2009 MRS spring meeting
San Francisco, CA · April 13-17

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Journal:	*2009 MRS Spring Meeting*
Manuscript ID:	draft
Symposium:	Symposium OO
Date Submitted by the Author:	
Complete List of Authors:	Becker, Holger Beckert, Erik; Fraunhofer Institut für Angewandte Optik und Feinmechanik Gärtner, Claudia; microfluidic ChipShop GmbH
Keywords:	microelectro-mechanical (MEMS), nanostructure, fluidics

Microfluidic manifolds with high dynamic range in structural dimensions replicated in thermoplastic materials

Holger Becker[1], Erik Beckert[2], Claudia Gärtner[1]

[1] microfluidic ChipShop GmbH, Carl-Zeiss-Promenade 10, D-07745 Jena, Germany
[2] Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, D-07745 Jena, Germany

ABSTRACT

In this paper, we present the manufacturing process of a polymer microfluidic device which is currently being used to investigate wetting properties of nanostructured microchannels replicated in hydrophobic thermoplastic materials like cyclo-olefin co-polymer (COC), polypropylene (PP) or polymethylmetacrylate (PMMA). These devices feature large structural dynamics (feature sizes between 200 µm and 200 nm). The mold insert necessary was fabricated using a combination of precision machining with single-point diamond turning (SPDT).

INTRODUCTION

Microfluidic components nowadays play a major role in ensuring the performance of many systems in analytical chemistry and the life sciences [1]. In many real-world applications, a set of requirements have to be met which differs significantly from properties reported in the literature by many academic groups. Amongst those requirements are:

1. A high dynamic range in structural dimensions. As an example, in a diagnostic cartridge for full blood analysis with external dimensions typically the size of a microscopy slide (75.5 × 25.5 mm), initial sample and reagent volumes are typically of the order of several µl (i.e. several mm^3), requiring chambers with dimensions in the mm-range. The various liquids are then transported and manipulated in microchannels which are typically in the size range of tens to hundreds of micrometers. Specific structures (e.g. obstacles to support mixing, cell or bead capture, passive valves) and the general tolerances are often one order of magnitude smaller (e.g. 1-10 µm), while structures influencing the surface properties (e.g. wetting) are in the submicron range. A single microfluidic device will incorporate structures in all these size ranges in all three spatial dimensions which generally is not possible for manufacturing methods based on lithographic techniques.
2. To enable commercialization of such a microfluidic device, the manufacturing technology used has to be scalable in the sense that it allows the fabrication of devices from low to mass production volumes at reasonable cost (typically for an analytical or diagnostic test in the low single-digit dollar range) without a switch in the basic technology.
3. Material selection has to be compatible with both the manufacturing technologies and the application needs in addition to meeting the cost restraints indicated above.

In order to fulfil these requirements, we have investigated the replication of microscopy slide sized micro- and nanostructured metallic mold inserts into thermoplastic materials like

PMMA, PP and COC using hot embossing and injection molding as manufacturing technologies. These replication technologies are established for the fabrication of macroscopic structures and have been increasingly used to generate microstructures as well [2]. However the combination of comparatively workpieces with a large dynamic range of structures has neither been subject to extensive academic research nor industrial manufacturing yet.

EXPERIMENT

Mold insert fabrication

A crucial step in the technology chain for the manufacturing of polymer components is the fabrication of a suitable mold insert (or mold master) structure which contains the inverse structure of the final polymer part. While electroplating of silicon or resist structures has been used frequently to generate a metallic (usually nickel or a nickel alloy) mold insert with features in the micrometer-range, this technology is usually not well suited for structures with a height larger than several hundred micrometers. Silicon [3] or resists [4] structures have been used directly as mold insert materials, however in addition to the above mentioned geometrical restraints their lifetime is significantly smaller than that of a metallic mold insert.
From the perspective of lifetime, metallic mold inserts are very attractive. The advances of precision- and ultraprecision mechanical machining in recent years have made it possible to achieve the required high dynamic range in geometrical features combined with the long mold insert lifetime required for economic viability of the method.
While ultraprecision machining using diamond tools had its origins in optical component manufacturing [5], e.g. large mirrors or grating structures for antireflex functionality [6], it can also be used for the manufacturing of mold inserts for polymer replication applications like microfluidic.
The mold insert for the microfluidic channel structure with an overlayed saw-tooth at the channel bottom (which is equivalent to a ridge top in the mold insert) was manufactured using a precision milling machine (Kern Evo Ultra-precision 5-axis machine center, Kern, Eschenlohe, Germany) to generate the microstructured channel (100 and 200 µm wide microchannels, 50 µm deep, overall layout see Fig. 1) and ultra precision single point diamond turning (SPDT) to generate the nanostructured channel bottom. On a turning machine (Nanoform 350, Precitech Inc., Keene, USA), two work pieces were arranged on an outmost diameter of the turning spindle, thus approximating a linear cut through the channel with a width of 100 µm and 200 µm respectively by the large turning radius. The working tool was a mono crystalline diamond cutting tool (see Fig. 2) with a tip shape adapted to the targeted saw tooth structure (2 µm pitch and 0.3 µm depth). Manufacturable materials for diamond tools are most non-ferrous metals as well as most polymers and some amorphous crystallic materials such as silicon. In case of the mould master for the channel structure a brass alloy of $CuZn_{39}Pb_2F_{38}$ was chosen due to its

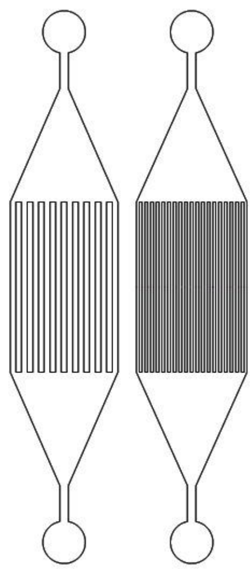

Fig. 1: Layout of device

good machineability. For production tools, harder materials such as electroplated NiP on steel bases are available.

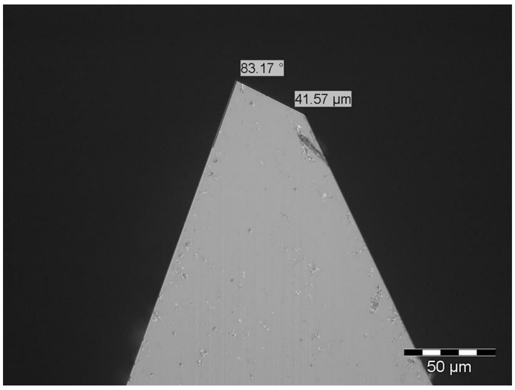

Fig. 2: Diamond cutting tool

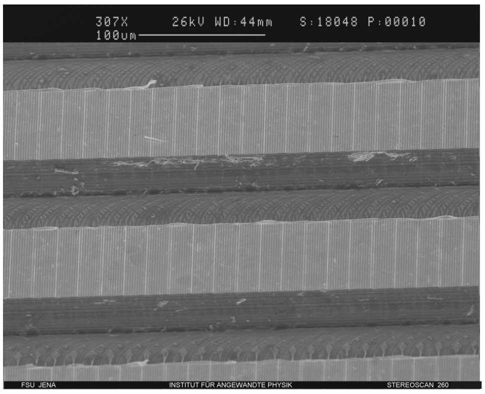

Fig. 3: SEM of mold insert

Additionally, it becomes more and more evident that cubic boron nitride (CBN) will be available in future within the same range of accuracies and geometries as diamond tools, thus eliminating the tool wear effect due to carbon affinity of diamond and allowing the ultra precision machining of steel moulds.
Fig. 3 shows a SEM-view of the manufactured brass mold insert. Visible are the milling structures from conventional machining as well as the saw tooth structure on the channel bottom. The machining degrees of freedom allow for different angles of the grating with respect to the flow direction as well as the structuring of more complex geometries such as steps with different heights down to the sub micron scale.

Polymer replication

The above described mold insert was used for the replication in a variety of thermoplastic polymers by injection molding and hot embossing.
For injection molding (Figs. 4,5), as can be seen in the overview images (Fig. 4a and 5a), the replication of the microstructure is not perfect yet (rounding of the edges). The nanostructure is well defined in both materials, however with greater replication accuracy in the case of COC than in PP. This can be associated with the shorter polymeric chain length and the better mold flow in the case of COC as well as the higher mechanical stability after cooling down which leads to a reduced structural deformation upon demolding.

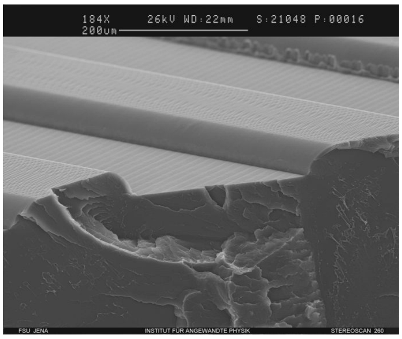

Fig. 4a: Overview of injection molded COC. Note the rounding of the micro-structured channel wall due to incomplete mold filling.

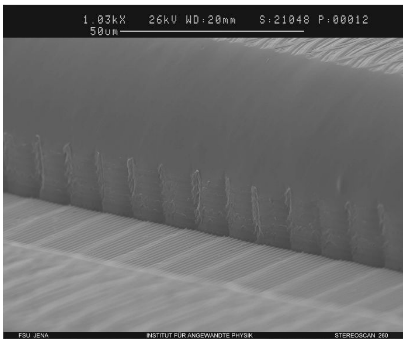

Fig. 4b: Close-up of the area channel-wall and nano-structure.

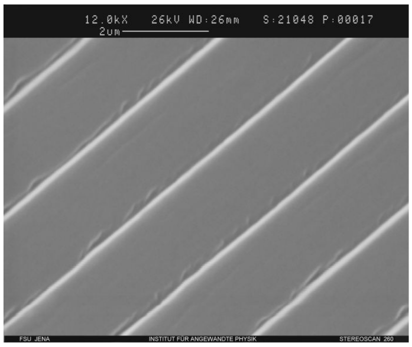

Fig. 4c: Close-up of the nano-structure. The dimensions are well preserved.

Experiments have also been carried out using the hot embossing process (Jenoptik Mikrotechnik HEX 02, Jena, Germany) which is known from the literature to have a very high replication accuracy [7,8]. This property could be confirmed both in COC and PMMA. Figures 6 and 7 show the replication results in these two materials, COC and PMMA. The master tool could be very well replicated, the microstructure (as indicated by the vertical sidewalls) as well as the nanostructure.

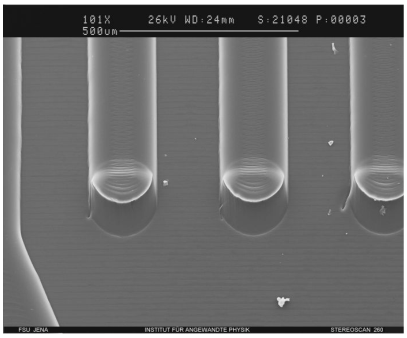

Fig. 5a: Overview of injection molded PP. Note the rounding of the micro-structured channel wall due to incomplete mold filling and some deformation at the ends due to demolding.

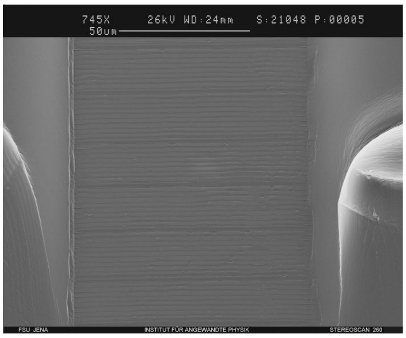

Fig. 5b: Close-up of a single channel with nanostructures.

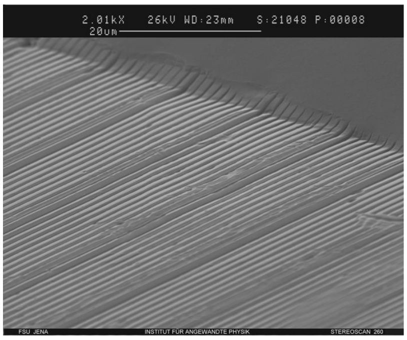

Fig. 5c: Close-up of the area channel-wall and nano-structure. The structures are not as well replicated as in the case of COC.

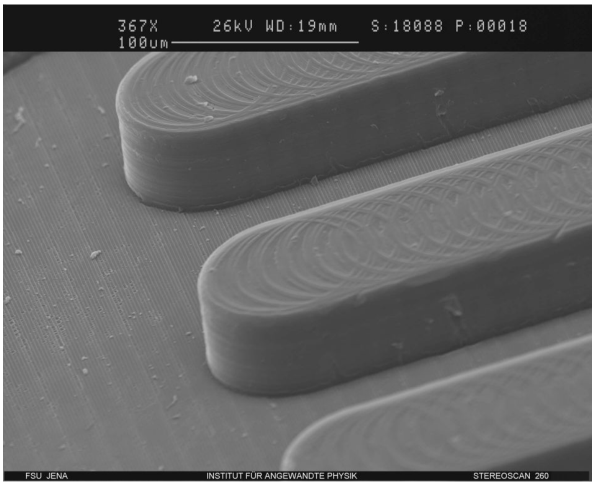

Fig. 6a: Hot embossed structure in COC. Note the high replication accuracy both of the micro- as well as the nanostructure.

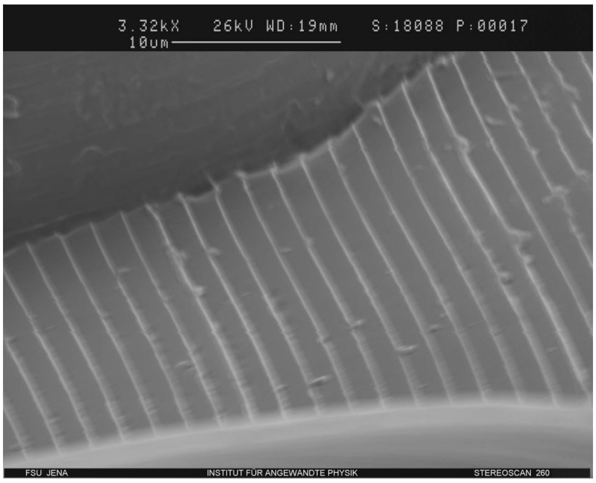

Fig. 6b: Detail of the nanostructure.

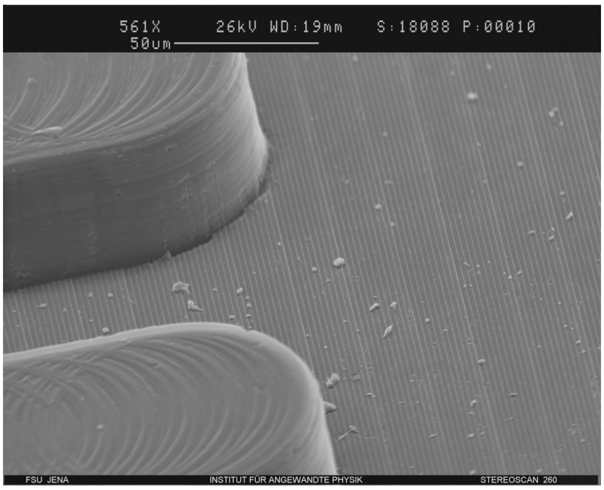

Fig. 7a: Hot embossed structure in PMMA. Note the high replication accuracy both of the micro- as well as the nanostructure.

Fig. 7b: Detail of the nanostructure. The resolution of the SEM could not be as high as in the case of COC as thermal damage in the PMMA cold be observed due to the electron beam.

CONCLUSIONS

We have been able to replicate a microfluidic channel device with a sawtooth-profiled nanostructure on the channel floor to allow wetting of the intrinsically hydrophobic polymer surface. The combination of precision milling with SPDT proves to be a suitable method for the generation of a mold insert for the subsequent replication technologies. Injection molding as the process which offers the biggest economic potential is well capable of replicating the nanostructure, albeit at the (possible) cost of a not optimally developed microstructure. It can be argued however that if this deviation is known, suitable corrective measures can be taken in the mold insert device. Hot embossing shows a very high replication accuracy both on the micron as well as on the nanometer scale, however cycle times are about 4-5 times as long as for injection molding, therefore making this method better suited for lower volume or prototype production.

ACKNOWLEDGMENTS

Parts of this work were funded by the European Commission in the project “Influs” under the contract NMP3-CT-2006-031980 and by the German Federal Ministry of Education and Research (BMBF) within the framework program “InnoProfile” (fund number 03IP609, "nanoreplica") and managed by Project Management Juelich, Forschungszentrum Jülich GmbH (PTJ).

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