mold are filled with molten metal by elevated-temperature pressure assisted infiltration. The obtained glass/metal composite can enable new types of micro-devices. Alternatively, the glass mold can be dissolved to extract free-standing metal microcomponents.

2. Results

Figure 1 shows in detail the process steps: 1. the fused quartz substrate is inscribed with a femtosecond laser according to a pattern that defines the volume to be removed; 2. the substrate is etched in HF at 2.5 vol% to selectively remove the material that was exposed to the laser; 3. the final fully etched glass mould is obtained; 4. the glass mould is placed in the infiltration chamber under vacuum with the metal feed on top; 5. the temperature inside the chamber is raised above the melting point of the metal to be infiltrated into glass mould cavities; 6. the pressure inside the chamber is increased to about 10 bar (1 MPa), creating a pressure differential which pushes the molten metal into the evacuated cavities. Finally, while maintaining the pressure, directional metal solidification is induced to minimize the effects of metal solidification shrinkage.

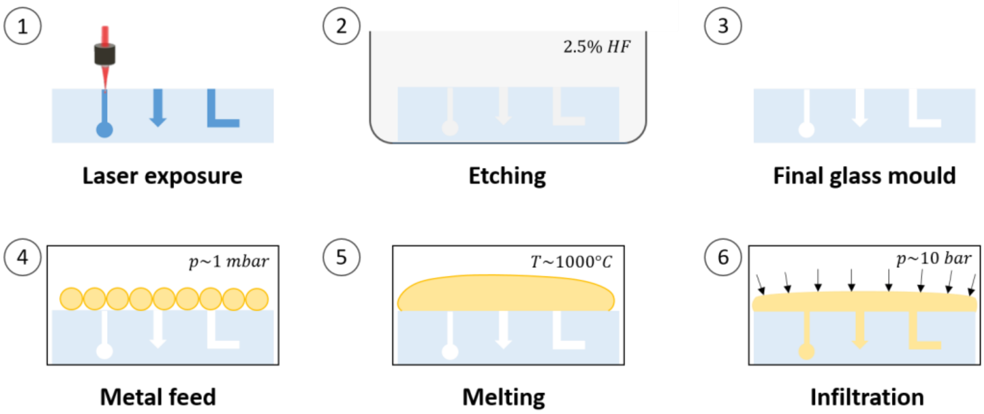

Fig. 1. Schematic of the microcasting process: 1. laser machining; 2. wet chemical etching; 3. final glass mould; 4. mould and metal feed are placed under vacuum in the infiltration chamber; 5. the temperature is raised to melt the metal; 6. about 10 bar of pressure is applied to obtain the infiltration of the cavities.

Depending on the post-processing steps used, different kinds of product can be obtained. Firstly, by dissolving the glass mould in HF, noble metal microcomponents are obtained. Figure 2 shows two examples of such structures still attached to the excess metal, which thus acts as a support. Arbitrary geometries of high-aspect ratio and micron-scale precision can be designed and produced in dense noble metals such as silver, gold, copper and their alloys.

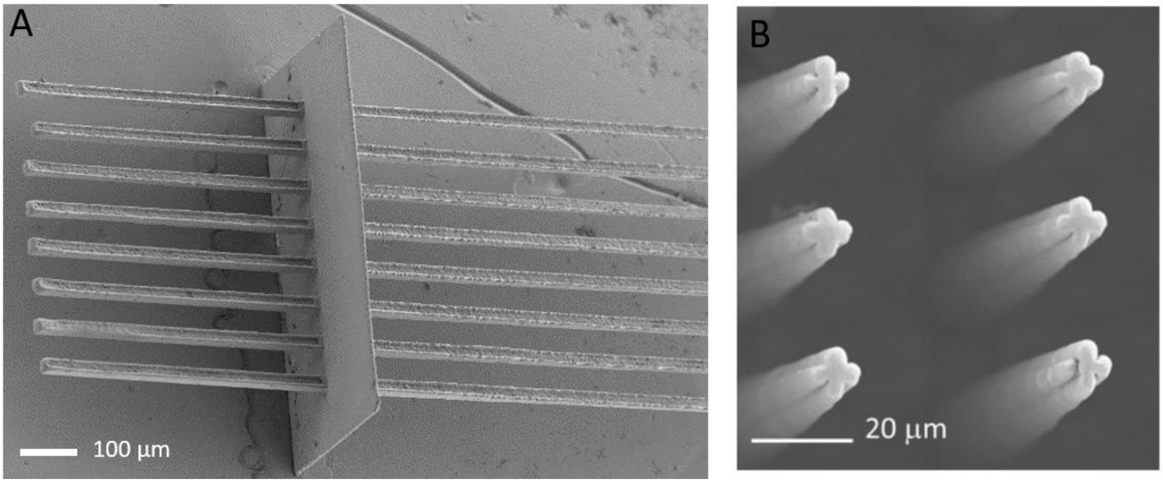

Fig. 2. Scanning electron micrographs of arrays of silver electrodes after dissolution of the glass mould. (A) High aspect ratio (about 1:100) electrodes. (B) Vertical electrodes with cross-shape at the tip.

Alternatively, it is possible to remove the excess metal (for example, by polishing) while maintaining the glass mould to obtain a glass/metal composite for applications in microtechnology. As an illustration, fork-shaped electrodes made of copper and a silver coil are produced and represented in Figures 3A and 3B, respectively.

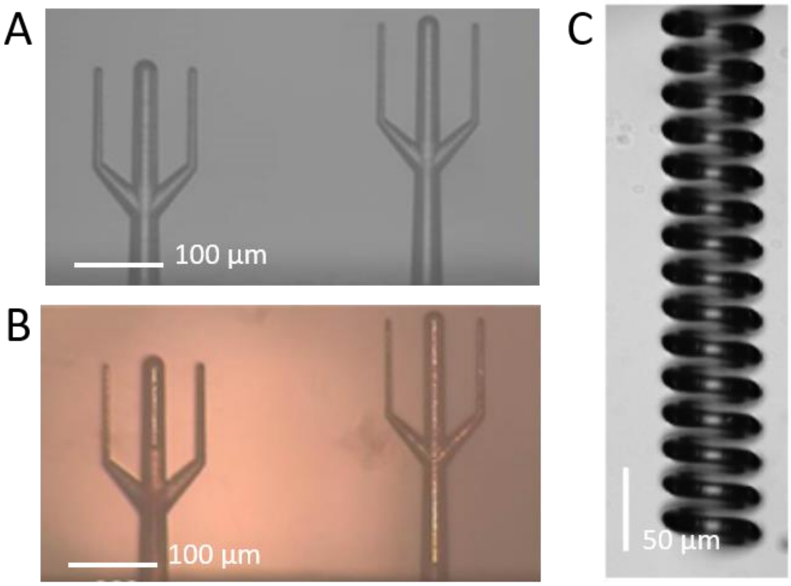

Fig. 3. (A) Optical microscope image of etched mould cavities. (B) Same cavities in (A) infiltrated with copper to create a pair of fork-shaped electrodes; (C) optical image of a silver coil. Both metal structures in (B) and (C) are embedded in the glass mould.

In conclusion, by combining in a single process the 3D capability and micron-scale precision of femtosecond laser glass machining with elevated-temperature pressure-assisted infiltration, we demonstrate a process that is able to produce both high-melting-point metals micro-casts and glass/metal composites for applications in microtechnology.

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