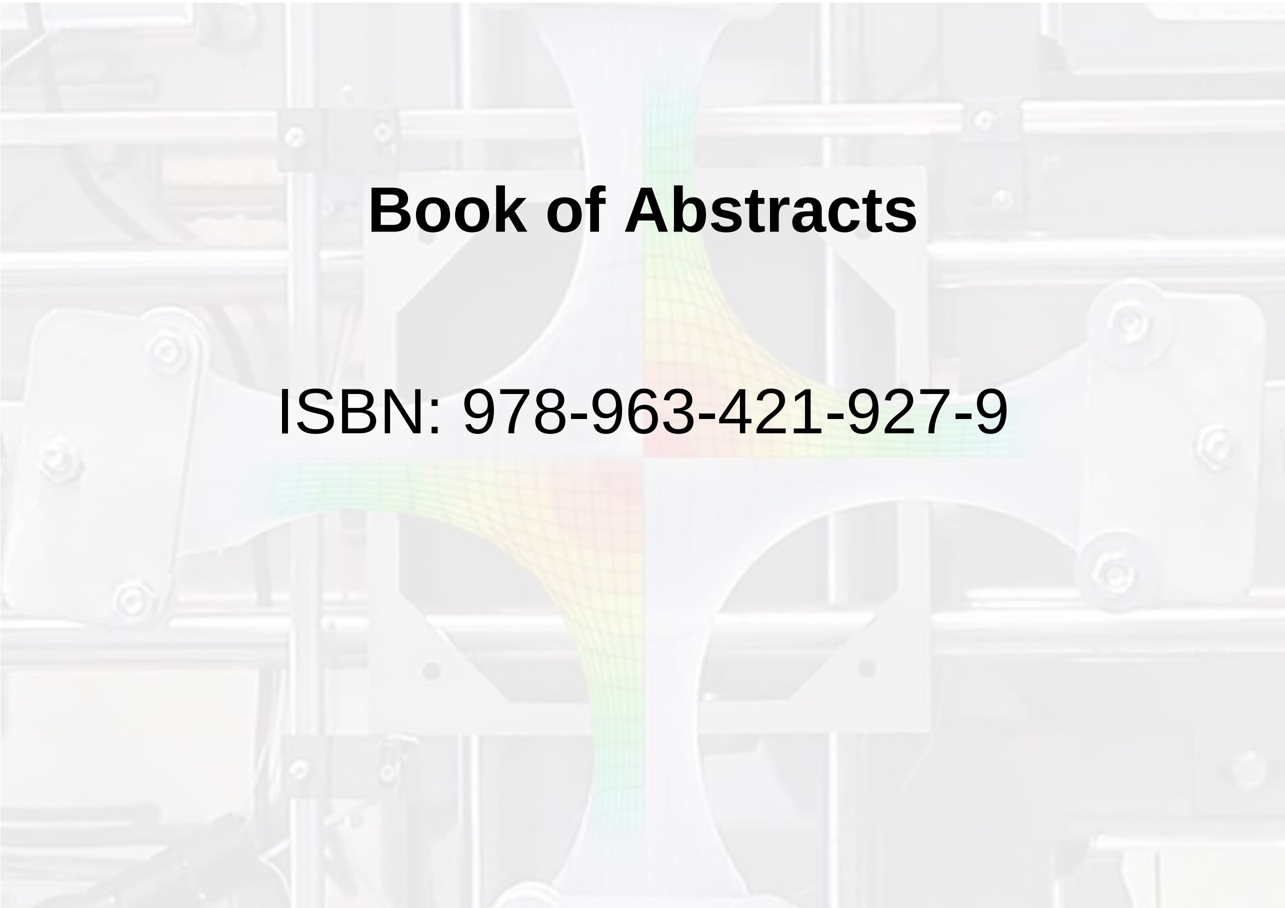
39th Danubia-Adria Symposium on Advances in Experimental Mechanics

September 26-29, 2023

Siófok, Hungary



Book of Abstracts

ISBN: 978-963-421-927-9

Organized by the Hungarian Scientific Society of Mechanical Engineering (GTE) under the auspices of the Danubia-Adria Society on Experimental Methods

https://www.danubia-adria.org/

https://gteportal.eu/en/home/

Shape Memory Epoxy Resin for Shape-Morphing Additive Manufacturing

Mana Nabavian Kalat[1], Maria Staszczak[1], Leszek Urbański[1], Andres Diaz Lantada[2] and Elżbieta Pieczyska[1]

[1] Institute of Fundamental Technological Research POLISH ACADEMY OF SCIENCES, Adolfa Pawińskiego 5B, 02-106 Warsaw, Poland, E-mail: mnabavian@ippt.pan.pl

[2] Universidad Politécnica de Madrid, José Gutiérrez Abascal 2, E-28006, Madrid, Spain

1. Introduction

Shape-morphing devices are gaining importance in various industrial fields, such as robotics, medicine, architecture, and aerospace [1]. They can change shape in response to external stimuli, enabling them to perform diverse tasks. Thermal-responsive shape memory polymers (SMPs) are well-suited materials for soft robotic applications due to their shape recovery ability in exposure to heat. However, optimizing material properties and developing reliable design and manufacturing process for complex-shaped soft robots remain challenging. Laser stereolithography (SLA) 3D-printing technology, offers a promising approach for fabricating detailed and complex shape-morphing objects with high resolution [2]. This study investigates the thermomechanical properties of a shape memory epoxy resin (SMEp) to quantify the shape memory parameters. Innovative designs for complex-shaped devices with integrated micro-actuators are proposed, and prototypes are manufactured using SLA 3D-printing directly from computer-aided designs in a single step. Finally, the prototypes undergo training to validate their shape memory behavior.

2. Material and 4D-printing process

Epoxy resin SOMOS WaterShed R XC11122 was used as a photopolymerizable prototyping material, suitable for additive manufacturing of highly detailed parts with high clarity, toughness and water-resistance. The dog-bone specimen (Fig. 1a) with the standard geometry for thermomechanical investigation as well as the complex-designed prototypes (Fig. 1b), were printed by SLA 3D-printing method, SLA-3500 laser stereolithography 3D-printer. The S-shaped micro-actuator (circled in red in Fig. 1b) in the prototypes connects all parts, by triggering which the configuration of the whole complex-shaped device is changed in a pre-determined mechanism. The micro-actuator was designed thinner than other parts, for obtaining fast flexibility and actuation upon heating.

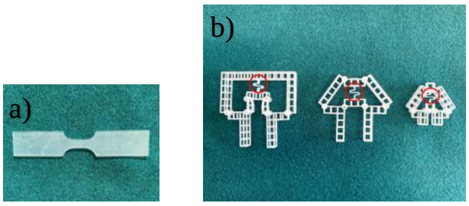


Fig. 1. a) Dog-bone specimen for thermomechanical investigation, b) Complex-designed prototypes containing an S-shaped actuator, circled in red.

3. Thermomechanical investigation

The thermomechanical properties of the SMEp dog-bone shape specimen with glass transition temperature (T_g) of 53˚C were investigated, using a tensile testing machine and an environmental thermal chamber, through the following steps: 1) Heating to T_g+20=75˚C, 2) Tensile loading to a pre-determined strain value at a constant strain rate of 10^{-2} s^{-1}, 3) Cooling the specimen to room temperature (T_g-20=75˚C) while keeping the maximum strain, 5) Unloading the specimen at a constant strain rate of 10^{-2} s^{-1}, 6) Heating the specimen to T_g+20=75˚C under zero-force to restore the original shape. Shape fixity and shape recovery of the SMEp were calculated from the experimental results (stress-strain curve in Fig. 2) using equations 1 and 2, respectively [3] [4]:

$$S_f = \frac{\varepsilon_{un}}{\varepsilon_m} \cdot 100\% \qquad (1)$$

$$S_r = \frac{\varepsilon_m - \varepsilon_{ir}}{\varepsilon_m} \cdot 100\% \qquad (2)$$

while ε_m, ε_{un} and ε_{ir} are the maximum strain loading, the strain obtained after unloading at room temperature, and the irrecoverable strain after heating, respectively. The mean values of shape fixity and shape recovery (obtained from four specimens) were found to be 95.05% and 74.80%, respectively, proving the suitability of the SMEp material for shape-morphing applications.

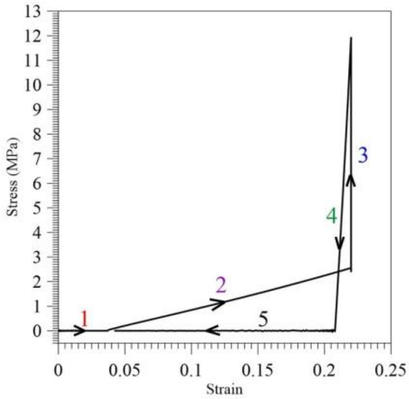


Fig. 2. Stress-strain curve of SMEp in a thermomechanical cycle.

4. Shape memory effect activation trials in the 4D-printed prototypes

The 4D-printed prototypes underwent shape-shifting training by local heating, deforming, cooling, and thermal recovery on the connecting actuator. This approach eliminated the need to heat and deform the entire device, resulting in shorter actuation time, reduced temperature gradients, and less thermal expansion. Figure 3a, b, and c illustrate the original, deformed, and recovered shape of one of the prototypes. The left and right apex angles in the device (in red), before and after shape recovery of the actuator, can serve as suitable parameters for estimating deformation and shape recovery in the prototypes.

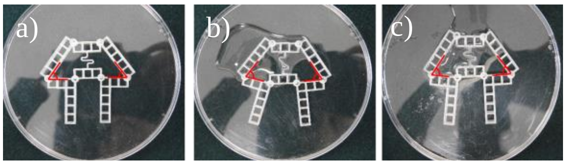


Fig. 3. a) original, b) deformed and c) recovered shape of the SMEp prototype

The approximate values of shape deformation and recovery in each prototype were calculated using the equations 3 and 4, respectively:

$$S_d = \frac{\theta_m - \theta_0}{\theta_0} . 100\% \qquad (3)$$

$$S_{r\theta} = \frac{\theta_m - \theta_{ir}}{\theta_m} . 100\% \qquad (4)$$

while, θ_0 is the initial value of the apex angle, θ_m is the apex angle after deforming the actuator, and θ_{ir} is the irrecoverable apex angle after the thermal recovery of the actuator at 75˚C. By changing the shape deformation in all three types of the devices from 20% to 35%, the shape recovery values above 92% was obtained. The high shape recovery values indicate how the material properties and the device design result in fast and precise shape-shifting in response to heat.

5. Conclusions

In this study, a successful optimization between:
- choosing and characterization of a thermal-responsive shape memory polymer
- innovative designing of devices for performing desired tasks
- using a reliable manufacturing process for fabricating the complex-designed prototypes with high quality,

led us to 4D-printing of complex-shaped adaptive prototypes with prompt and precise shape morphing properties.

Acknowledgments

The research has been carried out with support of the Polish National Center of Science under Grant 2017/27/B/ST8/03074 and 14th call of the KMM-VIN research fellowship programme.

References

[1] Chen, Q.; Lv, P.; Huang, J.; Huang, T.; Duan, H. Review Article Intelligent Shape-Morphing Micromachines. Research 2021.
[2] Lantada, A.D.; De Blas Romero, A.; Tanarro, E.C. Micro-vascular shape-memory polymer actuators with complex geometries obtained by laser stereolithography. Smart Mater. Struct. 2016, 25, 1–10.
[3] Tobushi, H.; Hara, H.; Yamada, E.; Hayashi, S. Thermomechanical properties in a thin film of shape memory polymer of polyurethane series. Smart Mater. Struct. 1996, 5, 483–491
[4] Staszczak, M.; Nabavian Kalat, M.; Golasiński, K.M.; Urbański, L.; Takeda, K.; Matsui, R.; Pieczyska, E.A. Characterization of Polyurethane Shape Memory Polymer and Determination of Shape Fixity and Shape Recovery in Subsequent Thermomechanical Cycles. Polymers (Basel). 2022, 14