EXPERIMENTAL ANALYSIS AND ANALYTICAL MODELLING OF THE TEMPERATURE-MEMORY EFFECT IN 3D PRINTED AUXETIC STRUCTURES

S. PANDINI[1], C. PASINI[1], N. INVERARDI[1], D. BATTINI[1], G. SCALET[2], S. MARCONI[2], F. AURICCHIO[2]

1: Department of Mechanical and Industrial Engineering, University of Brescia -
Italian Interuniversity Consortium on Materials Science and Technology (INSTM), Italy
stefano.pandini@unibs.it; c.pasini012@unibs.it; n.inverardi003@unibs.it;
davide.battini@unibs.it
2: Department of Civil Engineering and Architecture, University of Pavia -
Italian Interuniversity Consortium on Materials Science and Technology (INSTM), Italy
giulia.scalet@unipv.it; stefania.marconi@unipv.it; auricchio@unipv.it

Introduction

4D printing represents an innovative manufacturing approach, which allows to produce 3D printed objects that possess a desired, even complex, geometry and can change their shape over time (hence the 4th dimension in the name of the approach) [1]. Among various strategies, a 4D printed structure may be achieved by combining 3D printing, as processing tool, with the adoption of a shape memory material as part or main constituent of the printed object. When 4D printing involves shape memory polymers, the typical behaviour of printed objects concerns their ability to be deformed and fixed in a temporary shape, and to move back to the pristine one only when heated above a specific temperature. However, more complex response may be obtained for specific classes of polymers. Among these, particular interest is reserved to polymers presenting a broad distribution of their glass transition or melting temperature region, since they can remember not only the original shape but also the temperature at which they were deformed. Such a feature, also termed temperature memory effect (TME), may lead to an improved control of the shape memory response, both in terms of the temperature triggering the shapeshifting event and for what regards the possibility to exhibit a multiple shape memory effect, i.e. assuming more than one temporary shape and recovering each deformation step on a given temperature region [2].

In this study the 4D printing approach was explored on a commercial photopolymer [3], printed as a reverse-honeycomb structure by means of a stereolithographic apparatus (SLA) and subjected to specific thermo-mechanical histories to reveal and quantify its TME capabilities, that could be ensured by the polymer broad glass transition region. Moreover, this research work investigates the possibility to predict the TME response of 4D-printed structures by means of a finite element model, based on a thermoviscoelastic approach and calibrated on experimental viscoelastic data obtained by Dynamic-Mechanical Thermal Analysis (DMTA).

Methodology

An auxetic structure, printed as a planar object with a reverse-honeycomb cell arrangement, was realized using an SLA 3D printer (Formlabs Form 2) and the photopolymer resin named Clear FLGPCL02 (provided by Formlabs); more information concerning the printed structure may be found in [4].

The thermo-mechanical behaviour of the printed resin was characterized by means of DMTA, allowing to evaluate the glass transition temperature and the extent of the transition region, as well as to provide the data for a full description of the viscoelastic behaviour in terms of a storage modulus master curve.

The shape memory response was investigated upon application of both single deformation step, carried out at various temperatures across the glass transition region, and multiple deformation steps, sequentially applied at different temperatures across the glass transition region. The temperature memory effect was studied as a function of temperature along controlled heating ramps, in so-called thermally stimulated recovery tests, and as a function of time, in isothermal experiments.

The finite element model was developed as a thermoviscoelastic generalized Maxwell model, implemented in a FEM software (Abaqus) on the basis of the storage modulus master curve data [5], and its reliability was tested by comparing the analytical predictions with the experimental results).

Results

DMTA revealed that, probably due to a non-homogeneous crosslinked structure, the printed material features a broad glass transition, ranging between -20°C and 80°C (T_g being at about 30°C). The structure was subjected to deformation at various temperatures, ranging from T_{room} up to 100°C, and its shape recovery was studied as a function of temperature and time: the former set of tests revealed that recovery actually takes place at temperature close to the deformation temperature; the latter one that, for a given recovery temperature, recovery occurs at shorter times for structures deformed at a lower temperature. In another set of experiments, successive deformations were carried out at different temperatures, and a multiple shape memory response was achieved as a sequence of thermally triggered motions. This effect was successfully achieved both under planar conditions, where the structure was axially deformed at two different strain levels, and for more complex spatial motions, such as sequential in-plane and out-of-plane deformations. Finally, by comparing the recovery curves achieved for the various experiments with those predicted by the numerical model, an overall good correspondence was found, although results revealed that a proper calibration of the parameters involved in the time-temperature equivalence is required.

Conclusions

The present work explored the possibility of adopting a 4D printing approach to obtain objects with a complex shape, such as the auxetic cellular structure, and capable of a complex shape memory response, allowing to control the triggering temperature and to achieve multiple shape memory effects. The possibility to achieve, with a same material, finely controlled triggered actuation and sequential recovery processes on the basis of the applied thermo-mechanical history was observed, and this may be of great benefit for the realization of smart devices in various fields. Finally, the fair correspondence between experimental results and analytical model results allows to approach the prediction of complex shape memory response by means of an analytical tool of relatively easy calibration.

References

[1] Chu, H., Yang, W., Sun, L., Cai, S. et al. 4D Printing: A Review on Recent Progresses. Micromachines, 11, 796, 2020.

[2] Xie, T. Tunable polymer multi-shape memory effect. Nature, 464, p. 267-270, 2010.

[3] Inverardi, N., Pandini, S. Bignotti, F. et al. Sequential Motion of 4D Printed Photopolymers with Broad Glass Transition. Macromol. Mat. Eng., 305, 1, 1900370, 2020.

[4] Pandini, S., Inverardi, N., Scalet, G. at al. Shape memory response and hierarchical motion capabilities of 4D printed auxetic structures, Mechanics Research Communications, 103, 103463, 2020.

[5] Battini, D., Avanzini, A., Pandini, S. and Bignotti, F. Modeling approach and finite element analyses of a shape memory epoxy-based material. Lecture Notes in Mechanical Engineering, pp. 689–704, 2020.