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Investigating the capability of low-cost FDM printers in producing microfluidic devices

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ABSTRACT

Purpose: This paper aims to investigate the possibilities of using 3D printing by fused deposition modelling (FDM) technology for developing micro-fluidic devices by printing a benchmark test part. A low-cost desktop printer is evaluated to compare the minimum possible diameter size, and accuracy in the microchannel body.

Design/methodology/approach: The parts were designed using SolidWorks 2016 CAD software and printed using a low-cost desktop FDM printer and Polylactic acid (PLA) filament.

Findings: Desktop 3D printers are capable of printing open microchannels with minimum dimensions of 300 μm width and 200 μm depth.

Research limitations/implications: Future works should focus on developing new materials and optimizing the process parameters of the FDM technique and evaluating other 3D printing technologies and different printers.

Originality/value: The paper shows the possibility of desktop 3D printers in printing microfluidic devices and provides a design of a benchmark part for testing and evaluating printing resolution and accuracy.

Keywords: Microfluidics, Fused Deposition Modelling (FDM), 3D printing, Additive manufacturing

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Microfluidics is a technique for systematically manipulating and controlling fluids in micro-scaled channels. Since her first development in the 1970s, this technology has been explored by various industries for diverse applications and has gradually integrated into many fields, including biology, physics, medicine, and analytical chemistry [1,2]. Compared with traditional techniques, microfluidic technology has many merits, including low cost and a small footprint leading to portability, fast analysis speed, small sample consumption, and component integration [3].

A microfluidic chip, also known as lab-on-a-chip, is a set of micro-channels through which fluids flow, connected to achieve the desired features. This network of microchannels trapped in the microfluidic chip is linked to the outside by several holes of different dimensions (inputs and outputs) pierced through the chip. Through these pathways, fluids are injected into and evacuated from the device with some external active systems [4]. Owing to their microscale dimensions, microfluidic devices are typically operated at low Reynolds numbers, and fluidically characterized by laminar flow behaviour. Under laminar flow, mixing between adjacent parallel streams is minimal and diffusion is the only mechanism of mixing [5]. While mixing based on diffusion could take days in conventional flask-based systems, the small distances within microfluidic channels enable complete mixing within seconds or minutes, reducing volumes of samples and reagents, saving costs on reagents, and producing less waste [6].

Microfluidic devices can be fabricated from a range of materials using different processes including soft lithography, paper microfluidics, micromachining, injection moulding, and hydride paper-based open-channel microfluidics [7]. In the last two decades, soft-lithography using polydimethylsiloxane (PDMS) micro-moulding has been a widely used method as PDMS is biocompatible, cheap, and transparent (240 nm-1100 nm), has low autofluorescence, water-impermeable, and rapidly prototyped with high precision using simple procedures [8]. However, these processes can be time-consuming, imprecise, expensive, or challenging for design changes and they often require a dust-free (cleanroom) environment to ensure error-free devices. In addition, they show a lack of truly three-dimensional (3D) architecture and flexibility in device design.

Recently, three-dimensional printing (3D Printing) or additive manufacturing (AM) has emerged as a potentially revolutionary technology in the field of microfluidics. The main additive manufacturing techniques for microfluidics are fused deposition modelling (FDM), stereolithography (SLA), selective laser melting (SLS), inkjet/Poly-jet printing, and laminated object manufacturing (LOM) [9-15]. The advantages of 3D printing are its simplicity, fast and efficient prototyping with no need for photomasks, photoresists, and cleanroom facilities [16] which require neither tooling nor assembly, produce minimal waste and minimize distribution costs, so the ability to rapidly prototype a physical model in a few hours has already revolutionized the product design process by allowing designers to test designs before investing in tooling or fabrication processes [10].

3D printed microfluidics has found many applications in recent years, including the preparation of size-controllable siRNA nanocomplexes for the treatment of various diseases [17], droplet generation and tracking and identification of DNA using DNA melting analysis [18], structural energy storage devices [19], isolation of circulating tumour cells (CTCs) from blood samples for cancer treatments [20], fabrication of optical and electrochemical detection systems and sampling interfaces for analytical purposes [21], Ammonium analysis within environmental water [22] and pharmaceutical applications for drug delivery system and drug testing [23].

Given the low-cost microfluidic device fabrication techniques, FDM appears as a strong technology, it employs cost-effective thermoplastics such as polylactic acid (PLA), thermoplastic polyurethane (TPU), poly (methyl methacrylate) (PMMA), polyethylene terephthalate glycol (PETG), acrylonitrile butadiene styrene (ABS) and nylon. Despite the merit of being the least costly of other 3D printing techniques, FDM presents limitations in terms of resolution, dimensional accuracy, and transparency, and it poses difficulties in printing microchannels below 100 µm. Therefore, Dimensional accuracy combined with transparency on FDM technology is highly desirable yet challenging to attain.

In this paper, we describe the design and fabrication of a benchmark part for testing the capability of FDM 3D printers for producing microfluidic devices. We demonstrate that open microchannels can be printed using a commercially-available FDM 3D printer (below 300$) with a minimum feature width of 300 µm by examining printing resolution, dimensional accuracy, and repeatability. Finally, we discuss the limitations and some solutions of 3D printed microfluidic chips with low-cost FDM printers.

2. Materials and methods

2.1. Printing process

All designs were created using SolidWorks 2016 CAD software, exported to STL format, and then transferred to Ultimaker Cura for the slicing process. Parts were printed on a Creality Ender 3 V2 3D printer with a 0.4 mm nozzle, using a 1.75 mm transparent PLA commercial filament as a material. PLA filament was chosen since it is biodegradable and does not leave a hazardous footprint on the environment. The printing parameters were chosen as follows: layer height: 0.2 mm, wall thickness: 0.8 mm, infill density: 20%, infill pattern: cubic, infill orientation: 45°, build plate temperature: 60°C, extrusion temperature: 200°C and printing speed: 40 mm/s.

The test part design was based on a functional model implemented by other research studies investigating microfluidic chips, including common microfluidic features such as channels and circular holes, thus allowing additional inferences to be drawn.

The Benchmark part consisted of a set of open microchannels on both the x-axis and z-axis, with a width ranging from 100 µm to 600 µm and a depth ranging from 100 µm to 1000 µm, additionally to a set of holes with ranging diameters from 500 µm to 1200 µm.

2.2. Characterization

The printer repeatability was performed for the channels x_1 and z, in the matter of dimensional accuracy of the printer, by printing the part four times using the same printing parameters.

Features were measured and quantified using a Dino-Lite digital microscope and DinoCapture 2.0 software. All measurements were taken no less than four times in terms of achieving statistically significant results.

3. Results and discussion

Microchannel fabrication with FDM has been a challenge because of several reasons: (1) the filaments laid down by the extrusion process cannot be arbitrarily joined at channel intersections; (2) the lack of structural integrity between the layers results in weak seals; and (3) the size of the filaments extruded are larger than typical channels used in microfluidics. Therefore, the production of truly 3D microchannels under 100µm using FDM technology remains difficult [24].

However, resolution and accuracy are some of the key factors for 3D printed microfluidic devices. Many researchers focus on developing new methods for the optimization of these factors, rendering 3D printing compatible with the fabrication of microfluidic devices and helping enhance the development of custom microfluidics.

For example, 400 µm by 400 µm square enclosed channels were formed using two commercially-available FDM printers and were used successfully to demonstrate their applications in droplet generation & tracking, and identification of DNA using DNA melting analysis [18]. Channels below 100 µm were printed with cheap printers using thermoplastic polyurethane (TPU), making it versatile for microfluidic applications [25]. A microfluidic device consisting of serpentine channels measuring 260 µm in width and height with three inlets and one outlet was achieved using an FDM printer with a 0.2 mm nozzle and was used to synthesize metallic core-shell nanoparticles [26]. PMMA microfluidic chips with a minimum channel width of 300 µm were additively manufactured using a benchtop FDM printer on a PMMA substrate to ensure transparency [27].

Moreover, PLA has been extensively researched in the field of advanced microfluidics; it has been proven to be suitable for tissue engineering, and cell culture, and has been authorized by the FDA as a drug carrier [28]. Lucas P. Bressan et al. created a 3D printed transparent microfluidic device based on PLA for the synthesis of silver and gold nanoparticles [29]. Besides, Lucas C. Duarte et al. developed a 3D printed microfluidic mixing device, using PLA as a material, for mass spectrometric monitoring of chemical processes (MS) [30].

To investigate the printer resolution and accuracy, we designed a Benchmark test part consisting of different features (Fig. 1), including open channels on both the x and z-axis intending to test the producibility of channel widths and depths, holes in terms of examining the circularity and two y-shaped channels with two different angles to specify the precision of printing angles. All the measurements of the different features are presented in Table 1.

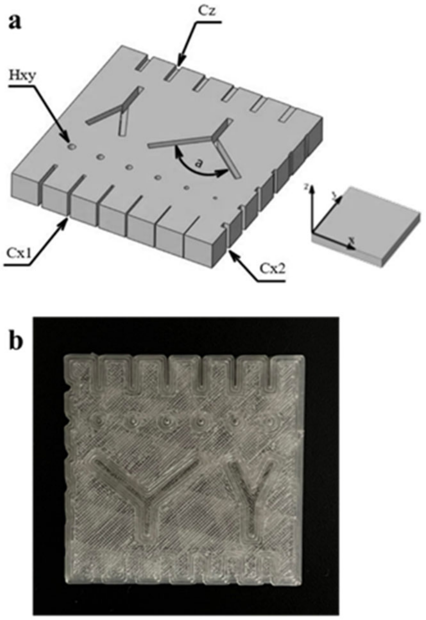


Fig. 1. a) CAD design of the Benchmark part showing all the features and print orientation; b) image of a sample of printed parts

After printing the samples, taking the first images with the digital microscope, and carrying out the first measurements, we observed that the printed holes and Cx_2 channels have shown bad quality and undesirable results in terms of shape and size. Holes haven't appeared in a rounded

Table 1.
Features measurement

Feature	Measurement	Normal measurement series
Channels x_1 (Cx_1)	Width, µm	100, 200, 300, 400, 500, 600
Channels x_2 (Cx_2)	Depth, µm	100, 200, 400, 600, 800, 1000
Channels z (Cz)	Depth, µm	100, 200, 400, 600, 800, 1000
Holes xy (Hxy)	Diameter, µm	500, 700, 900, 1000, 1100, 1200
Angle (a)	Angle, °	100, 50

Table 2.
Printed holes compared to their designed size

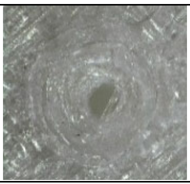
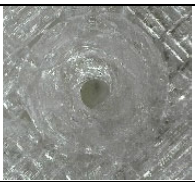
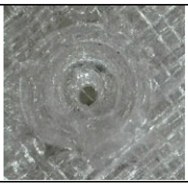
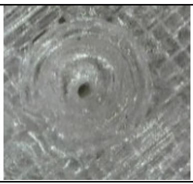
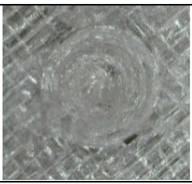
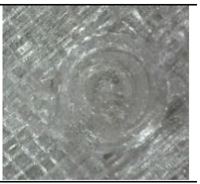
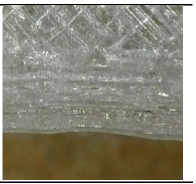
Designed size, µm	1200	1100	1000	900	700	500
Printed holes						

Table 3.
Printed channels (Cx_2) compared to their designed size

Designed size, µm	1000	800	600	400	200	100
Printed channels z						

shape (Tab. 2) and the measured diameters have shown a large deviation from the nominal sizes, they were much smaller than what was intended, additionally, holes with a diameter below 1000 µm weren't successfully printed and have shown a noticeable shrinkage which has resulted in closed holes (Fig. 2d). Therefore, this problem of shrinkage might be caused by three main reasons: material shrinkage which is the contraction of the material while it cools down, layer compression caused by the compressive force applied while the deposition of the first layer causing the bottom layers to squish out and expand beyond their intended borders, and finally mesh resolution that takes place because holes are not designed precisely spherical (polygon-based approximation) which results in holes that are smaller than expected. As shown in Table 3, Cx_2 channels have shown no discernible shape in channels with nominal heights dimensions of 200 and 100 µm. Additionally, a slight concavity has been shown in the shape of channels with 400µm nominal height. Otherwise, channels with designed dimensions of 600, 800, and 1000 µm, were printed with curved edges and sloping walls which weren't convenient with the CAD designs, showing significant deformation. This can be caused by the low XY resolution of the printer, as a result, the precision of the final printed feature was affected. Printed channels weren't measured because it was an offset between the two walls and so the comparison in terms of size between the CAD design and printed features wasn't performed.

As mentioned before, the Benchmark part was printed four times, and the dimensions of channels (z and x1) were measured several times. Figure 2 shows the results of printing accuracy and precision. After taking all the necessary measurements, we calculated their average, plotted each measured value against its nominal value which corresponds to the CAD dimension, and compared both values to examine the accuracy and precision of features.

As a result, we obtained an average deviation of 15.6 µm throughout all measurements. Specifically, we found that the z-axis tends to have the highest accuracy of 8.5 µm deviation, whereas the x-axis proved to be the least accurate

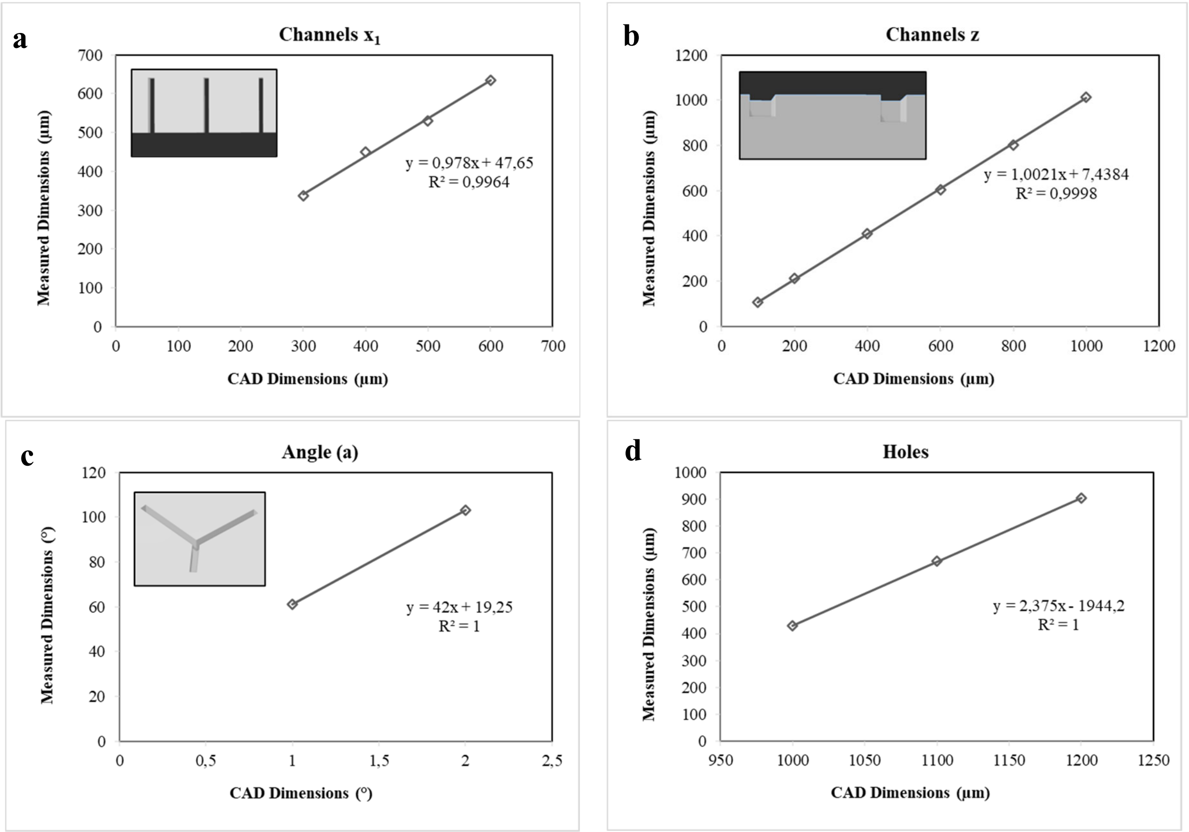


Fig. 2. a) Measured channel widths on the x-axis compared to CAD-designed depths; b) Measured channel heights on the z-axis compared to CAD-designed widths; c) Measured y-shaped channel angle compared to designed angle; d) Measured diameters of holes compared to CAD-designed

with a deviation of 37.7 µm. Therefore, the printing orientation should be done on the z-axis for optimum channel size accuracy.

Altogether, the printed features showed a deviation from the CAD dimensions, and this deviation depends on the orientation of the features on the build plate. Printed channels on the x-axis and z-axis, below 300 µm wide and 200 µm deep, respectively, were hard to be obtained and were not further examined.

To demonstrate the results obtained below, we printed a model microfluidic device with 300 µm width and 200 µm depth. The device consisted of a Y-shaped open channel (Fig. 3a) which can be applied for mixing. The device was successfully printed which approved the results obtained above. To test the performance of the channel, we applied green ink to see fluid behaviour inside the channel (Fig. 3b) and we observed that fluid flows easily. As shown in the figure, the applied ink has gotten outside the holes and that's because the channels are not closed and embedded into the device. However, this study aims to investigate the accuracy of the FDM printer, thus the printed models were made just to test the results obtained with the Benchmark part and not to be tested and applied for specific microfluidic utilization.

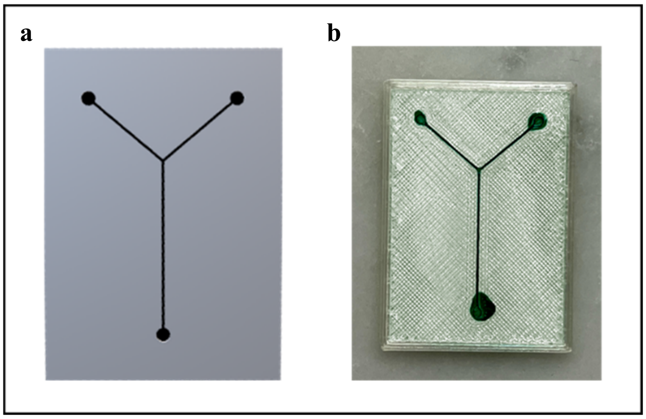


Fig. 3. a) CAD design of Y-Shaped open channel; b) FDM printed sample with green ink showing the channels

In terms of transparency, Valentin Romanov et al. [18] showed that it is a function of nozzle temperature, printing speed, and cooling rate. They have also shown that transparency can be achieved by lowering the nozzle closer to the printing bed, so they have reduced the gap between the nozzle and the printing surface to 30 µm which resulted in complete sealing and high transparency of the surface. Matt D Nelson et al. [25], they have left a distance of 50 µm between the nozzle and the build plate and they obtained a noticeable improvement in transparency and optical qualities, they also found that samples with widths varying from 200-800 µm have a transparency greater than 85%. Hence, to improve the transparency of our printed microfluidic devices, we have to work on improving nozzle temperature, printing speed, cooling rate, and especially the distance between the nozzle and printing plate which have to be decreased compared to the normal distance set by the printer.

Surface roughness is a major challenge of the FDM technique. In our case, the printed models have shown a noticeable roughness. The rougher surfaces can be a result of the stacking layers of the printed material which creates a wavy-profiled wall. This may limit the possibility of FDM printing to be applied in several microfluidic applications, including biological applications and especially those depending on exact symmetry, as it can affect the laminar flow inside the channels and many other factors. However, the value of the surface roughness depends on the two important parameters, including layer height and wall thickness, so to improve the surface quality of our printed microfluidic devices, by decreasing the surface roughness and increasing resolution, we have to work on optimizing these factors and well study their impact on the quality of the printed microchannels. Additionally, several post-processing techniques can be applied to obtain smoother surfaces with desirable characteristics, for example, PLA can be smoothed with chemicals like THF or MEK.

4. Conclusions

To sum up, in this work, we only focused on investigating the accuracy of the FDM 3D printing technique. We tested the ability of a low-cost FDM 3D printer in printing microfluidic features. We described the design and the fabrication of a benchmark part with common microfluidic features such as channels and circular holes to evaluate the printer's accuracy and resolution. The printed features have shown a deviation from the nominal features with better accuracy on the z-axis. It was demonstrated that open channels with 300 µm width and 200 µm depth can be successfully printed with commercial FDM printers.

Transparency, surface roughness, and biocompatibility are some of the challenges related to the 3D printed microfluidics with the Fused Deposition Modelling technique. Future works will focus on improving the transparency, decreasing the surface roughness, and studying the biocompatibility by optimizing the process parameters, comparing different materials, testing novel methods, and employing different post-processing techniques. Furthermore, we will investigate the ability of printing enclosed channels with different shapes and sizes for some specific applications.

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