

THE FOLDING BEHAVIOR OF 4D DLP PRINTED PNIPAM BASED HYDROGELS

Solis, Daphene M¹, Czekanski, Aleksander^{2*}

^{1,2} Mechanical Engineering, York University, Toronto, Canada

* Corresponding author: alex.czekanski@lassonde.yorku.ca

Abstract —Hydrogels have attracted the attention of growing fields such as tissue engineering because of their unique characteristics such as biocompatibility with several cell types and tunable properties. In our study, we selected poly N-Isopropylacrylamide (pNIPAM) based hydrogel as this material has low critical solution temperature close to the human physiological temperature. However, more information is required on how manufacturing processes can affect the mechanical behaviour of the printed structure. In-vat polymerization processes stand out among additive manufacturing processes capable of efficiently producing NIPAM-based hydrogels. Among them, the digital light processing (DLP) process allows for its high resolution, printing speed, dimensional and spatial control of the printing process, isotropy of the layers and reduced process cost when compared to other vat polymerization processes. This work is dedicated to investigating how crosslinking rate and thickness of 4D DLP printed NIPAM based hydrogels affect their folding behaviour. Two different printing approaches were investigated: (i) a constant thickness exposed to constant light intensity over all the sample surfaces, and (ii) a constant thickness but exposed to a gradient light intensity over the sample surface. Results show that printed sample thickness plays a key role in the bending of the samples. Samples smaller than 0.25 mm bend uncontrollably and erratically, samples between 0.25 mm and 0.55 mm bend longitudinally, obtaining the final shape of a cylinder, while samples thicker than 0.55 mm are unable to bend. The variation of light intensity generates variations in the crosslinking rate of the samples, where regions with higher crosslinking rates are more rigid and with less bending capacity.

Keywords: *N-isopropylacrylamide (NIPAM); thermo-responsive hydrogel; 4D printing; folding*

I. INTRODUCTION

The synthesis of poly(N-isopropylacrylamide) (pNIPAM) was reported for the first time in 1968, greatly arousing the interest of the scientific community because of its temperature-responsive behavior [1]. Since then, hundreds of scientific

publications explore its chemical and physical characteristics, besides its association with different living cell types, been even called by some authors the most important thermo-responsive polymer [2]. Its response to temperature variations is mainly perceived by its folding behavior. The folding behavior of pNIPAM based hydrogels is related to their swelling and deswelling capacity. The control of this mechanism can guarantee control over the final shape obtained by the hydrogel [3].

Studies on the swelling kinetics of pNIPAM discovered that the swelling occurs to a collective diffusion of polymer networks, while the shrinking behavior is affected not only by this mechanism but also by heterogeneous structural changes within thin the network [1]. Since the outermost layer is the first one to collapse it ends up creating a surface layer that impermeabilizes the structure restricting the outflow of water from the hydrogel interior. During a brief moment, the shrinking process is stopped, until the internal hydrodynamic pressure becomes high enough to overcome the strength of the impermeable layer and the shrinking process is continued.

This behavior leads to believe that the area/surface volume ratio has great relevance for the bending behavior of pNIPAM-based hydrogels. Therefore, the thickness of the printed geometry, or the thickness of specific regions of the printed geometry, is the main factor that determines its folded final shape. A similar approach to the already widely exploited sheet metal bending, with the difference that in the metal fold there is no swelling of the plate.

Yoon et al (2014) [2], Naficy et al (2017) [4], Gladman et al (2016) [5] and Breger et al (2015) [6] agreed that pure pNIPAM based hydrogels, as well as bilayer structures such as pNIPAM-AAc hydrogels curvatures, are dependent on its swelling ratio, modulus, layer thickness and the ratio of layer thickness, in the specific case of bilayer structures. Stoychev et al (2011) [7], for example, produced star-like patterned polycaprolactone-poly(N-

isopropylacrylamide) structures to act as thermoresponsive microcapsules no bigger than 400 μm . These authors identified a similar pattern, in which the thickness must be properly adjusted to each structure to obtain the desired folding angle. For their specific structures, 4 μm led to the desired folding behavior, thicker structures led to a larger curvature radius and incomplete folding of the capsules, while thinner structures resulted in smaller curvature radius and multiple rolling.

This work is dedicated to investigating the folding behavior of micro hydrogels: to determine thickness that leads to a better folding mechanism, and to investigate the crosslinking rate that impacts the folding behavior of the printed hydrogels.

II. METHODOLOGY

For our study we selected NIPAM (>97%) - Sigma-Aldrich, 1.50 mol% Irgacure 2959 - Sigma-Aldrich (photoinitiator), and 1.47 mol% N,N'-methylenebis (acrylamide) (BIS) - Sigma-Aldrich (crosslinker). The materials were dissolved in 2.5 ml deionized water and mixed at ambient temperature until complete dissolution (approximately 20 minutes) using a magnetic stirrer. The hydrogel was photopolymerized and crosslinked through an adapted digital light processing (DLP) process, each layer was exposed to a 365 nm / 50 W UV light incidence for 14 min. The polymerization process was conducted inside a controlled temperature chamber, at 5 ± 0.5 $^{\circ}\text{C}$, controlled by an air-cooling system Tempronics ThermoStream, with constant airflow of 6 standard cubic feet per minute.

The samples were printed in 2 different forms: (i) with a constant thickness and exposed to constant light intensity over all the sample surface, and (ii) with a constant thickness but exposed to a gradient light intensity over the sample surface.

The homogenous samples were manufactured in a rectangular shape, with dimensions of 35 mm length, 10 mm width and their thickness were varied between 0.2 and 1.5 mm and were irradiated with 2.51 mW/cm^2 UV light

The samples printed with a light intensity gradient had the same dimension, but approximately 2/3 of their surface irradiated with 2.51 mW/cm^2 UV light intensity and the other 1/3 of its surface was irradiated with, 5.57 mW/cm^2 which represents approximately 45% more light intensity. A schematic illustration of how the light gradient was applied is shown in Figure 1.

After printing the samples were washed with deionized water to remove any unreacted monomer, then left inside a refrigerator at 5 $^{\circ}\text{C}$ for 4 hours while immersed in deionized water, and then immediately immersed in hot water at 40 $^{\circ}\text{C}$

after removal. Water-based blue pigmentation was added to the water to increase the colour contrast between the hydrogels and the water to improve the visualization.

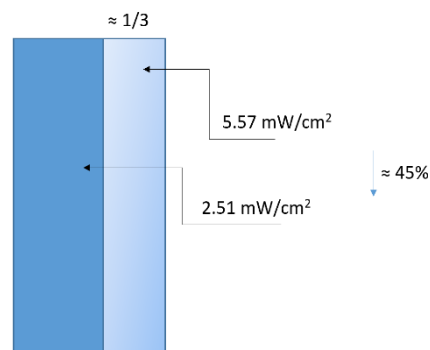


Figure 1. Schematic representation of how the light gradient was applied to the sample

III. RESULTS AND DISCUSSION

Figure 2 shows the thickness effect on the samples folding behaviour. In Figure 2 (a), it is possible to see that very thin samples, with less than 0.25 mm, presented an undefined/erratic bending behaviour, folding itself into a small bundle. This erratic behaviour occurs because water exudation occurs quickly in all the samples. Since its surface area/volume ratio is high, all regions of the sample are losing water practically simultaneously.

The samples with thicknesses between 0.25 and 0.55 mm presented an ordinated and defined folding behavior, as shown in Figure 2 (b). The biggest part of the samples folded as a tube over the sample length side, however, some twisting and very rare folding were also observed over the sample width side. This behavior aligns with the concept that the outermost portion of the sample will lose water first, and the exudation mechanism will extend to the innermost regions. The moment a certain region loses water, it contracts, which generates the bending behavior.

However, if the thickness of the printed hydrogel is greater than 0.55 mm, the shrinkage due to the exudation will not be enough to generate a bend and the sample will only present a slight curvature of its ends as can be seen in Figure 2 (c).

When aiming for the artificial production of a singular vascular-like conduit, the ideal folding behavior for the hydrogels would be a longitudinal folding with minimum overlapping and with a folding radius able to keep a space inside, to act as the lumen. Such folding was obtained using a homogeneous structure

printed with a thickness of approximately 0.5 mm, and it is presented in Figure 3.

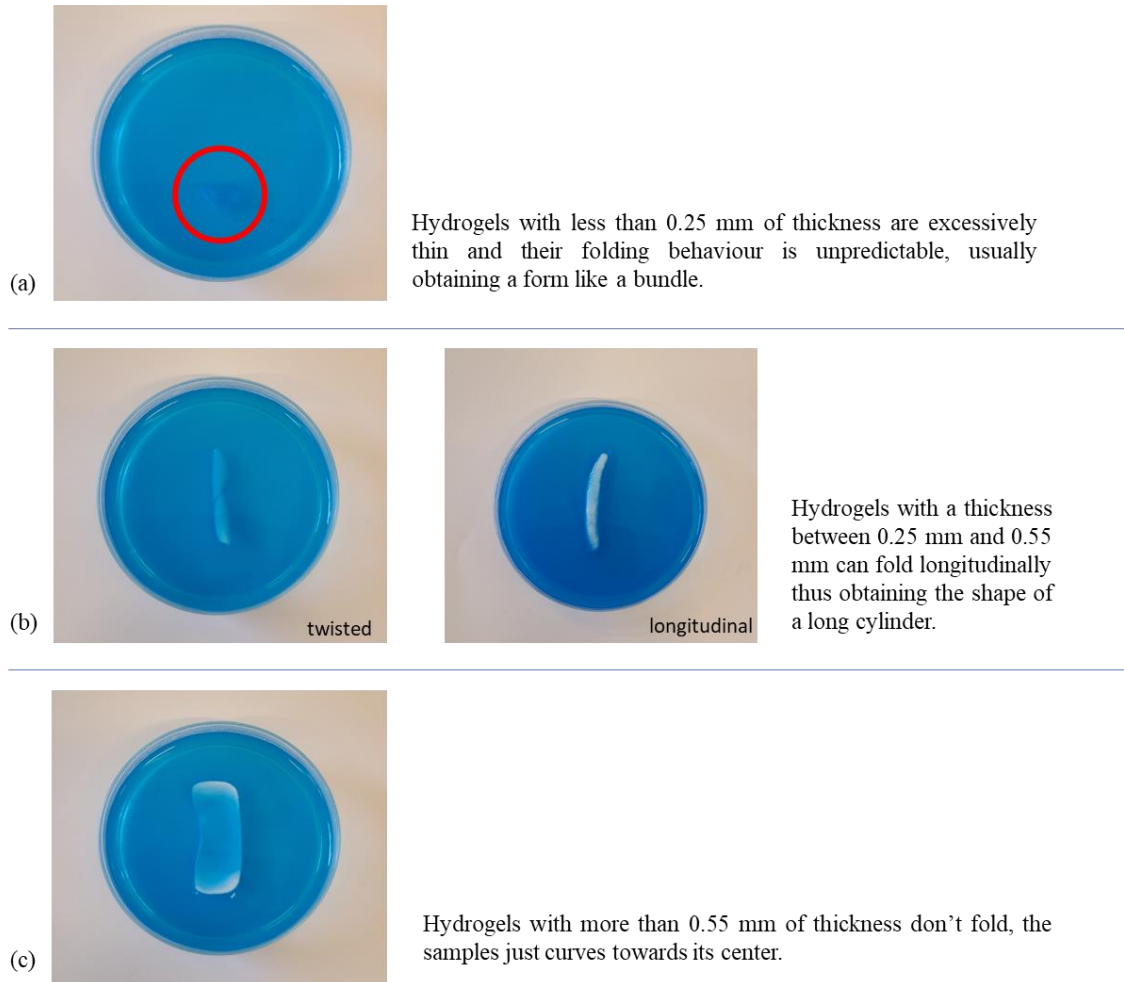


Figure 2. Hydrogel samples manufactured with a thickness of (a) less than 0.25 mm (the red circle emphasizes the region where the hydrogel is located) (b) between 0.25 to 0.55 mm and (c) more than 0.55 mm

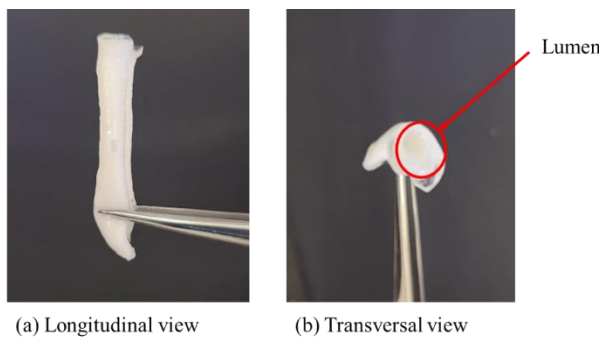


Figure 3. NIPAM based hydrogel folded in the desired shape to be used as a vascular like conduit showing (a) longitudinal and (b) transversal views

Figure 4 shows a printed part with two different rates of crosslinking. The folded region (on the left) was submitted to a light intensity 45% lower than the unfolded region (on the right). The higher light intensity led to a higher crosslinking rate and by consequence a higher stiffness of that region, which turned it unable to fold.



Figure 4. Sample printed with different rates of crosslinking.

CONCLUSIONS

Our study confirmed that poly N-Isopropylacrylamide (pNIPAM) based hydrogel is a perfect candidate for a 4D printing solution as the sample thickness influences hydrogel's bending behavior. Excessively thin samples (>0.25 mm) had non-controllable fold behavior, while samples between 0.25 and 0.55 mm presented an ordinated and defined folding. It also revealed that for tubular folding (in a longitudinal shape) with a hollow interior, samples with 0.5 mm proved to be the best configuration.

Furthermore, our study also demonstrated that higher light intensities lead to higher crosslinking in the materials leading to a stiff region, with a lower ability to fold when compared with a region with a lower crosslinking rate. These findings can be used to fabricate samples with variable cross-linking rates. In those regions, the fold should receive lower light intensity as opposed to regions that should not fold receive higher light intensity.

Further investigation still should be done for a full understanding of the hydrogel folding Mechanism. This would allow us to determine (i) the crosslinking rate of different regions, and (ii) the corresponding mechanical properties such as tensile strength.

ACKNOWLEDGMENT

This research was supported by the Natural Sciences and Engineering Research Council (NSERC) and the Social Sciences and Humanities Research Council (SSHRC) programs.

REFERENCES

- [1] Y. Kaneko, R. Yoshida, K. Sakai, Y. Sakurai, and T. Okano, "Temperature-responsive shrinking kinetics of poly (N-isopropylacrylamide) copolymer gels with hydrophilic and hydrophobic comonomers," *J. Memb. Sci.*, vol. 101, no. 1–2, pp. 13–22, 1995, doi: 10.1016/0376-7388(94)00268-4.
- [2] C. Yoon, R. Xiao, J. Park, J. Cha, T. D. Nguyen, and D. H. Gracias, "Functional stimuli responsive hydrogel devices by self-folding," *Smart Mater. Struct.*, vol. 23, no. 9, 2014, doi: 10.1088/0964-1726/23/9/094008.
- [3] S. Naficy, R. Gately, R. Gorkin, H. Xin, and G. M. Spinks, "4D Printing of Reversible Shape Morphing Hydrogel Structures," *Macromol. Mater. Eng.*, vol. 302, no. 1, pp. 1–9, 2017, doi: 10.1002/mame.201600212.
- [4] D. S. Solis, A. Czekanski. "3D and 4D additive manufacturing techniques for vascular-like structures - A review," *Bioprinting J.*, vol 25, 2022, doi: 10.1016/j.bprint.2021.e00182.
- [5] A. S. Gladman, E. A. Matsumoto, R. G. Nuzzo, L. Mahadevan, and J. A. Lewis, "Biomimetic 4D printing," *Nat. Mater.*, vol. 15, no. 4, pp. 413–418, 2016, doi: 10.1038/nmat4544.
- [6] J. C. Breger *et al.*, "Self-folding thermo-magnetically responsive soft microgrippers," *ACS Appl. Mater. Interfaces*, vol. 7, no. 5, pp. 3398–3405, 2015, doi: 10.1021/am508621s.
- [7] G. Stoychev, N. Puretskiy, and L. Ionov, "Self-folding all-polymer thermoresponsive microcapsules," *Soft Matter*, vol. 7, no. 7, pp. 3277–3279, 2011, doi: 10.1039/c1sm05109a.