TOWARDS 3D PRINTED MICROFLUIDIC DEVICES IN α-ALUMINA

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ABSTRACT

3D-printing in microfluidics is a relatively new approach. However, most of the applications are printed in polymeric material, limiting the use in high temperature applications. This paper describes the first steps towards a 3D printed microfluidic device in α-alumina. This material could potentially be used in applications with temperatures up to 1000 °C. In this paper we shortly discuss the history of 3D printing and microfluidics, the material properties of α-alumina, the theory on membrane deflection, and proposed structures to test this theory, gas-tightness, metal adhesion properties of α-alumina.

KEYWORDS

Laminated object manufacturing, 3D printing in α-alumina, high temperature microfluidics

INTRODUCTION

3D printing

After the Second (electricity and assembly line manufacturing) Industrial Revolution the world was mainly based on Fordism, a concept of mass production originally based on the large-scale manufacturing of cars. However, the demand for customized goods is increasing, goods that no longer can be made with conventional methods. Additive manufacturing (AM) is, in contrast to subtractive (e.g. milling, turning, grinding) and equivalent manufacturing (e.g. casting, forging), a relatively new field (roughly 40 years compared to centuries), and sometimes referred to as the third industrial revolution[1]. It is defined by the American Society for Testing and Materials (ASTM) as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"[2].

One major technique in AM, and often used as a synonym for AM, is 3D printing. Though the first patent is from almost 10 years earlier[3], this technique emerged in the early 1980s with a patent on the first commercial stereolithography (SLA) machine[4]. After SLA, the field of 3D printing evolved and matured, making that more 3D printing techniques were developed. With the expiration of the first patents, 3D printing became open-source, which greatly reduced the costs and boosted the development of each printing technique and even hybrid techniques. A 2010 Gartner's Hype Cycle Report[5] identified 3D Printing as a transformational technology in the Technology Trigger phase of the Hype Cycle[6]. According to the ASTM F42 subcommittee on Additive Manufacturing Technologies, established in 2009, the field encompasses 7 distinct printing methods[2], which are nowadays used in all kinds of industries, ranging from aerospace to automotive and medical equipment. This makes the prediction that it was only 5 to 10 years away from mass adoption, back in 2010[5] a quite valid prediction. The seven distinct 3D print methods are listed in table 1 together with a reference to their first patent.

Table 1: The seven distinct 3D printing techniques with their corresponding first patents and date of filing.

3D printing technique	U.S. patent no.	Date of filing
Material extrusion[3]	4,078,229	Jan. 27, 1975
Directed energy deposition[7]	4,323,756	Oct. 29, 1979
Material jetting[8]	4,665,492	Jul. 2, 1984
Vat photopolymerication[9]	4,575,330	Aug. 8, 1984
Sheet lamination[10]	4,752,352	Apr. 17, 1987
Powder bed fusion[11]	5,121,329	Oct. 30, 1989
Binder jetting[12]	5,204,055	Dec. 8, 1989

Microfluidics

Another relatively new field is microfluidics. Starting in the 1950s with the development of modern ink-jet printing technology[13]. The real revolution came when the first miniaturized gas chromatograph was realized in 1979 by Terry *et al.*[14]. Manz *et al.* extended this principle to the concept of micro total analysis system in 1990[15] (nowadays known as lab-on-a-chip devices). With the support of the Defense Advanced Research Projects Agency (DARPA) of the US Department of Defence, the development of field-deployable microfluidic systems that can be used for the detection of chemical and biological threats was boosted[16]. The next revolution in microfluidics came with the development of soft lithography[17]. However, this method uses molds/stamps which are often fabricated using a microfabrication line and the used materials are not industry compatible, preventing large-scale manufacturing[18].

3D printing in microfluidics

With 3D printing no molds/stamps are required and more complex 3D structures can be fabricated. Since 2012, this is being used for direct manufacturing of microfluidic reaction-ware[19]. Although, the efficiency of the microfluidic device depends largely on the chosen 3D printing method[18], all reported applications in microfluidics lack the possibility for being used at high temperatures and in harsh chemical conditions. This is solved by using α-alumina. In table 2 a comparison between α-alumina and two commonly used materials in (high temperature) micro-electro mechanical systems, i.e. silicon and silicon-rich silicon nitride (SiRN), is given.

Table 2: Comparison α-alumina with traditional MEMS materials.

Property [unit]	Si	Si_xN_y	α-Al_2O_3
Density $[\mathrm{g\,cm^{-3}}]$	2.28-2.38	2.37-3.25	3.00-3.98
Thermal conductivity $[\mathrm{W\,m^{-1}\,K^{-1}}]$	84-100	10-43	12-38.5
Heat capacity $[\mathrm{J\,kg^{-1}\,K^{-1}}]$	668-715	673-1100	451-955
Thermal expansion $[10^{-6}\,\mathrm{K^{-1}}]$	7-8	1.4-3.7	4.5-10.9
Melting temperature [K]	1700-1723	2661-2769	2277-2369
Young's modulus [GPa]	140-180	297	215-413
Poisson's ratio [-]	0.265-0.275	0.28	0.21-0.33
Resistivity $[10^{-8}\,\Omega\,\mathrm{m}]$	10^{6}-10^{10}	10^{16}-10^{21}	10^{18}-10^{24}

α-Alumina can be printed by using a patented technique based on digital light processing (DLP) and laminating object manufacturing (LOM)[20]. In this LOM technique, photosensitive resin mixed with α-alumina particles (i.e. the 'slurry') is transported to the building platform using a foil roll. The building stage is pressed onto the foil and is patterned with DLP. Repeating this, allows layers to be built on top of each other, as is shown in figure 1. In subsequent post-processing the resin is evaporated and the α-alumina particles are sintered.

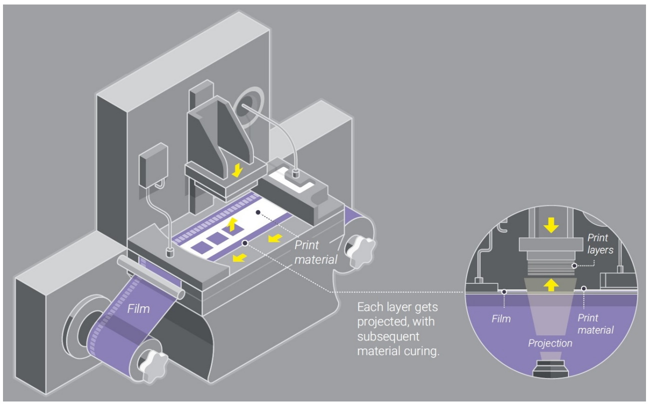

Figure 1: Working principle of the patented DLP-LOM printing method for ceramics[20]. Picture taken from Admaflex 130 flyer of Admatex[21].

PROPOSED EXPERIMENTAL WORK

The use of α-alumina and this printing technique is a new approach in microfluidics. Therefore, there are still quite some unknowns in the development of a microfluidic device. Examples of these unknowns are:

1. How good is the leak-tightness of the printed material after sintering as function of wall thickness;
2. What is the maximum operating pressure as function of wall thickness;
3. How good is the adhesion between sintered α-alumina and glue when tubing/capillaries are glued into the inlets;
4. How good is the adhesion between sintered α-alumina and deposited thin-film resistive metal tracks for heaters/temperature sensors;
5. What is the surface roughness of sintered α-alumina;
6. What is the optical transparency of sintered α-alumina;
7. How to incorporate heaters in a 3D printed system;
8. How to incorporate temperature sensors in a 3D printed system.

Unknowns 1, 2, 3, and 5 can all be examined with one test structure, shown in figure 2. This test structure has cylindrical chambers with a diameter of 1 cm with varying top and bottom wall thicknesses (0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm) and an inlet channel on the long side of the cylinder for an $^1/_{16}$ inch tubing, which can be glued into this channel. Schematics of the chambers are shown in figure 2. These chambers will be printed both parallel and perpendicular to the printing direction. He-leakage tests will be performed in order to check the porosity of different wall thicknesses and the adhesion of glue between the α-alumina and the tubing. As final tests on these chambers, the maximum operating pressure will be determined, while monitoring the deflection of the thin α-alumina wall. The deflection of this wall can be approximated by the deflection of a thin clamped circular plate loaded by a uniform pressure (see also figure 3)[22]:

$$w(r) = \frac{P}{64D}(a^2 - r^2)^2 \tag{1}$$

where, $w(r)$ is the deflection under pressure P at point r of radius a. D is the flexural rigidity, and is given by $Eh^3/(12(1-\nu^2))$, where E is Young's modulus, h the membrane thickness, and ν Poisson's ratio.

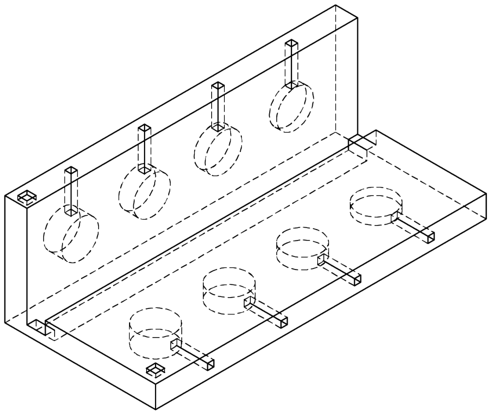

Figure 2: Designed pressure chambers for He leakage tests and failure pressure tests. The chambers are 1 cm in diameter.

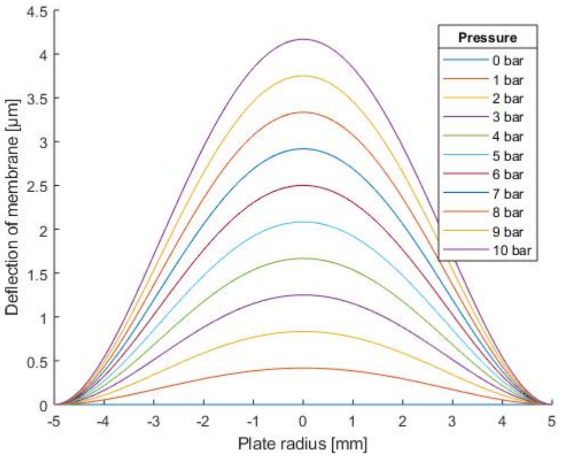

Figure 3: Deflection of a 0.5 mm thick membrane with a radius of 1 cm, a Young's modulus of 215 GPa and a Poisson's ratio of 0.21 according to the clamped thin circular plate with uniform pressure theory[22].

Unknown number 4 can be investigated using the same device. Metal can be deposited using either DC magnetron sputtering or e-beam physical vapor deposition (evaporation). Metals of interest are, for example, Au and Pt, which are commonly used metals in microfluidics[23]. Adhesion properties can be studied using the Scotch tape test[24], and the resistance versus temperature behavior in the range 20 °C – 1000 °C.

CONCLUSION

All above mentioned experiments are purely conceptual. The printing of the test structures did not proceed yet, as there are a lot of design rules for sintering. However, once these results are obtained, it becomes evident whether 3D printing of α-alumina is an applicable method for the fabrication of high temperature microfluidic structures.

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