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New microfluidic functionalities by nano- and micro-patterned moulds

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Abstract
FaBiMed is a European project established to develop new manufacturing strategies for medical micro devices, using polymer replication in production of cost effective miniaturized micro and nanostructured components in biocompatible and functional materials. One demonstration line is dedicated to compact disposable lab-on-chip devices and requires micro and nano-structuring of the mould surface in order to change wetting characteristics of microfabricated devices and enable them with additional microfluidic functional features such as micro-channels or cell filters. Such features must be effectively replicated by hot-embossing (HE) or microinjection moulding (IM), at the same time avoiding time-dependent clogging by residual polymer, after multiple replication cycles. The paper describes the mould manufacturing process combining four sequential technologies as well as the replication results.

Keywords: Microfluidics, Lab-on-Chip, Point-of-care, Hot-embossing, Injection moulding, Replication, Tooling, DLC

1. Introduction

The main objective of the FaBiMed project is to develop new routes in manufacturing of medical microdevices by micro/nanoreplication in polymers. Main difference between these new routes and conventional manufacturing process is higher flexibility and cost efficiency. Nowadays, merchandising of these kinds of products is limited because their benefits are offset by their high cost. Moreover, current manufacturing methods strongly rely on techniques inherited from semiconductor industry reducing flexibility and space for innovation [1].

The first demo-line of the FaBiMed project is a compact disposable microfluidic device developed by Senslab. The lab on chip sensor aims to measure complex parameters of capillary whole blood such as glycated haemoglobin which should be applicable by analytical lay persons for home care also. The sensor device consists of a micro-patterned polymer film and a basic sensor comprising electrochemical multi-detection units. Both compounds have to be precisely joined with each other to prevent leakages. The polymer film is made from biocompatible materials commonly used for medical and diagnostic applications. Less than 5 µl blood sample will be transported through the microfluidic lab-on-chip system by capillary forces alone. In order to obtain the value of the complex parameters the sample has to be hemolysed, proteolysed and subjected to four different measurements in the microfluidic system. Therefore the device is divided into chambers for the defined sample and waste uptake, reagent depots, incubation and reaction columns, measuring chambers, and connecting channels. Details about the design are subject of an ongoing patent application process and can't be presented for this reason.

Depending on the function locally defined hydrophilic or hydrophobic surfaces are needed. In addition, incubation and reaction columns have to be sub-structured to ensure a large ratio of surface to volume. This is reached by combining large-scale structuring (milling) with unconventional tooling techniques for the functional parts of the mould (LBM and DLC structuring by Ion Implantation). The functional surfaces should be integral parts of the tool which will be replicated by hot embossing or compression injection moulding.

2. Mould manufacturing technologies

To fulfil the design specification four mould manufacturing technologies from centimetre to submicron scale were united in a combined process. Flat areas and features with the lateral dimensions of hundreds of micrometres were manufactured using micro milling. The following laser beam machining was used for production of very small structural details with the lateral size of tens of micrometres [2]. Laser polishing reduced the surface roughness and harmonized the surface quality on different machined structures to Rz values of 0.5 to 1 micrometre. Finally, the mould insert surface was coated with a layer of diamond like carbon (DLC), which improves HE and IM processes due to its ability to reduce de-moulding forces, improved feature integrity and enhanced die lifetime and reusability. Micro and sub-micron fluidic features were fabricated on the DLC layer using a two-step mask-and-etch process. First, gallium mask was created by direct focused ion beam (FIB) implantation, followed by etching unmasked areas in oxygen inductively coupled plasma [3]. This approach allowed placing micro and nano patterns in the selected areas of non-planar surfaces of irregular shape such as moulds for HE or IM. Applying structure specific technologies only where they are needed saves cost in mould manufacturing and allows flexible building, eliminating and rebuilding of features in moulds to realize reconfigurable tools.

2.1. Sequential combination of milling and laser structuring

The process combination of precision milling and laser beam machining was implemented for the microfluidic system mould in common tool and die making steel (1.2343). According to the geometrical specifications, the corresponding fluid geometries were machined by applying micro milling using milling tools of >300 µm. All other structures, such as micro channels with defined profile cross-sections as well as 90 degree transitions at channel structures were subsequently machined by laser ablation. Here it was essential to respect the exact positioning of the individual machining stages to one another. With structural dimensions of <20 µm, accuracy requirements of below 1 µm were reached regarding positioning of the areas to each other.

2.2. Laser Polishing

The resulting surface roughness after laser structuring amounted to Rz=5 µm. Especially in the area of the microfluidic channels, this surface roughness causes an obstruction of the capillary filling of the system in the hot embossed part. Thus it is mandatory to rework the active fluidic areas selectively in order to realize better filling.

The respective surfaces were reworked with the lower power density of the laser beam in order to reduce roughness peaks and to generate a smoother surface profile (Rz=1 µm). Thus it is also possible to specifically influence and control the fluidic flow within the microfluidic system. By adjusting roughness and surface profiles, areas can be generated within the microfluidic system to promote or inhibit filling.

2.3. DLC Coating and microstructuring

Steel moulds were coated with 20 µm thick DLC film grown by chemical vapour deposition (CVD). Microstructures were fabricated by a simple two-step process which allows for batch fabrication of high relief structures from nano to micro and even millimeter scale with high accuracy. The fabrication process begins with FIB surface implantation of Ga ions in the desired pattern into DLC in the Zeiss Auriga system using 30 keV beam energy, current ranging between 4 and 10 nA and a dose level of the order of 10^{17} ions/cm². Ga penetrates into the first few nanometers of the carbon surface and creates a hard-mask resistant to plasma etching. The implantation is followed by inductively coupled plasma (ICP) etching which removes DLC in the unmasked area but leaves the masked areas intact. Rate of the micropatterning was ~ 0.2 mm^2/hour, but can be readily improved by at least a factor of 4. The Ga mask is removed by selective dry etching.

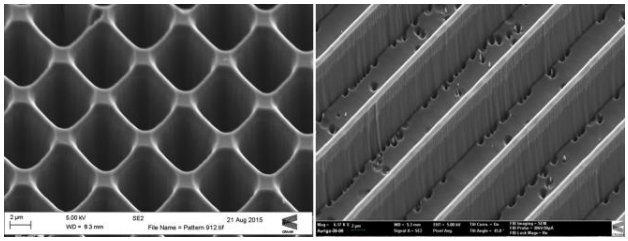

Figure 1. SEM images of micro-pattered DLC coated steel mould. Patterns for replication of 8 µm high pillars (left) and 1 µm wide fluidic channels (right) are shown.

3. Replication Results

High accuracy and fidelity in replication of functional patterns was demonstrated on relevant plastic foils with the multiscale demonstrator moulds. This was proven by complete structure transfer from mould to foil. Millimetre wide channels and reservoirs, micron wide fluidic channels, pillar cell filters and solid square structures were successfully fabricated in a single replication step on top of a complex 250 mm² microfluidic chip from the mould insert into a 250 µm thick polycarbonate film by hot embossing (figure 1). Optimum results were reached at 210 °C controller temperature and 60 bar mould pressure.

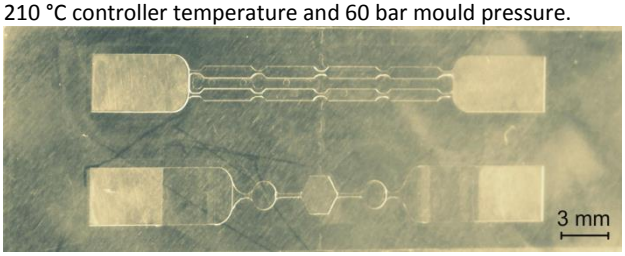

Figure 2. Replicated microfluidic demo structure in polycarbonate.

Figure 2 shows SEM pictures of specific structure details in the DLC layer. The 2 µm wide line structures as well as different mesh structures down to 1 µm on the mould insert resulting in pillar structures on the foil with a height of 5 µm were replicated completely realising high aspect ratios up to 5.

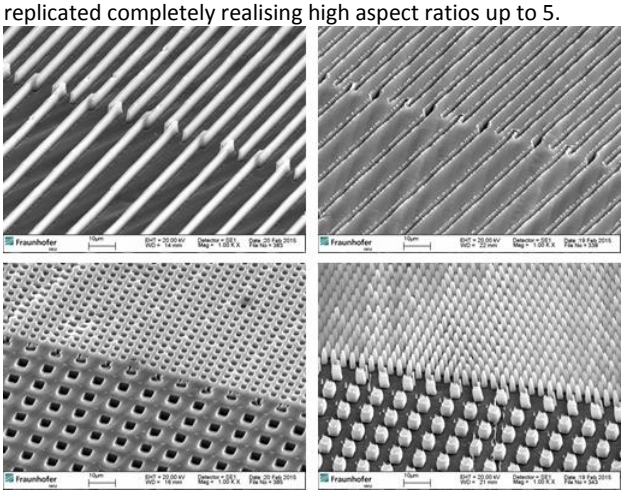

Figure 3. SEM pictures of DLC line structure (above) and pillar structure (below) with mould insert (left) and replication in polycarbonate (right). Scale is always 10 micron, Magnification 1000x.

4. Discussion and perspectives

Four different structuring technologies were combined to manufacture cost-efficient mould inserts for microfluidic chip replication in polymers. This will enable functional surface modification by combined meso-micro-nano structures using simple and profitable replication technologies. The potentials were evaluated with different mould inserts and demonstrated by a complex fluidic structure used for a compact disposable microfluidic device with new functionalities like area dependent wetting characteristics and cell filtering areas.

Further work until the end of the project will be focused on reducing demoulding issues and the realising resilient results with a complete functional demonstration mould to make the technology accessible for biomedical science applications.

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