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Printing miniature valves by micro-SLA for soft robotics

F. Boudoire[1], H. A. Sonar[2], S. Unterhofer[1], D. Bayat[1], S. Lani[1], J. Paik[2]

[1] *CSEM, Micro & Nano Systems Division, 2002 Neuchâtel, Switzerland*
[2] *EPFL, Reconfigurable Robotics Laboratory, 1015 Lausanne, Switzerland*

florent.boudoire@csem.ch

Abstract

Solenoid valves are characterized by high actuation frequencies desirable in many fields and in particular in robotics. Manufacturing such valves by UV-stereolithography would grant high resolution, miniaturization, and design flexibility. Using this fabrication technique, we developed miniature solenoid valves with a lifetime of more than 5 million cycles. To achieve this long lifetime, we optimized in particular the surface microstructure of the valve, to achieve low friction coefficients, by studying the effect of the print layer height.

UV-stereolithography, polymer, valve, tribology

1. Introduction

The field of soft robotics is gaining traction in recent years due to its high compliance capabilities. Soft robots typically rely on pneumatic actuation to interact with their environment. This actuation is performed by solenoid valves that control the pressurization with a response time on the millisecond scale. Miniature pneumatic valves with dimensions below 20 mm are interesting in this field for streamlined integration, in particular for wearable devices.[1] Additive manufacturing provides unique opportunities to miniaturize such valves while providing design flexibility for improved integration.[2] We present the development of polymer-based miniature valves produced by UV-stereolithography (SLA). In a first part we describe the valve design and fabrication. In a second part we present the protocol we followed to optimize two important parameters of the stereolithography process, the exposition time and layer height, for optimal dimensional fidelity and surface microstructure. And in a third part we present the actuation performance and lifetime of the optimized valve.

2. Results and discussion

2.1. Valve design and fabrication

The valves are composed of a solenoid assembly mounted on a polymer-based valve body featuring an embedded permanent magnet plunger (Figure 1). The solenoid assembly is composed of a copper solenoid (wire diameter 0.112 mm, 868 turns) and an aluminium heat sink with a gyroid morphology fabricated by selective laser melting. A steel core, also fabricated by selective laser melting, is inserted between the polymer valve and the copper solenoid to strengthen the magnetic field during operation.

We fabricated the polymer-based valve body by UV-stereolithography. We used the HiTemp resin from Formlabs to produce this valve since the polymer resulting from this resin can withstand the temperature of 80°C reached by the solenoid under operation. We printed the valve using a custom high-resolution SLA 3d printer based on a digital light processing (DLP) projector (Visitech, wavelength of 385 nm) with a projected pixel size of 15 µm. We programmed a custom Python software to control the DLP-SLA 3d printer that allows full control of the system hardware. A feature implemented in this software allows us to insert a Sm_2Co_{17} magnet plunger inside the valve during printing. We can indeed pre-program a layer at which the print will stop, allowing for manual insertion of the magnet inside the valve. The magnet is secured inside the valve thanks to a ferromagnetic plate fixed to the print platform. After insertion we can resume the fabrication process. This strategy results in a monolithic valve body with an embed magnetic plunger as described in the rendering presented in Figure 1.

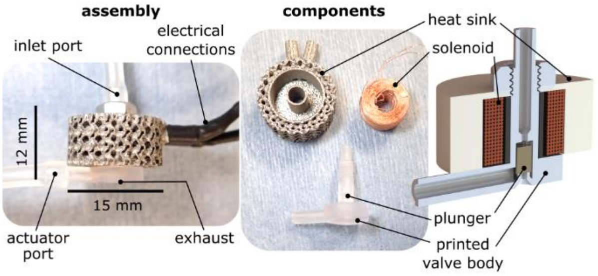

Figure 1. 3D printed miniature valve assembly and components

2.2. Optimisation of the print parameters and tribological surface analyses

To guide the embedded magnetic plunger inside the polymer-based valve body-controlled tolerances need to be achieved. Therefore, we optimized the exposition dose for the Formlabs HiTemp resin for different layer heights. This optimisation was performed using a similar strategy to generate working curves as what was presented by Luongo et al.[3], generating a set of defined exposition intensities using different greyscale levels in projected images. We printed parts featuring lines of 300 µm width and 300 µm height printed with 26 different exposition doses. The lines height and width were then measured using a Bruker interferometer. The dose yielding the dimensions closest to the set dimensions was then used for printing at the corresponding layer height. This process was repeated for each layer height presented in Figure 2 and 3.

Once we calibrated the optimal dose for accurate printing, we performed a tribological study of surfaces printed at different layer heights. The goal was to obtain the lowest coefficient of friction (COF) for the surfaces guiding the magnet plunger inside the valve body. We printed parallelograms at different layer heights with the optimised exposition doses and measured the coefficient of friction, in the direction that the magnet plunger follows during actuation, using an Aton-Paar tribometer. Three measurements were performed for each sample, using a ruby static counter parts, a normal force of 50 mN, a total measurement distance of 20 m and a linear speed of 1 cm/s. The measured coefficient of friction was averaged for each of the three measurements. The average and standard deviation of the three obtained values for each layer height are presented in Figure 2.

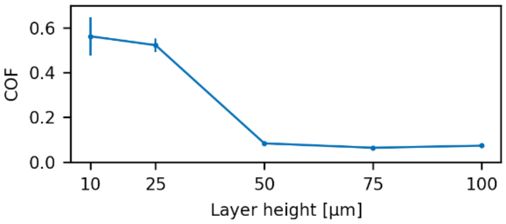

Figure 2. Coefficient of friction measured orthogonally to the printed layers as a function of the layer heights

A sharp decrease in coefficient of friction is observed for layer heights starting from 50 μm and above. This change in coefficient of friction can be explained by looking at the surface morphology for these different layer heights (Figure 3).

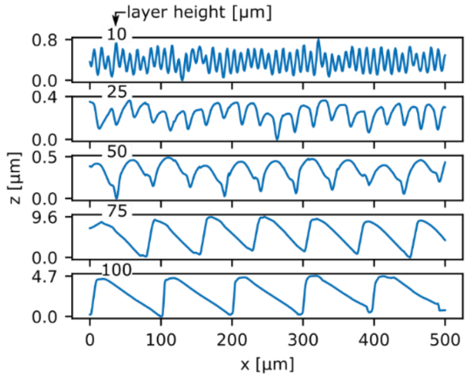

Figure 3. Surface profiles measured by interferometry for different layer heights

A sharp decrease in coefficient of friction is observed for layer heights starting from 50 μm and above. This change in coefficient of friction can be explained by looking at the surface morphology for these different layer heights (Figure 3). The scalloping observed for each layer is due to the resin absorption giving rise to an exponentially decaying exposition dose profile during printing[4]. We postulate that the increased frequency of this scalloping structures with decreased layer height leads to a larger area of contact for parts sliding against this surface, explaining the higher coefficient of friction at lower layer height. Hence, we decided to print the valve with a layer height of 50 μm, keeping the coefficient of friction at only 0.1 while keeping an acceptable resolution in the vertical print direction.

2.3. Valve performance and lifetime assessment

To assess the valve performance, we provided a constant pneumatic pressure at the valve inlet while measuring the pressure at the valve outlet. We actuated the valve at 10 Hz by switching the polarity at this frequency on the solenoid, using 0.2A of current. We measured a proper actuation at this frequency with up to 30 kPa inlet pressure (Figure 4).

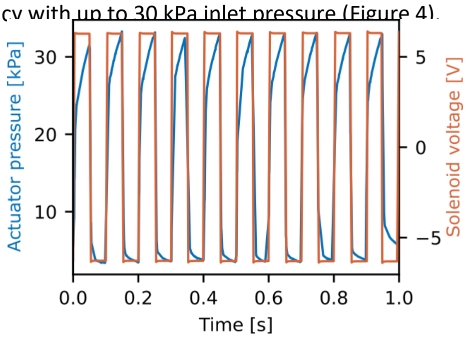

Figure 4. Characterization of the valve actuation at 10 Hz under 30 kPa

To benchmark the lifetime of the valve, printed with the optimised parameters leading to a surface coefficient of friction of only 0.1, we performed long term measurements at the 10 Hz actuation frequency. For three different valves we measured a lifetime of over 5 millions cycles (Figure 5), proving that the valves wear is mitigated by their low surface friction.

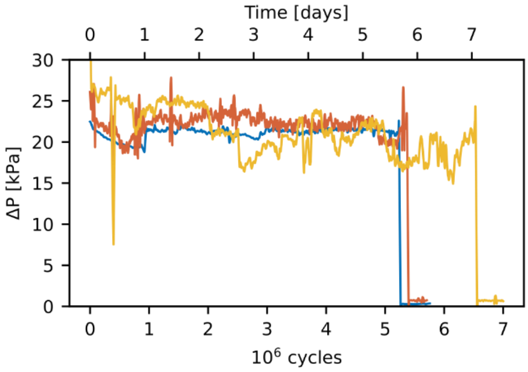

Figure 5. Measured pressure variation over the number of actuation cycles for three different valves, at an actuation of 10 Hz

3. Conclusions

We optimized a custom high resolution SLA printing process, based on a digital light processing UV projector, to 3d print miniature valves with an embed magnet plunger. Using a combination of microstructure analysis by interferometry and tribological characterisations we optimized the fabrication parameters to obtain accurate prints with low friction surfaces. This control allows an accurate guidance of the plunger inside the valve body, resulting in an actuation at high frequency with a lifetime of more than 5 million cycles under operation. The valves can be easily adapted and integrated to a wealth of applications thanks to their straightforward monolithic design and the adaptability granted by additive manufacturing. In conclusion, we have proved through optimization of tolerances and surface quality that SLA is suited to the production of miniaturized valves fitting the requirements of soft robotics actuation.

References

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