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Analyzing Shrinkage in 4D Printing: A Parametric Exploration for Optimal Combinations

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Abstract – In the burgeoning field of 4D printing, this study delves into the critical parameters influencing heat-induced shrinkage to optimize shape transformation. Utilizing a hobbyist FDM-based 3D printer, samples were fabricated using thermoplastic PLA filament, with meticulous control over key parameters such as activation temperature, bed temperature, nozzle temperature, and printing speed. Results underscored an 100°C activation temperature as optimal, consistently yielding pronounced and controlled shrinkage. Additionally, a bed temperature of 30°C, nozzle temperature of 185°C, and a printing speed of 90 mm/s emerged as pivotal settings for achieving desirable outcomes. These findings provide a comprehensive roadmap for researchers and practitioners, offering insights to refine 4D printing processes and enhance control over shape transformation. By strategically selecting and optimizing these parameters, the study paves the way for advancements in precision, repeatability, and versatility in 4D printing applications. As the technology continues to evolve, these insights contribute significantly to shaping the future landscape of additive manufacturing, fostering innovation and opening new avenues for dynamic, shape-shifting structures with enhanced functionality.

Keywords – 4D Printing, Thermal Gradient, Polymer, Shrinkage, FDM.

I. Introduction

In the rapidly evolving field of additive manufacturing, 4D printing has become a ground-breaking technology that allows objects to change in real time. Even with great advancements, the technological obstacles related to 4D printing methods still exist, so a more thorough investigation of how printing factors affect the critical factor of shrinkage is required.

The purpose of this paper is to explore the complex relationship that exists between shrinkage and printing parameters in 4D printing methods. The foundation is laid by Wang et al.[1], who suggest an effective multispeed fused deposition modeling (4D printing) method. When we examine their process, our attention turns to comprehending how differences in printing factors can affect the inherent strain and consequent shrinkage in flat precursory designs.

Important insights into the creation of intricate structures with rolling, morphing, and self-bending properties are provided by Bodaghi et al.[2] In addition to introducing new structures, their work offers a chance to look at how printing settings affect shrinkage when it comes to functionality that is driven by performance.

The necessity for precise simulation techniques for FDM-printed monolayer shape memory polymer (SMP) models is addressed by Wang et al.'s research [3]. The paper highlights the value of taking printing parameters into account in comprehending and forecasting the deformation processes, illuminating the relationship between parameters and shrinkage as we look at their simulation methodology.

Table 1 : Different parameters used to explore thermal deformation

Reference	Parameter(s)	Output
[5]	Printing angle	Bending radius
[6]	Printing direction	Recovery time
[1]	Printing speed	Bending curvature
[7]	Nozzle temperature; layer thickness and printing speed	Bending angle and the unfolding angle
[4]	Printing speed and printing direction	Curvature
[8]	Printing speed	Bending angle and curvature
[9]	Layer thickness and printing direction	Shape-recovery ratio
[10]	Printing direction	Bending angle
[11]	Nozzle temperature; layer thickness and printing speed	Recovery time and ratio
[12]	Printing speed	Deformation
[3]	Nozzle temperature, bed temperature, layer thickness and printing speed	Bending angle
[2]	Printing speed	Bending dimensions
[13]	Dimensions, nozzle temperature, bed temperature, printing angle and printing speed	Bending angle

The investigation is made more thorough by the various viewpoints provided by scholars like Hendrik Thölking & al.[4] . Their attempts to improve the accessibility of 4D printing simulations highlight how crucial it is to take printing characteristics into account when making precise shape transformation predictions.

The purpose of this article is to provide a comprehensive understanding of the impact of printing parameters on shrinkage separately for better understanding and to be used as starting point for our next works.

Furthermore, this study aims to apply the knowledge gathered from shrinkage analysis to identify the best printing parameter combinations for every individual printed item. Through the utilization of shrinkage data, scholars and professionals may methodically determine and use the most effective combinations, propelling the domain of 4D printing forward and enhancing the functionality of printed items. We hope to provide light on the complex interaction between printing parameters, shrinkage, and the best combinations in 4D printing processes with this targeted investigation.

II. Materials and Method

All samples in this study were fabricated using a hobbyist Fused Deposition Modeling (FDM)-based 3D printer, specifically the Extended2+ from Ultimaker. The printer was using 1.75 mm diameter thermoplastic Polylactic Acid (PLA) filament. Layer by layer, material was deposited by the extrusion process using a heated print nozzle with a 0.4 mm diameter. PLA's glass transition properties were used to quickly solidify the PLA polymer designs at the build platform once they cooled.

The 3D printing procedure was customized using Cura Software. This produced the G-code in text format by allowing the print path, print speed, and filament feeding to be specified.

All experimental data were obtained from printed samples that were heated to 85 °C in a water bath, with the exception of the data shown in Fig 1. Samples that were rectangular in shape and had dimensions of 30 mm x 5 mm x 1mm were used to examine how printing parameters affected heat-induced shrinkage.

The heated sample was first flattened to reduce thermal gradient-induced deformation and allow for direct measurement of the neutral plane's length. For each sample, the formula:

$$\varepsilon s = -(L - L0)/L0 \times 100\% \quad (1)$$

was used to calculate the shrinkage strain (εs), where L is the deformed length and L0 is the original length.

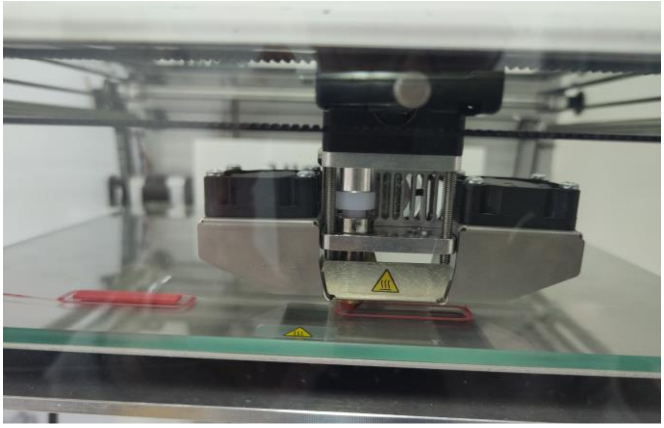

Fig. 1 : Process of printing simples

III. RESULTS

A. Optimal Thermal Activation Temperature:

In order to ascertain the optimal temperature for thermal activation, shrinkage tests were carried out across a temperature range of 50°C to 100°C. Among the investigated temperatures, the research showed that an 100°C water bath consistently produced the most significant heat-induced shrinkage. This study emphasizes how important thermal activation is to getting the best possible 4D printing outcomes, and 100°C turns out to be the ideal temperature for further investigation.

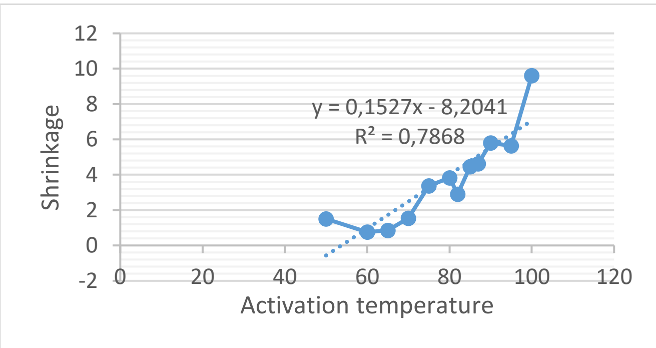

Fig. 2 : Shrinkage due to activation temperature

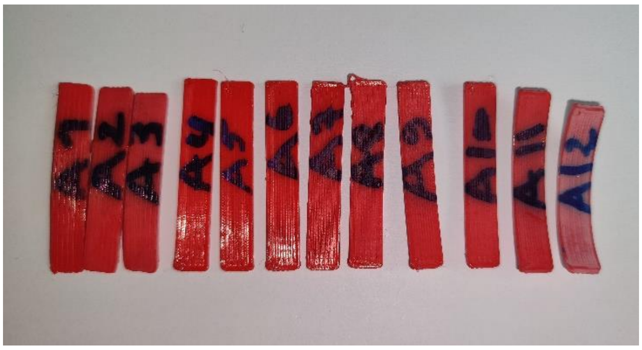

Fig. 3: The printed simples after different thermal activation

B. Bed Temperature Influence on Shrinkage:

Experiments were carried out with bed temperatures ranging from 30°C to 70°C to investigate the effect of bed temperature on shrinkage. The most beneficial findings in terms of shrinking were, surprisingly, found at a bed temperature of 30°C. This indicates that managing the bed temperature is essential for maximizing the efficiency of the 4D printing process, with 30°C standing out as the most successful value for attaining the required shrinkage characteristics.

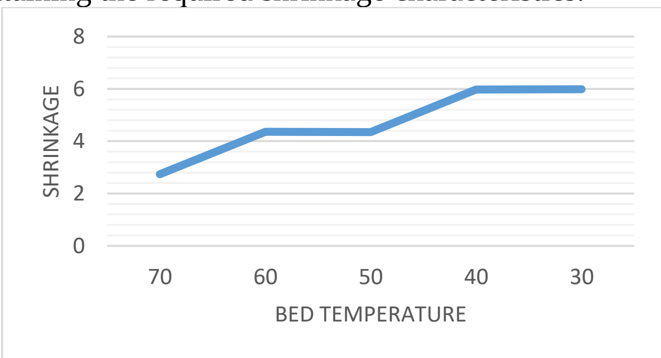

Fig. 4 : Shrinkage due to bed temperature

C. Nozzle Temperature Optimization:

In order to learn more about how nozzle temperature affects shrinkage, a temperature range of 185°C to 210°C was investigated. The results clearly showed that the most noticeable and well-controlled heat-induced shrinking occurred at a nozzle temperature of 185°C. This temperature threshold is found to be the ideal nozzle setting, guaranteeing steady and dependable 4D printing performance.

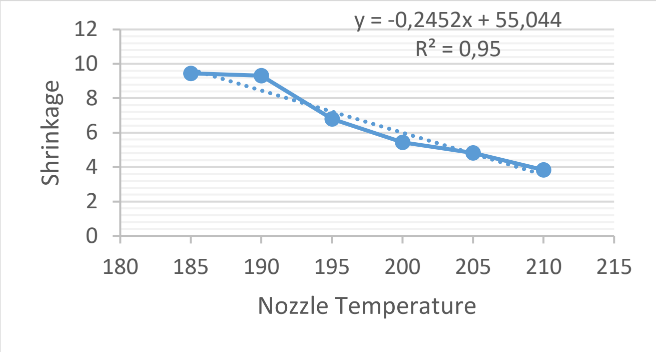

Fig. 5 : Shrinkage due to only nozzle temperature

D. *Effect of Printing Speed on Shrinkage:*

50 mm/s to 90 mm/s printing speeds were used in the trials to determine the effect of printing speed on shrinkage. Interestingly, the results showed that the best results in terms of consistent and controlled shrinkage were obtained at a printing speed of 90 mm/s. This result emphasizes how important it is to optimize printing speed and give it great thought in order to get the desired results from 4D printing.

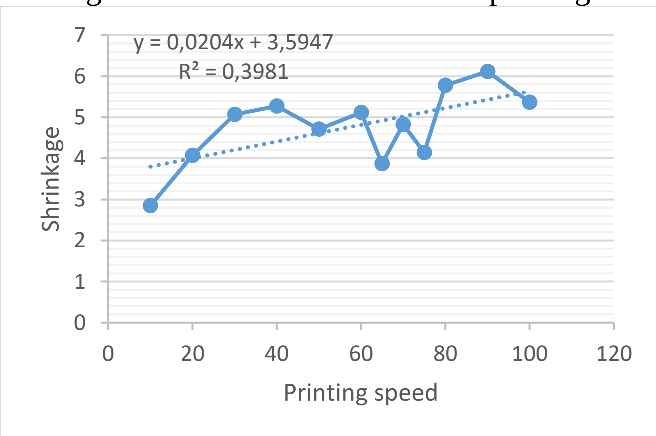

Fig. 6 : Shrinkage due to printing speed

IV. DISCUSSION

In our exploration of 4D printing parameters, a salient finding was the influence of varying activation temperatures on heat-induced shrinkage. Specifically, our results illuminated that an 100°C activation temperature consistently optimized the desired shrinkage outcomes, contrarily to all other references using 85° as thermal stimulus value [1-12]. Only [13] who used 98° as temperature trigger. Intriguingly, our investigation further revealed an intricate relationship between fabrication temperature and printing speed. Notably, lower fabrication temperatures coupled with higher printing speeds appeared to induce pronounced built-in strain within the printed structures. This nuanced interplay underscores the criticality of balancing temperature and speed parameters, as their confluence directly impacts the resultant built-in strain and, consequently, the efficacy of shape transformation in 4D-printed objects. Such insights hold significant implications for advancing the precision and control of 4D printing processes, offering a foundation for further research and innovation in the realm of additive manufacturing.

V. CONCLUSION

In summary, the results clearly demonstrate the critical influence of temperature parameters (activation, bed, and nozzle) and printing speed on the shrinkage characteristics of 4D-printed samples. The identified optimal values (100°C activation temperature, 30°C bed temperature, 185°C nozzle temperature, and 90 mm/s printing speed) provide valuable insights for refining the 4D printing process using multiple layers with different strains and achieving superior control over shape transformation, subject of our further works.

REFERENCES

[1] F. Wang, F. Luo, Y. Huang, X. Cao, and C. Yuan, “4D Printing Via Multispeed Fused Deposition Modeling,” *Advanced Materials Technologies*, vol. 8, p. 2201383, Oct. 2022, doi: 10.1002/admt.202201383.

[2] M. Bodaghi, R. Noroozi, A. Zolfagharian, M. Fotouhi, and S. Norouzi, “4D Printing Self-Morphing Structures,” *Materials*, vol. 12, no. 8, p. 1353, Apr. 2019, doi: 10.3390/ma12081353.

[3] Y. Wang and X. Li, “An accurate finite element approach for programming 4D-printed self-morphing structures produced by fused deposition modeling,” *Mechanics of Materials*, vol. 151, p. 103628, Dec. 2020, doi: 10.1016/j.mechmat.2020.103628.

[4] H. Thölking, F. Cerbe, and M. Sinapius, “Analytical-numerical simulation of 4D-structures printed with FDM,” *Materials Today: Proceedings*, p. S2214785323005576, Feb. 2023, doi: 10.1016/j.matpr.2023.02.040.

[5] A. Chalgham, A. Ehrmann, and I. Wickenkamp, “Mechanical Properties of FDM Printed PLA Parts before and after Thermal Treatment,” *Polymers*, vol. 13, no. 8, p. 1239, Apr. 2021, doi: 10.3390/polym13081239.

[6] S. Nam and E. Pei, “The Influence of Shape Changing Behaviors from 4D Printing through Material Extrusion Print Patterns and Infill Densities,” *Materials*, vol. 13, no. 17, Art. no. 17, Jan. 2020, doi: 10.3390/ma13173754.

[7] Y. Wang and X. Li, "4D-printed bi-material composite laminate for manufacturing reversible shape-change structures," *Composites Part B: Engineering*, vol. 219, p. 108918, Aug. 2021, doi: 10.1016/j.compositesb.2021.108918.

[8] R. Noroozi, M. Bodaghi, H. Jafari, A. Zolfagharian, and M. Fotouhi, "Shape-Adaptive Metastructures with Variable Bandgap Regions by 4D Printing," *Polymers*, vol. 12, no. 3, p. 519, Mar. 2020, doi: 10.3390/polym12030519.

[9] W. Wu, W. Ye, Z. Wu, P. Geng, Y. Wang, and J. Zhao, "Influence of Layer Thickness, Raster Angle, Deformation Temperature and Recovery Temperature on the Shape-Memory Effect of 3D-Printed Polylactic Acid Samples," *Materials*, vol. 10, no. 8, p. 970, Aug. 2017, doi: 10.3390/ma10080970.

[10] Y. S. Alshebly *et al.*, "Bioinspired Pattern-Driven Single-Material 4D Printing for Self-Morphing Actuators," *Sustainability*, vol. 14, no. 16, p. 10141, Aug. 2022, doi: 10.3390/su141610141.

[11] M. Barletta, A. Gisario, and M. Mehrpouya, "4D printing of shape memory polylactic acid (PLA) components: Investigating the role of the operational parameters in fused deposition modelling (FDM)," *Journal of Manufacturing Processes*, vol. 61, pp. 473–480, Jan. 2021, doi: 10.1016/j.jmapro.2020.11.036.

[12] Y. S. Alshebly, M. Nafea, H. A. F. Almurib, M. Sultan Mohamed Ali, A. A. Mohd Faudzi, and M. T. T. Tan, "Development of 4D Printed PLA Actuators with an Induced Internal Strain Upon Printing," in *2021 IEEE International Conference on Automatic Control & Intelligent Systems (I2CACIS)*, Shah Alam, Malaysia: IEEE, Jun. 2021, pp. 41–45. doi: 10.1109/I2CACIS52118.2021.9495898.

[13] P. Wu, T. Yu, M. Chen, and D. Hui, "Effect of printing speed and part geometry on the self-deformation behaviors of 4D printed shape memory PLA using FDM," *Journal of Manufacturing Processes*, vol. 84, pp. 1507–1518, Dec. 2022, doi: 10.1016/j.jmapro.2022.11.007.