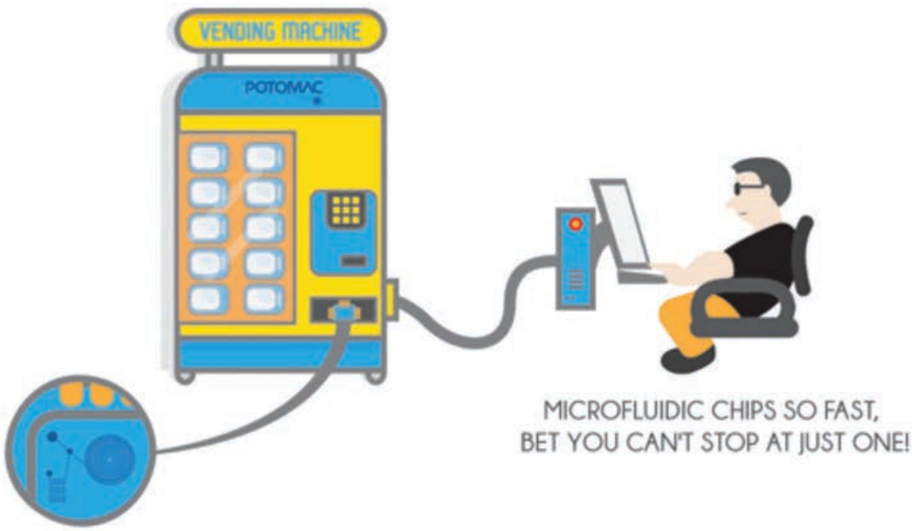
Microfluidic Prototypes: A VIRTUAL VENDING MACHINE



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When we look at the evolution of modern manufacturing processes, it can be seen that digital fabrication has allowed them to become more and more automated. Smart machines are taking on an increasing part of non-creative labour, leveraging the creativity of talented designers. For example, not too long ago, a typical design office was crowded with drafting tables, stacks of paper, rulers, compasses, and some pretty intricate tools almost no one today would know how to use.

One of the requirements for a design engineer was a “dimensional imagination”, a capability to imagine and draw an object in three dimensions. And then the final drawings were forwarded to a model shop, where workers manufactured the prototypes of metal, plastic, and wood, using various manually controlled machinery and tools. Mistakes were often revealed only during assembly, and the whole cycle had to be repeated.

How different the picture is today. 2D and 3D CAD software for mechanical design has completely changed an engineers’ life, allowing rapid design iteration and revision, and paving the way to fast digital prototype fabrication and short design cycles. Similar evolution has occurred in electronic design. By simply sending a file to a 3D printing service, a printed circuit board fabricator, or a CNC machine shop a designer can procure relatively inexpensive prototypes in near real time. From the 10,000 foot perspective, these digital fabrication services resemble virtual vending machines for customised products. In this article, we preview work underway at Potomac that applies a virtual vending machine concept to fabrication of microfluidic prototypes.

The word “microfluidics” is not quite new. It is used to describe behavior of very small volumes of liquid flowing through channels ranging from tiny capillaries to 1 mm “pipelines”. A good example a blood flow in a human body. Commercial technologies suitable for control of small volumes of liquids first appeared in 1980s and were used in ink-jet printing. But biomedical applications always were and still remain the most challenging and exciting field for microfluidics. Development of new drugs, genetic studies, point-of-care diagnostics, and fast analysis of air and water for presence of toxins and pathogens are just a few of the areas in which microfluidic product development is underway — and in which rapid prototyping is needed.

A typical microfluidic system prototype consists of a fluid handling structure with miniature channels, wells, mixing structures, and connection ports that are coupled to external micropumps, microvalves, electronic modules, and similar actuation and analytical modules. The fluid handling structure is different in almost every application, and early stage prototyping and optimisation of the system often requires construction of small quantities of several designs. In following sections, we describe an approach to building miniature fluid handling structures that allows a designer to quickly and inexpensively obtain customised prototypes of his own design. For simplicity, we will refer to these miniature fluid handling structures as microfluidic chips.

The user experience is designed to be much like buying unique microfluidic chips from a virtual vending machine. Quick, low-cost turnaround requires that the chips conform to several design rules that constrain chip size, feature dimensions, and fabrication materials. Within these constraints, however, the designer is free to follow his imagination. Two of the most popular substrate materials, PMMA and polystyrene are available to the designer, and dimensional constraints have been chosen to be compatible with some of the most popular feature sizes. The substrate is embossed with a user-designed pattern to form an open microfluidic structure which is then capped with a pressure-sensitive adhesive tape to produce a closed fluidic structure. Adhesive compositions designed for biocompatibility are used to minimise risk of contamination of bio fluids.

The User Experience

The designer begins the fabrication process by submitting CAD files describing the chip layout in the 2D DXF format that can be generated by most CAD software. After uploading files to the Potomac website, he/she is quickly given a report summarising any specific drawing elements that do not conform to the published design rules, and provided an opportunity for resubmission after modification. Accepted files move to a streamlined quoting process, and the designer receives a quotation by email shortly after file acceptance. The company's receipt of a credit card prepayment moves the files into the fabrication queue. After fabrication the completed microfluidic chips are packaged and shipped by the method selected in the payment process, and tracking information is provided at the time of shipment. In contrast with alternative approaches to prototyping, this virtual "vending machine" gives the designer an almost effortless digital approach to fabrication in standard thermoplastic materials. Members of the Potomac sales group are available by telephone or email for presubmission questions and follow up support.

Inside the "Vending Machine"

SOFTWARE

Successful fabrication of even the simplest microfluidic chip requires integration of several process steps and a means for communication of design information to the equipment involved. To keep fabrication costs low and accelerate turn-around times, customer interfaces and every step of fabrication must be automated as much as possible. In addition, the user experience of the overall fabrication process is strongly influenced by the software interface to the machine. Consequently, software plays an important role in the implementation of the vending machine concept.

Proprietary software is used at the time of submission to check incoming design files for problems such as open structures, overlapping lines, missing drill files and similar issues. Conformance with design rules regarding feature sizes and overall chip size is also checked. The software identifies problem areas on the drawing and delivers a detailed report to the user if corrections are needed. When the submitted design files are ready for download into the appropriate machine, a quotation is automatically generated for quick review by a sales engineer and then forwarded to the customer.

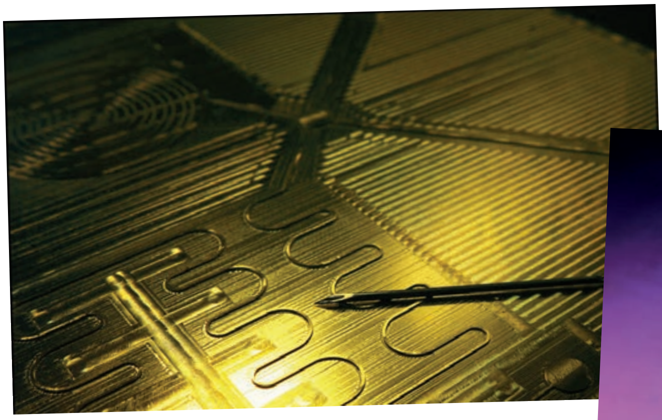
The first fabrication step is mould fabrication for hot embossing of the fluidic structure into the substrate. Completion of credit card payment processing releases the design files to the fabrication queue, where they are downloaded into the appropriate mould fabrication machine as it becomes available. Direct import of the designer's DXF file into the laser or mechanical micromilling equipment used for mould fabrication is needed to minimise engineering time spent on file correction. Separate DXF files are needed for description of the microfluidic structure and for via drilling and substrate excision patterns. A third file is necessary for supplemental design information, such as desired materials, feature depths, and similar factors that are not included in the CAD files.

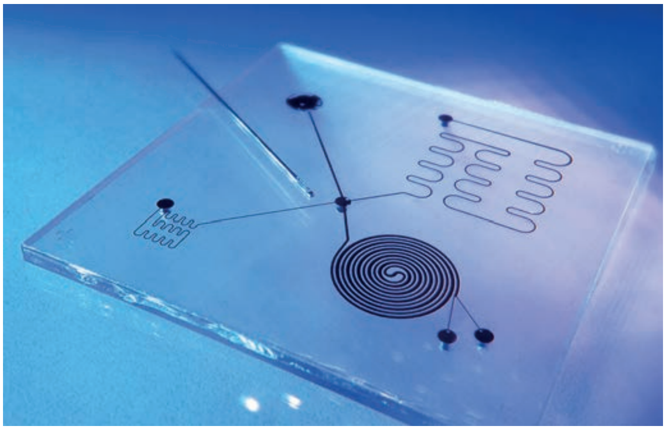
MOULD FABRICATION

Fabrication of the mould master is often the most time consuming and expensive step in manufacturing microstructures through replication processes. The quality of the final device is greatly determined by the quality of the mould used for replication. The selection of materials and processes that are being used for mould master fabrication mainly depends on the type of replication process, physical dimensions of the microstructures, and life expectancy of the mould. Metals such as stainless steel, aluminum, and brass are attractive choices for the mould materials. They offer not only high thermal and mechanical strength, but also high thermal conductivity required for fast heating and cooling cycles during replication. Precision laser milling of high-temperature plastics is an alternative mould fabrication technique that is well-suited to production of moulds with fine or complex features.

The majority of established techniques for microfabricating metal moulds are based on standard lithographic processes for patterning of various types of substrates. As alternative mould fabrication techniques, mechanical and laser micromilling offer the benefits of higher throughput and reduced cost, and are consequently used in our digital fabrication process. Although micromilling cannot achieve the fine resolution or minimum feature size of many lithographic techniques, it is well suited to the many microfluidic applications that require structures and feature spacing in the range of 50–500 µm. In addition, micromilling allows fabrication of multi-level structures in the same machining cycle with limited impact on cost and throughput.

<< *Figure 1a: Metal master mould after micromilling by CNC* >>





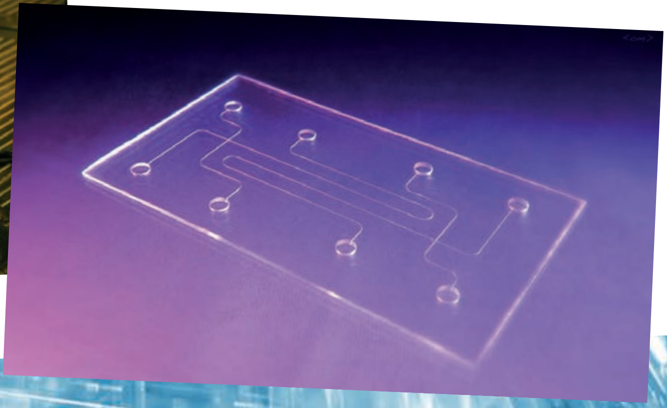
<< *Figure 2. Fully functional microfluidic chips can be fabricated quickly and cost effectively* >>

The quality of milled moulds is subject to some operational constraints that include surface roughness in the micron range on machined surfaces and restrictions on inside corner radii. In most applications, these are not significant limitations.

REPLICATION

Historically, several fabrication methods for polymer microfluidic devices have been demonstrated. These include injection moulding, soft lithography, laser ablation, and hot embossing. From these, we have chosen to use hot embossing since it is relatively simple, easy to implement and adaptable to fast turnaround. For high production volumes, multi-cavity injection moulding is a proven option but suffers from long and costly process development cycles. However, even at higher volumes, hot embossing with an optimised tooling system can provide a competitive edge in applications that require high quality.

<< *Figure 1b: Exact mirror of the master mould is replicated to the embossed thermoplastic* >>



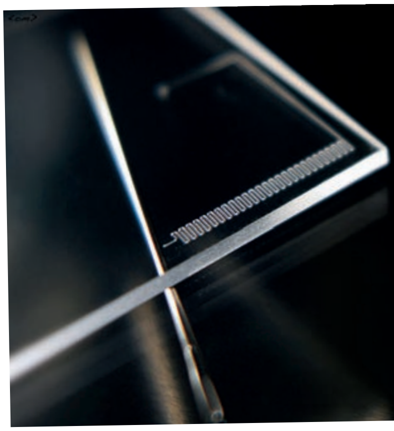
During each hot embossing cycle, a piece of thermoplastic material sheet is cleaned thoroughly, dried, and placed on top of the fabricated mould master. The mould and plastic are then sandwiched between heated platens of a hydraulic press and subjected to a pressure-time cycle that has been optimised for each material and is influenced by the microstructure size and shape to be replicated. Layer design of the embossing stack to promote uniformity of pressure and temperature has also been optimised for the materials of interest. If suitable embossing parameters are used, the resulting plastic microstructures are the exact mirror of the inserted mould.

EMBOSSED SUBSTRATE POST PROCESSING

Following mechanical via drilling and edge contouring, the parts are cleaned with distilled water and isopropyl alcohol and dried with nitrogen in preparation for an initial quality control inspection and closure of the embossed features by bonding a sheet of featureless polymer. This QC step involves measurement of critical dimensions such as microchannel width, depth, and/or spacing and verification that channels and holes are free of contaminants and fine debris.

COVER ATTACHMENT

Closure of the microfluidic structures is accomplished by attachment of an unpatterned cover sheet. Various bonding approaches, including thermal bonding, solvent bonding, ultrasonic bonding, laser welding, and tape adhesives have been described in the technical literature, depending on the materials and the constraints imposed by the final microfluidic application. To achieve successful bonding, most of these techniques require meeting one or more conditions such as specific surface chemistries, relatively high temperatures, extremely clean surfaces and a dust-free environment, and/or specialised tools. Use of adhesive layers for bonding and sealing of microfluidic parts is the simplest and probably most reliable available technique. Adhesive bonding additionally offers simple integration of non-similar standard or even nonconventional materials in microfluidic applications. In this approach, a layer of adhesive material is applied to the featureless cover layer followed by bonding to the embossed surface. The adhesive sealing process is further simplified by the use of specially-formulated, commercially-available adhesive tapes that are utilised as cover in our quick turn process. These combine a thin polymer cover layer with a thin layer of pressure-sensitive adhesive. They eliminate the need for separate adhesive application and streamline the cover attachment process.



<< Figure 3: Hot embossing step is followed by via holes drilling, edge contouring, and cover attachment. >>

PACKING AND SHIPPING

After a final inspection to assure proper sealing, the completed parts are carefully placed inside clean plastic bags and then prepared for shipment. Proper cushioning material may be used to separately surround the bags containing delicate parts in order to prevent any possible product-against-product damage and to protect contents from shock and vibration during the delivery process. Different shipping options including overnight, second day air service, and ground shipping are available within the United States and are typically specified in the manufacturing contract. International shipping is also offered with delivery times varying by destination location.

Conclusions

We have previewed here ongoing development work at Potomac aimed at providing a designer with a fast, low-cost approach to prototyping and low volume production of microfluidic flow structures. It provides an attractive alternative to do-it-yourself fabrication of devices in PDMS or patching together a maze of less than optimum subcomponents. The designer is now able to quickly explore new concepts by digital fabrication of custom designs developed on his computer, submitted by internet, and fabricated in popular polymer materials.

The user experience is intended to be similar to purchasing items from a virtual vending machine that delivers customised products. Like any vending machine, this virtual one won't be a replacement for full service interactions with an appropriate group of humans. And we want to emphasise that Potomac continues to offer full-service microfabrication services. But there are times when a vending machine offers exactly the products that the occasion demands.

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