Collaborative White Paper

Micro - Device Manufacturing

A Collaborative Journey Through Advanced Technologies in Glass Laser Micro-Fabrication, Electroforming, and Injection Muolding

- FEMPTOPrint
- 3D AG
- FHNW University of Applied Science and Arts Northwestern Switzerland

Abstract

In this whitepaper, a production chain demonstrating the cost-effective manufacturing process of microfluidics components is presented. This process was made possible through the collaboration of two Swiss companies, FEMTOPrint and 3D AG, along with the University of Applied Sciences (FHNW).

A selective glass etching process was employed for mastering the microfluidics features (FEMTOPrint). Subsequently, it was secured in the nickel shim family through an electroforming process (3D AG). The nickel shim was then turned into a tool for injection moulding (3D AG).

This tool was successfully employed in various injection moulding techniques resulting in a few thousands polymer parts with microfluidic features (FHNW). The features were moulded in PMMA, COC, COP, and analyzed by confocal microscopy. The latter have shown very high structural fidelity over the entire process.

FEMTOPrint, 3DAG, FHNW

Content

Introduction

When manufacturing microstructures, all steps must be aligned to achieve structure fidelity in mass-scale production. The identified technology most suitable for mass-scale production will dictate the details of earlier phases, such as mastering and tool manufacturing. This collaborative analysis examines an optimal value chain for replicating microstructures through injection moulding.

Injection moulding is the most widely used industrial process for mass manufacturing polymer-based products and devices. Additionally, there is a growing need to incorporate functional structures into polymer parts in next-gen technology products.

A vast number of origination technologies to create functional structures are available on the market, including various types of lithography, direct laser writing, e-beam, polymer ablation, glass ablation, and many others.

Each of them features a distinct set of advantages and disadvantages. A novel methodology that features laser processing of glass in combination with subsequent electroforming of nickel replicas for tooling is shown to be an optimal manufacturing chain for the high-pressure conditions applied in injection moulding.

Origination by FEMTOPrint

Advanced Laser Writing Process for Master Fabrication

Within this context, advanced 3D masters in glass with micrometre precision and excellent repeatability are produced using a subtractive, direct-write microfabrication process.

This process utilises femtosecond laser writing followed by wet etching. For the demonstration purposes of this work, the glass plate with generic microfluidics channels and logos of the three partners were prepared on the glass plate, presented in Figure 1.

Localized Glass Modifications for Precision

The fabrication process for master components exploits highly localized material modifications triggered by non-linear absorption during the laser exposure step. The primary requirement for the laser process to be effective is a transparent substrate material, typically glass.

This transparency allows the laser light to be focused within the bulk of the material without any disturbance. If the laser parameters are correctly adjusted, a multiphoton absorption process can be initiated within the focal volume (voxel), inducing a significant change in the material properties over an area as small as 2 µm in XY and 10 µm in Z. These localized modifications in glass exhibit various properties depending on the laser parameters used.

For instance, the etching rate of the material can be selectively increased by up to 500:1 compared to the bulk unmodified pristine glass. By scanning the laser or moving the substrate, an image of the master to be fabricated is created within the material. Subsequently, due to the high etching contrast, the substrate may be immersed in a wet etching solution that selectively etches away the exposed material, culminating in the production of the finished component.

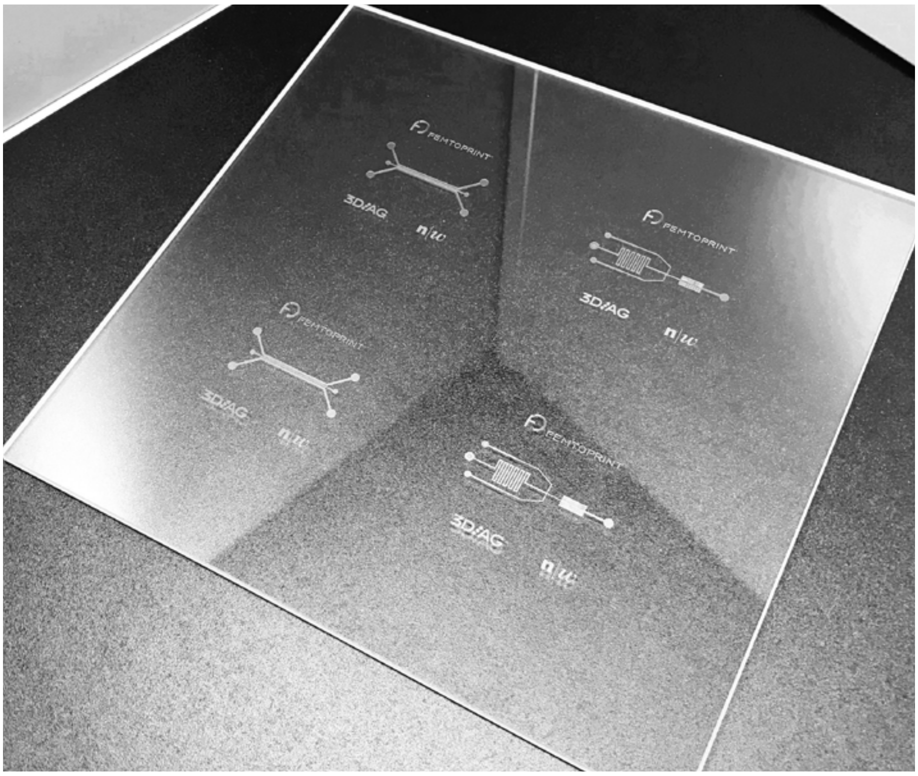


Figure 1. Example of master fabricated on 150x150x3 mm^3 fused silica substrate.

Revolutionizing Microfluidic Fabrication with 3D Master Production

The process of creating 3D masters proves to be exceptionally compelling for microfluidic applications. In a single exposure step, this innovative technique allows the fabrication of multi-depth channels, slopes, funnels, holes, pillars, and various other intricate shapes. Figure 2 illustrates the pronounced advantages in both complexity and variety of shapes, marking a significant leap forward in micro-device manufacturing.

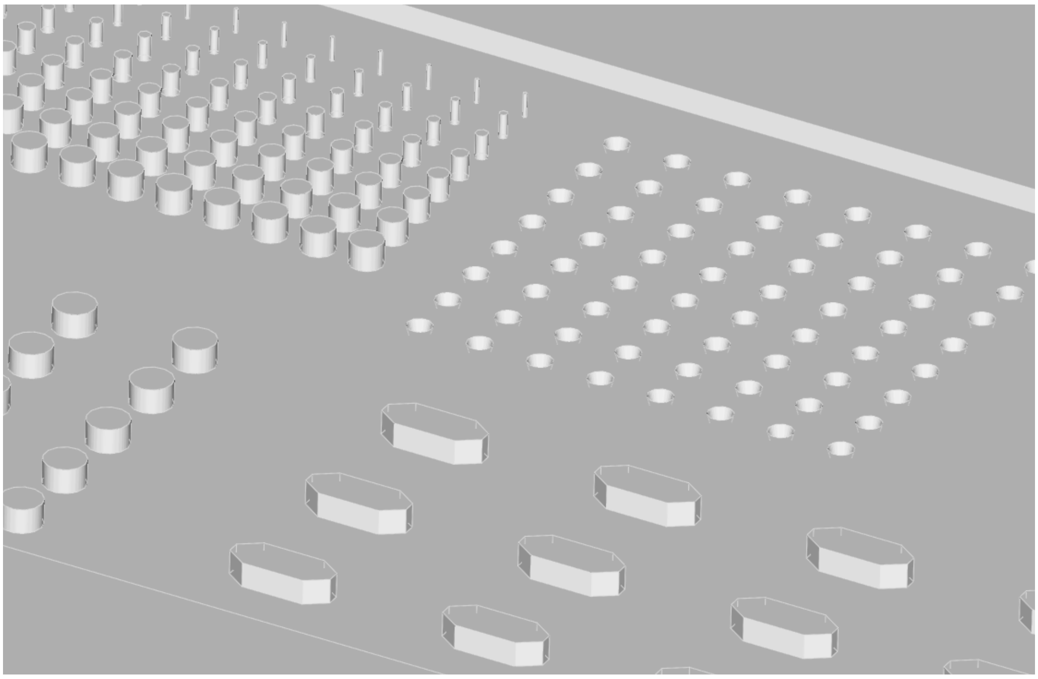


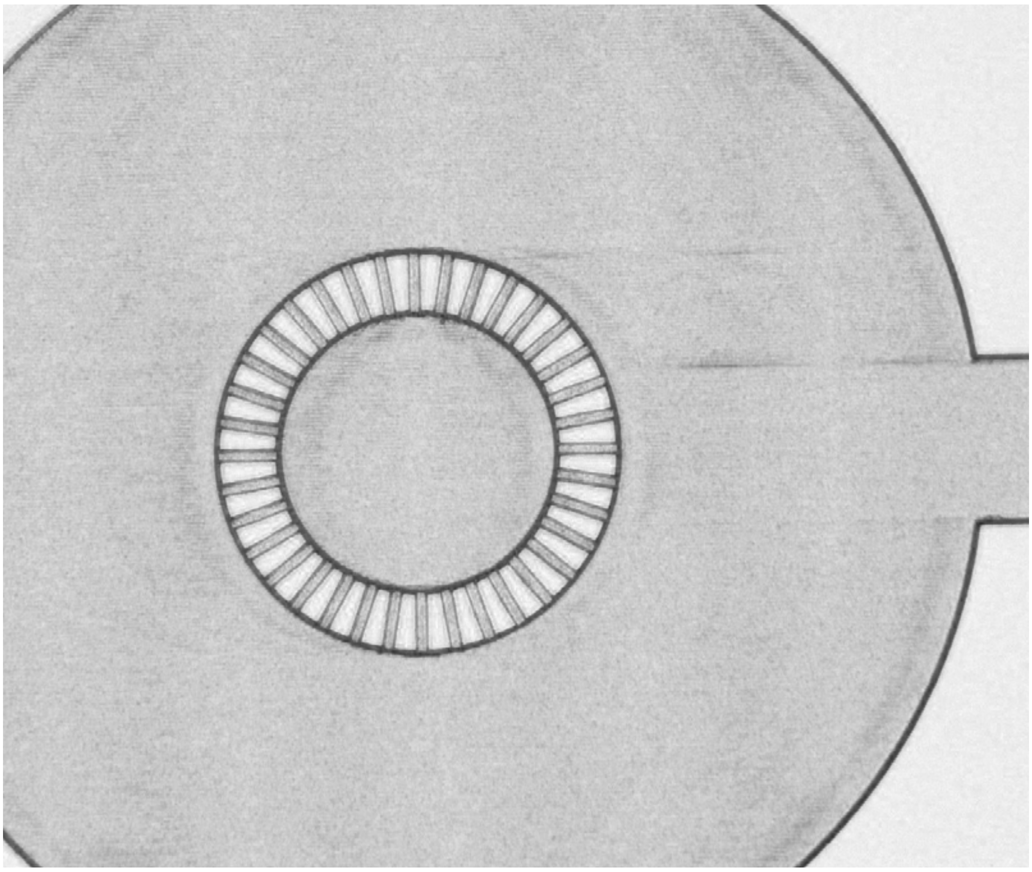
Figure 2. Examples of pillars and holes with different shapes. Top line: pillars with increasing diameter from 10 µm to 80 µm (left), holes with 15° taper and depth of 40 µm (centre), truncated pyramids (right). Bottom line: circular pillars (left) and hexagons (right).

About Micro-Machining Technology

Additionally, the ability to control and fine-tune the micro-features in the glass masters can ease the next fabrication steps. For instance, the introduction of small sidewall draft angles of 3 to 5 degrees is of extreme importance to facilitate the separation as well as for the demolding after the injection moulding (as seen on page 11). If the sidewalls are perfectly vertical or have a negative angle, the demoulding process might be problematic and could lead to catastrophic damage to the master or may not work at all. Adding such straightforward, process-specific micro-features represents an added value compared to lithographic processes, where the integration of the same features would require sophisticated procedures, thus increasing process complexity and costs.

Lastly, the glass micro-machining technology can achieve tolerances approaching 1 µm in XY and 2 µm in Z, alongside exceptional repeatability, and alignment precision between features < 2 µm. This remarkable precision, crucial to achieving advanced microfluidic functionalities, is an indisputable advantage, particularly in fabricating large-scale devices, where even minor misalignments could significantly impact the fluidic behaviour, potentially leading to defective products. Figures 3 and 4 present the range of the structures that are often manufactured with FEMTOPrint's technology.

Figure 3.
Example of filter channels with a width of 10 µm



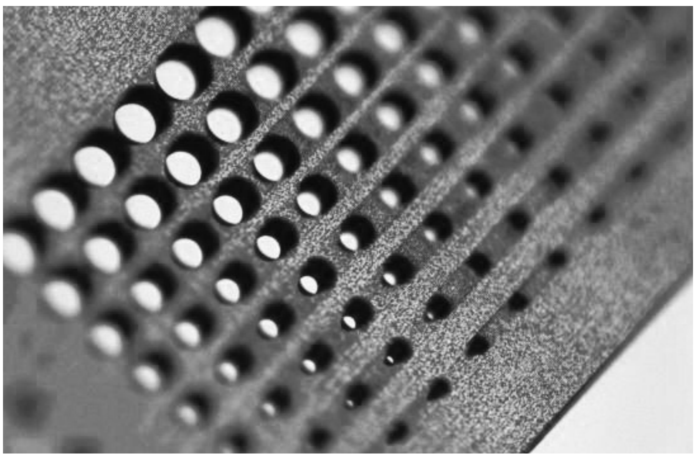
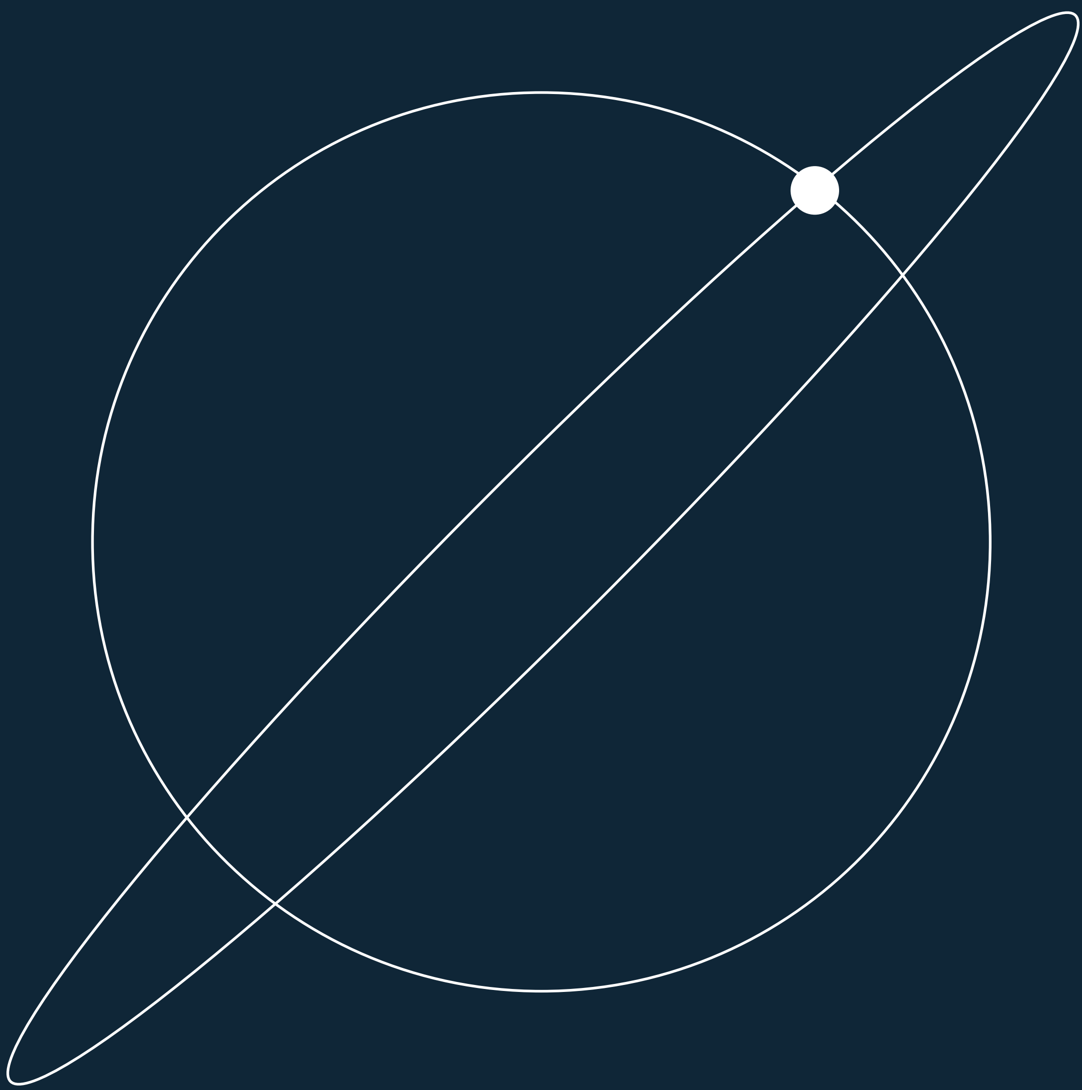


Figure 4. Close-up view of the pillar array. The widths vary from 10 µm to 80 µm, with a consistent height of 60 µm.

Electroforming Shims by 3D AG



Electroforming is a process involving the electrodeposition of metal onto a base material. It stands out for its ability to transfer intricate structures with nanometre precision creating so-called nickel shims. It is essential to emphasise that almost every base material can undergo electroforming. This chosen method is key for achieving accuracy and fidelity in final products.

Process Overview

The process involves immersing an anode and a cathode in an electrolytic bath and passing a direct current of electricity through the solution. This results in the transfer of metal ions onto a cathodic surface, ultimately plating the metal onto the base material. Electroforming is a specific type of electrodeposition that produces a relatively thick layer of metal (50 µm to approximately 4000 µm), which can be separated into a nickel shim to create a faithful replica of the original structure. In Figure 5, the schematic of the electroforming tank is presented.

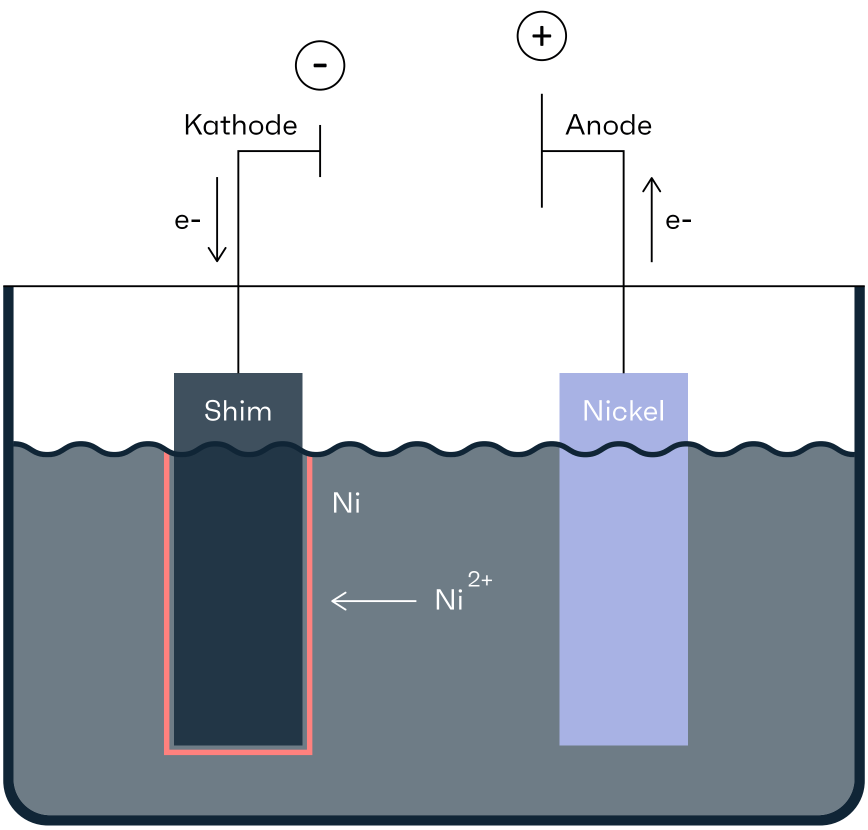
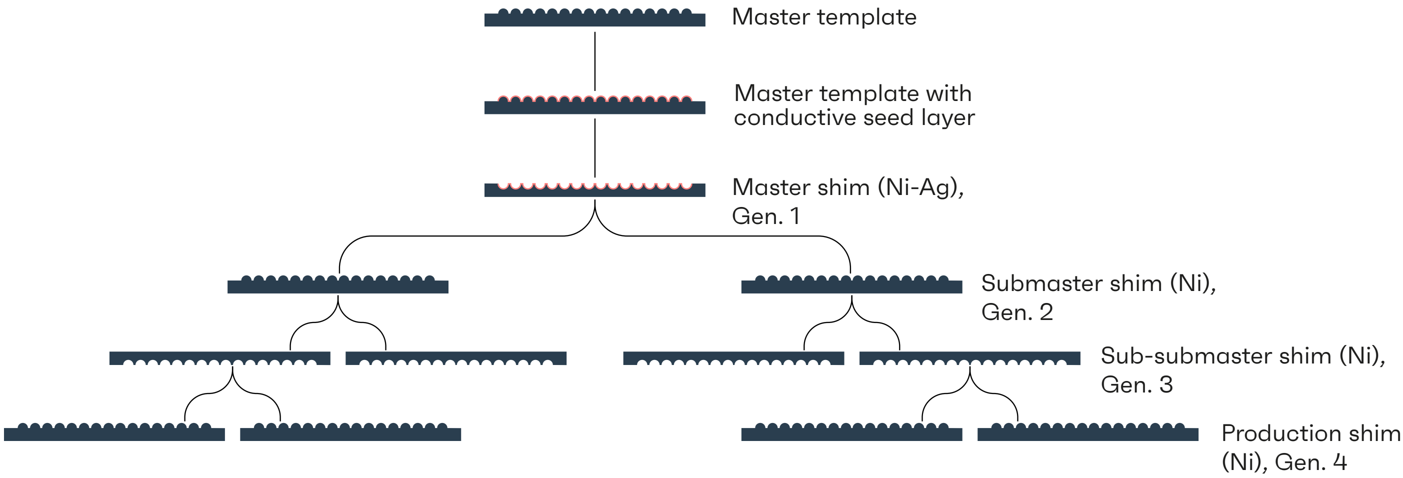


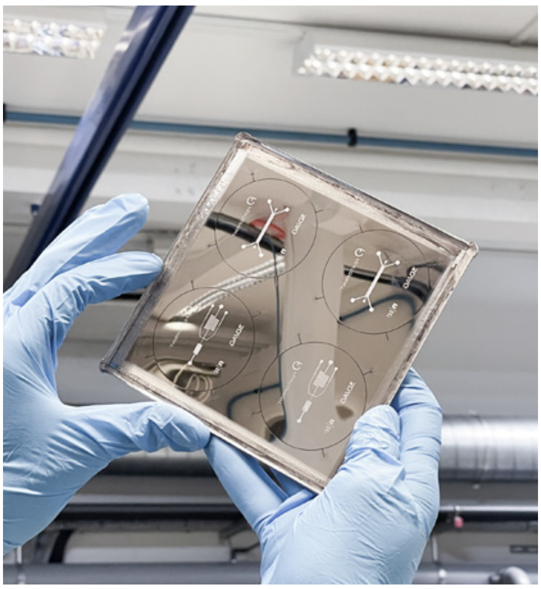
Figure 5. Schematic drawing of nickel electrodeposition. Nickel ions are transferred from nickel pellets to a metalized base material and form a nickel shim.

Shims Family

Electroforming offers a distinct advantage in creating nickel shims families. This method of manufacturing allows the production of multiple copies from a single master template, thereby reducing both costs and lead times. Each shim copy holds the opposite polarity and represents a generation of the shim family. The generations are created to sustainably preserve the structure for industrial manufacturing. A schematic drawing of a nickel shim family is presented in Figure 6 below to aid in comprehension.

Figure 6. Nickel shim family, from master to multiple sub masters and production shims. Parallel copies are possible to preserve the master for a larger number of subsequent copies.



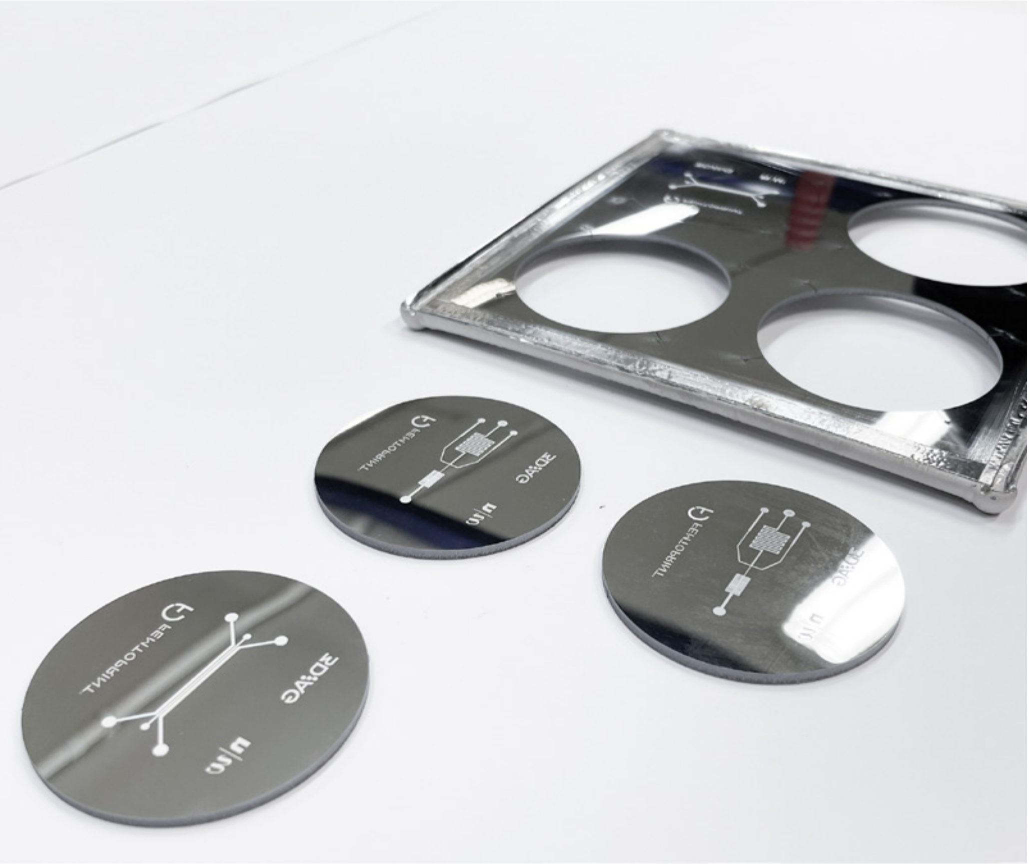


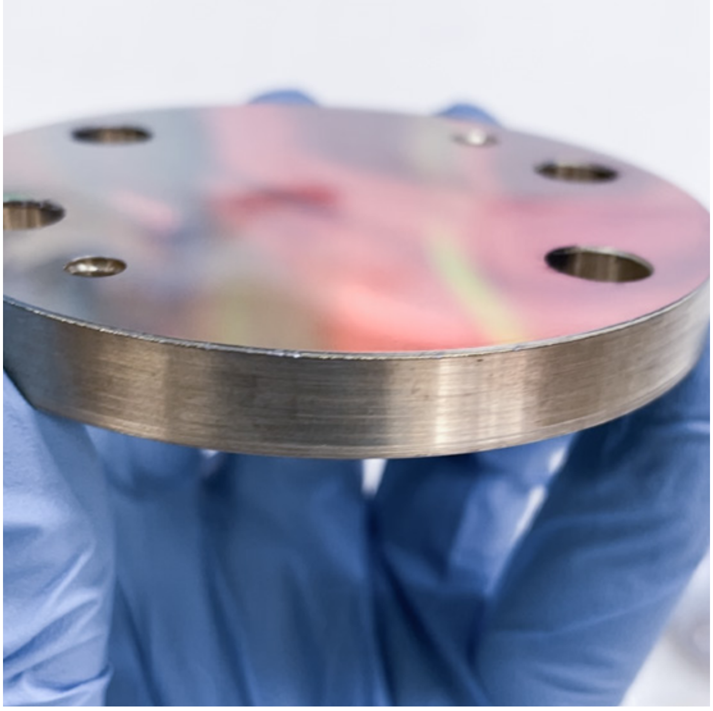
Mould Preparation

For the purposes of this collaboration a nickel shim family was created from the glass base material provided by FEMTOPrint. To create moulds, a specific nickel shim was electroformed to a thickness of 2000 µm with a total thickness variation (TTV) of +/- 5%. This thickness and precision are crucial to use the shim as moulds in the following process of injection moulding by FHNW. The nickel shim was laser cut into precise moulds as seen on the next page in Figure 8.

Figure 7. 2000 µm nickel shim.

Figure 8.
Precisely cut-out laser moulds.

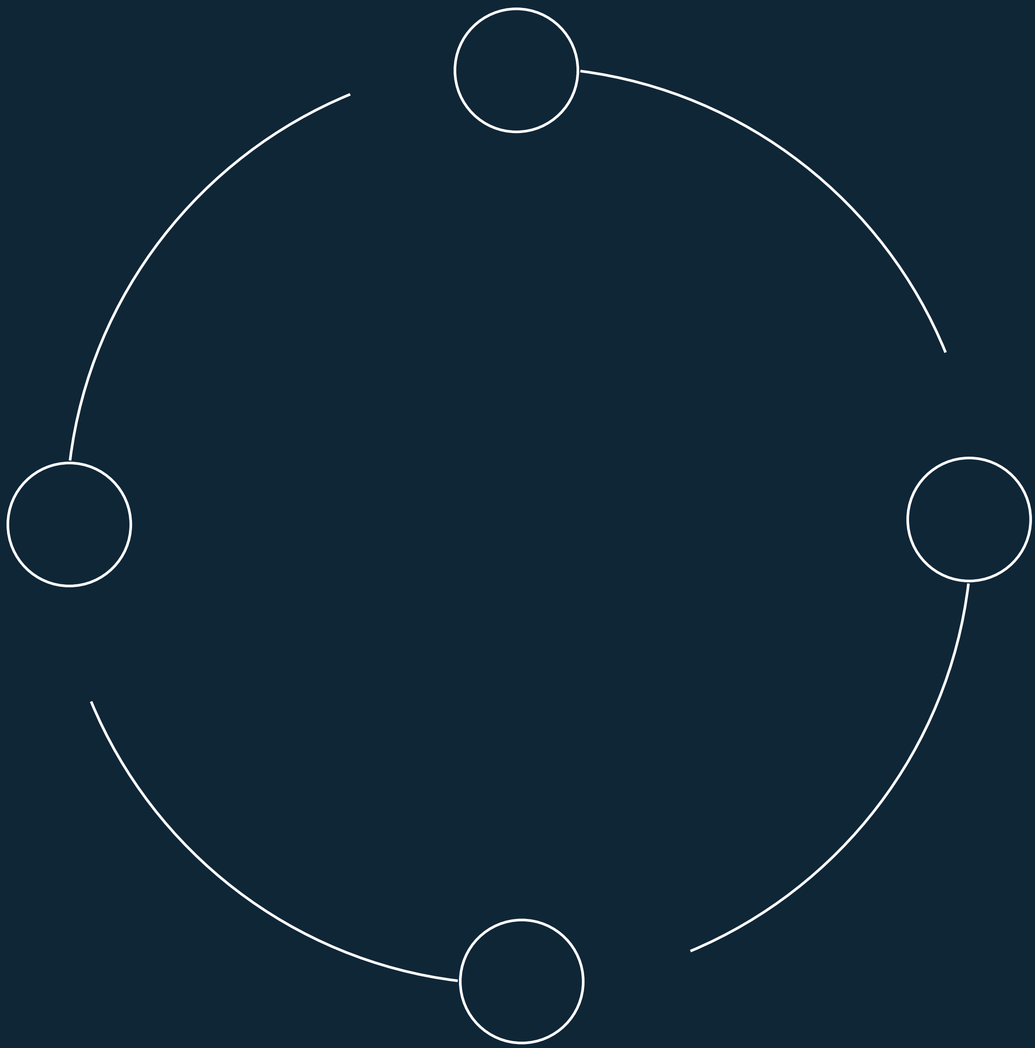




If tighter tolerances are required an alternative method can be utilised, for instance, electroforming thin nickel shims of a few hundred micrometres with the same relative TTV and attachments to a prefabricated base. This attachment is achieved through microscopic laser welding along the edges. In the course of this work, this was not executed hence an exemplary picture with holographic structure laser welded to brass insert base is presented in Figure 9.

Figure 9. Laser cut and welded shim to base insert.
Top part shim with a holographic structure, bottom brass insert base.

Injection Moulding by FHNW



Injection moulding is the most widely used industrial process for mass manufacturing of polymer-based products and devices, providing a higher degree of desired freedom. The injection moulding cycle essentially consists of four subsequent steps, i.e. plastification, mould filling, packing and demoulding, which are all equally important for the quality of the final part.

The Injection Moulding Process

In the plastification step, the polymer material is subjected to high temperatures to form a homogeneous melt which is transported by a single screw, creating a melt cushion at the front of the barrel. The molten polymer is then transferred under high pressure into a mould cavity (filling phase) defining both the outer geometries and the final surface quality of the part. This mould cavity is usually held at low temperatures to promote the solidification of the material, while the pressure is kept high to compensate for the material shrinkage during solidification (packing phase). Once the material has cooled down sufficiently and become solid, the mold opens and the part is ejected.

For the replication of micro- and nanoscale surface topographies, such as those present in microfluidics or micro-optics applications, the injection moulding process faces additional challenges that need to be taken into account. Incomplete filling of micro- and nanoscale surface features can result due to low mould temperatures, and high pressure gradients within the mould cavity can lead to differences in shrinkage and internal stresses which in the final part manifest as optical inhomogeneities. Moreover, accurate axial separation of the two mould halves is a prerequisite for preventing damage to the solidified surface topographies upon mould opening.

Thermal Dynamics in Polymer Replication: Complexities in Surface Replication

On the one hand, the filling of the micro- or even nanoscale features at the mould surface needs to be completed prior to the solidification of the polymer. This frequently requires adaptation of the mould temperature to higher values, thus slowing down the cooling process and giving the polymer melt more time for complete filling of the surface topographies. There is a clear preference from an industrial point of view to keep the mould temperature constant (isothermal process) during the manufacturing process.

Mould Temperature Control

If complete replication cannot be achieved under isothermal conditions, so-called variothermal mould temperature control may be required. In this case, the mould temperature is raised above the solidification temperature of the polymer during filling and subsequently cooled down again during the packing phase. Inevitably, this results in substantially longer cycle times and thus higher costs per part.

Injection compression moulding is another process variant, which involves the filling of a slightly opened cavity to ~95% followed by a slight compression stroke to close the mould and complete the cavity filling. While this process variant requires more complex tooling, it offers some distinct advantages. The homogeneous pressure distribution results in better control over the part shrinkage, minimises internal stresses, and improves the optical homogeneity of the part. Moreover, the cavity pressure level is substantially lower in comparison to traditional injection moulding, which allows for larger parts to be manufactured on smaller machines.

Replication of Microfluidics Shims

For this collaboration, we successfully moulded two generic microfluidic designs that were originated by FEMTOPrint in glass, transferred into nickel shims by electroforming by 3D AG, and subsequently post-processed at FHNW to yield the final insert geometry, which we then integrated into one of our versatile injection compression moulding tools available for process development for industrial customers and partners.

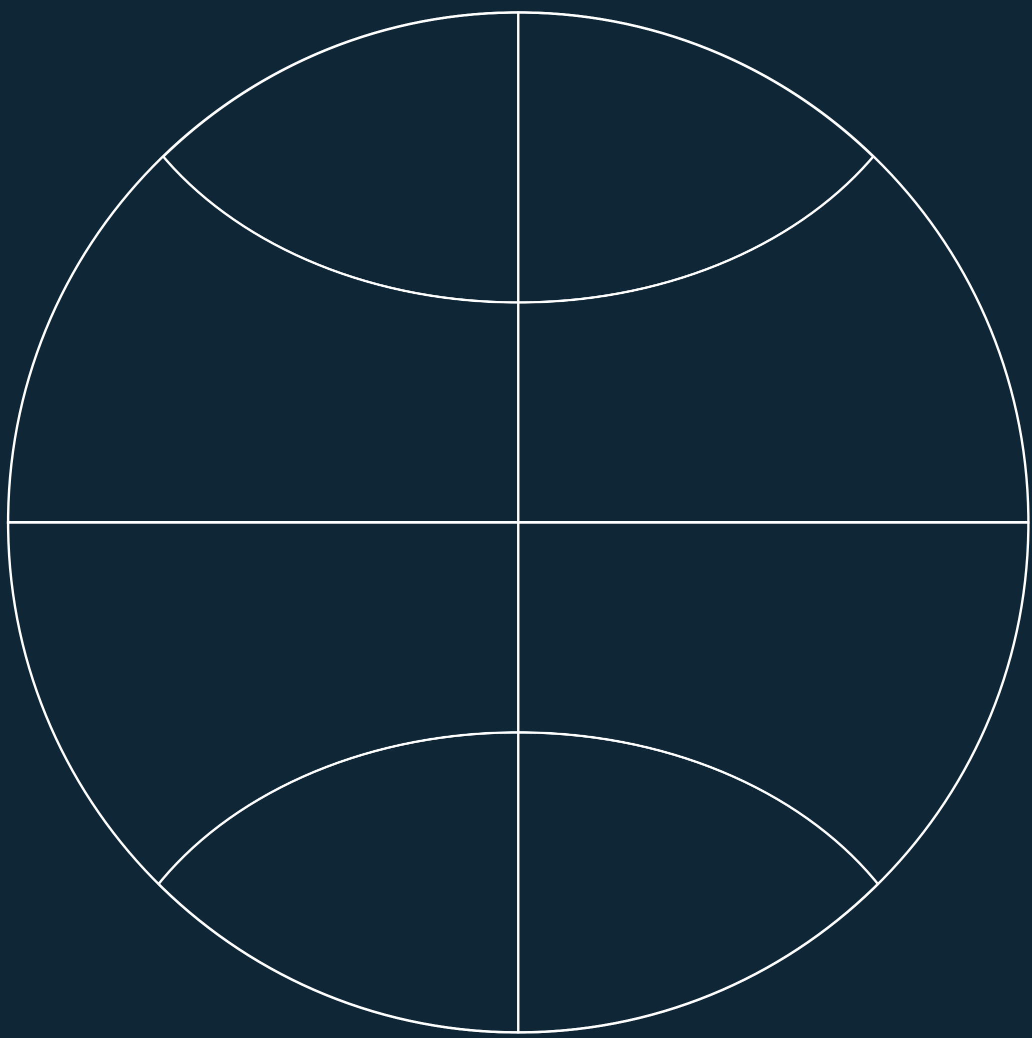
Making use of different process variants (isothermal, variothermal, with/without compression stroke), we could demonstrate influences on the resulting replication quality. By optimising process conditions, we managed to achieve very good replication in COC, COP, and PMMA - the materials of primary interest for this whitepaper.

		PMMA 7N	PMMA 7N low	COC 6013 S-04	COP1020R	COP1020R vario
		Data sheet values				
Melt temperature range	[°C]	220-260	220-260	250-300	250-300	250-300
Mould temperature range	[°C]	60-90	60-90	95-130	75-100	75-100
		Experimental values				
Melt temperature	[°C]	260	250	300	280	280
Mould temperature	[°C]	90	80	130	90	110-90
Injection speed	[cm^3/s]	45	30	55	45	15
Holding pressure	[bar]	800	600	800	800	600
Cycle time	[s]	32	42	28	32	120

Table 1. Injection moulding parameters used for the replication of microfluidic shims. PMMA was moulded at two different mould temperatures and for COP, both isothermal and variothermal mould temperature control was used.

Collaborative Achievements

FEMTOPrint / 3D AG / FHNW



Collaborative Achievements

In endorsing this whitepaper, we have effectively showcased a swift and cost-effective process chain—from glass to nickel to polymer—for the production of microfluidic devices.
This accomplishment is the result of a successful partnership between FEMTOPrint, 3D AG, and FHNW.

The obtained results are highly promising, and we firmly believe that this process chain holds significant potential for realising intricate microfluidic devices and expediting the development cycles in microfluidics. We are enthusiastic about tackling your challenging projects and collaboratively elevating them to an industrial level.

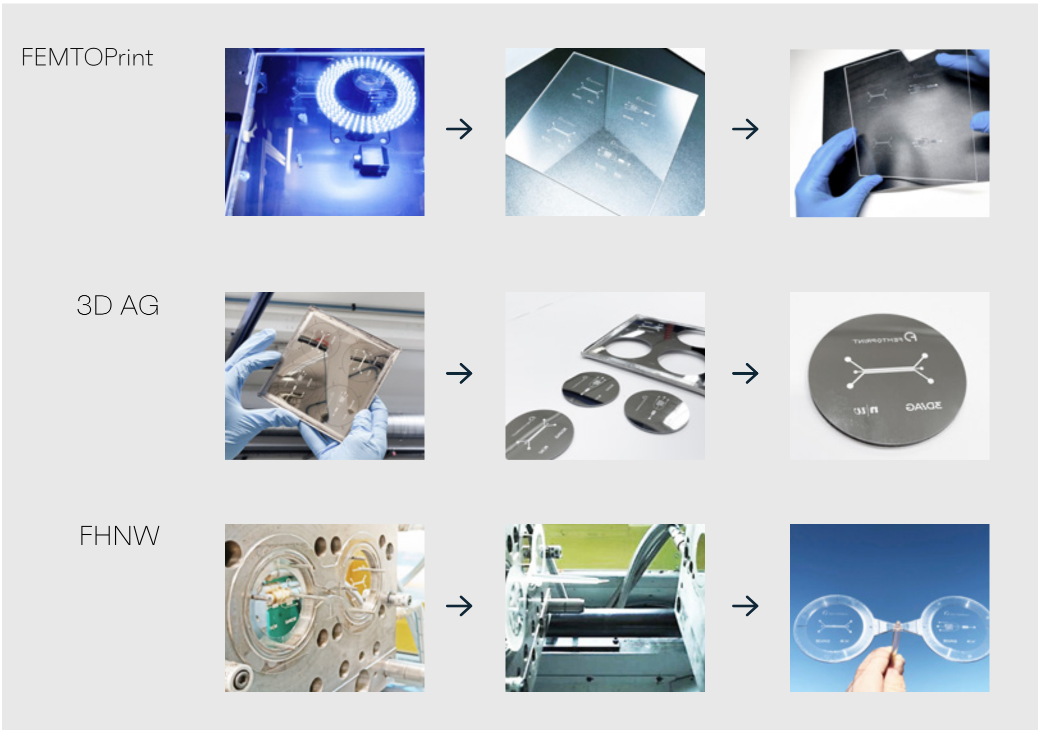


Figure 10. Case study summarising the collaborative achievements performed for this paper. Beginning in origination by FEMTOprint (top row) through electroforming Nickel shims and tool making by 3D AG (middle row) to mass scale production by FHNW (bottom row).

Cross-Check of Master, Shim and Polymer Parts

The topographical features on the nickel shim and replica produced in PMMA, COC, and COP, respectively, were analysed by confocal laser-scanning microscopy (CLSM) to judge the replication quality. Most of the microstructures were very well replicated, as seen in Figure 11.

Some of the features in the polymeric replica are not fully replicated at the edges (most prominently seen for the hexagon structure). In order to improve the replication, variothermal injection moulding was applied to enable complete filling of the micro-cavities, thus providing a perfect replica (shown in Figure 11 for COP). The effect of variothermal mould temperature control becomes essential when replicating rather fine channels, as seen in Figure 11.

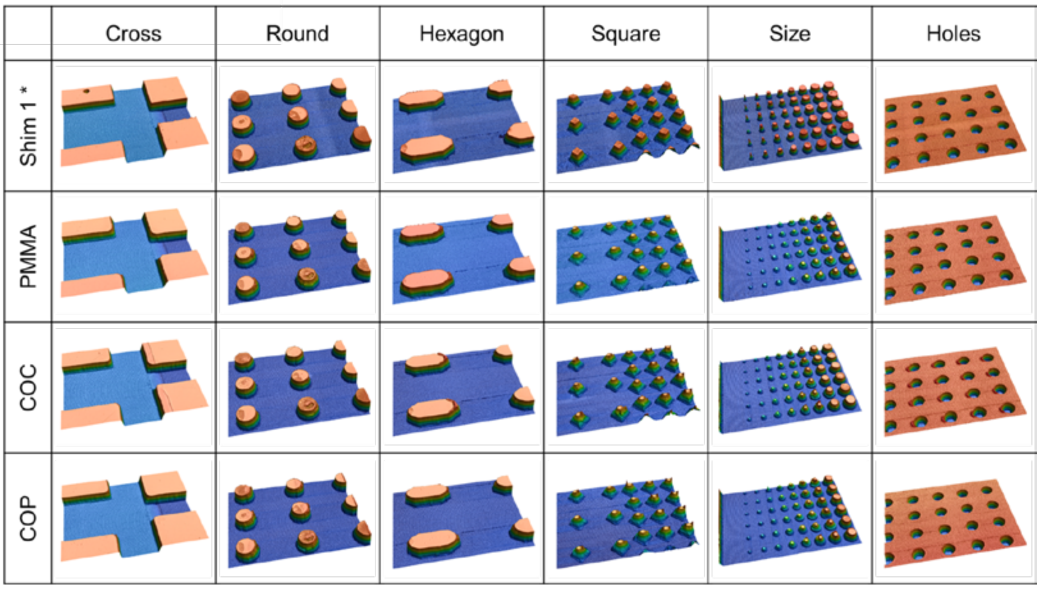


Figure 11. CLSM images of different microstructures present on the microfluidic shim.
Note that the topography of the nickel shim has been inverted (indicated by *) to allow for direct comparison.

In figure 12 we can observe how the replication fidelity improved significantly when variothermal mould temperature control was applied, leading to better definition of the edges of the microstructures. Note that the topography of the nickel shim has been inverted (indicated by *) to allow for direct comparison.

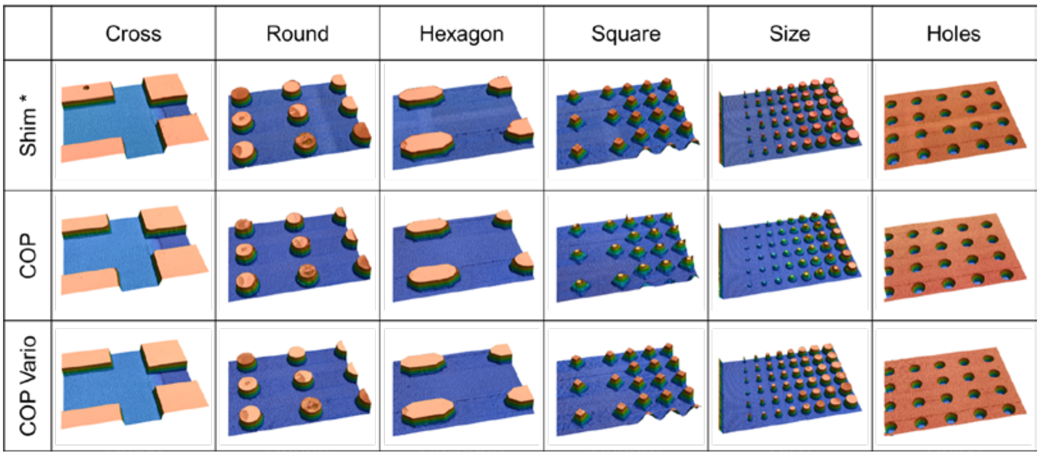


Figure 12. CLSM images of different microstructures present on the microfluidic shim.

On figure 13 CLSM images of a region on shim 2 features the very fine connecting channels between two larger channels. With conventional moulding conditions, these features cannot be sufficiently well replicated, as seen by the rounded edges. In contrast, when using the variothermal process, perfect replication is achieved. Note on figure 12 that the topography of the nickel shim has been inverted to allow for direct comparison.

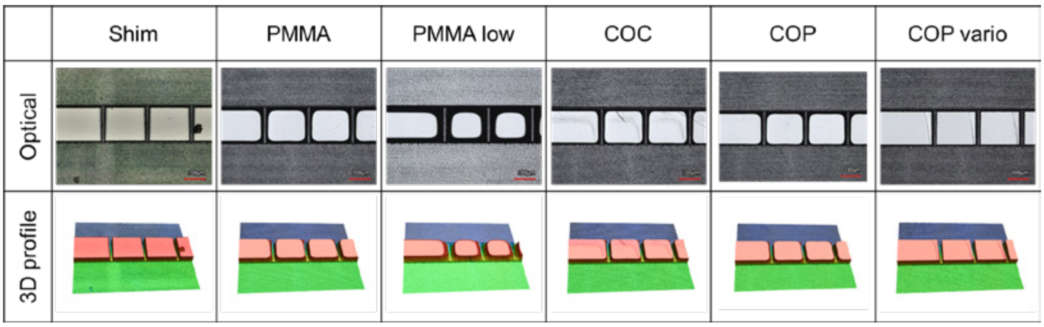


Figure 13`. CLSM images of a region on shim 2 featuring very fine connecting channels between two larger channels.

About the Authors

Dr. Marek Krehel
CTO at 3D AG

Dr. Marek Krehel, an Optical Engineer, joined 3D AG in 2017 and has been serving as the Chief Technology Officer since September 2022. He earned his doctoral degree in Engineering from ETH Zurich in 2014, focusing on Polymeric Optical Fiber for biomedical sensing at Empa. Following his doctorate, he worked as a Senior Research Associate at Luzern University of Applied Sciences, specializing in light redirection systems from 2014 to 2017. Prior to this, he contributed to Philips Research in Eindhoven, characterizing scattering systems in light-guiding applications. Dr. Krehel obtained his master's degree in this field from Wroclaw University of Technology.

Dr. Andrea Lovera
CTO at FEMTOPrint

Andrea earned a PhD in photonics from EPFL in 2014. Later, joined FEMTOprint as Field Engineer, contributing to tech maturation, business model evolution, and expansion. Since 2017, leads the Engineering department and serves as CTO, overseeing company technical development and strategic evolution on the board.

Prof. Dr. Per Magnus Kristiansen
Head of the Institute of Polymer Nanotechnology FHNW

Prof. Dr. Per Magnus Kristiansen studied Materials Engineering at ETH Zürich, where he also earned his PhD in the Polymer Technology group in 2004. In the following five years, he worked for Ciba Specialty Chemicals, initially focusing on the market introduction of novel clarifiers and research on supramolecular additives. From 2007, he was part of the Automotive Application Technologies team, serving clients along the entire value chain with additive solutions. In 2009, he joined the FHNW University of Applied Sciences and Arts Northwestern Switzerland as a Professor in Polymer Engineering and Nanotechnology. Since 2016, he has been the head of the Institute of Polymer Nanotechnology (INKA) at FHNW, where he also served as Deputy Head from 2011 to 2016.

About the Partners

With over 30 years of experience in micro and nanotechnology, 3D AG stands as a prominent tooling and process development company based in Switzerland. Specialising in mastering distinct processes for a diverse array of structures, our core competencies include electroforming high-quality nickel moulds up to 1,300mm x 1,800mm.

We excel in the step and repeat multiplication of structures, creating a larger area for mass-scale applications. Originally developed for upscaling nano security elements, our high-precision electroforming and recombination skills set us apart.

Based in Switzerland, FEMTOPrint is an industry-leading contract development and manufacturing company offering unique laser micro-fabrication services for glass micro-devices. Our mission is to go beyond industry boundaries to help improve lives through outstanding products in areas like health, consumer goods, energy, transportation, and communication.

We specialise in advanced laser technologies to deliver breakthrough 3D glass micro-devices with high-quality and precision in the micron range for applications in medical, biotech, optics, photonics, quantum, semiconductors, aerospace, AR & VR, watchmaking, and more.

Some of our strengths:

- Extraordinary engineering expertise and multidisciplinary competencies
- Advanced micro-manufacturing technology for high-precision, 3D glass microsystems
- Trusted CDMO for more than 200+ partners
- Control of the entire value chain, vertically integrated services
- ISO 13485:2016 and 9001:2015 certified

The FHNW Institute of Polymer Nanotechnology (INKA) focuses on applied R&D in the area of functional polymer surfaces, which involves three core competence fields:

- Surface texturing on the micro and nano scale, covering the entire value chain with particular focus on industrial replication technologies such as injection moulding and hot embossing and subsequent processes like bonding and laser cutting.
- Surface functionalization by means of chemical modification or coating technologies involving UV curing, e-beam and atmospheric plasma.
- Surface analytics including topographical and chemical analysis down to the submicron scale.

FHNW's facilities encompass two technical centres with state-of-the-art polymer processing equipment and coating technologies, two analytical laboratories and a chemistry lab.

For surface texturing, we use a variety of existing moulds but also develop custom-specific tooling if needed. We make use of ultra-short pulse laser micromachining (in-house) as well as a variety of mastering technologies through our broad network of reliable and experienced partners.