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Material Behaviour

Experimental analysis of heterogeneous shape recovery in 4d printed honeycomb structures

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ABSTRACT

Additive manufacturing of complex structures with functional and programmable attributes (*i.e.,* 4D printing) enables complex and innovative designs with tunable, adaptable or shape memory properties. To capitalize on the potential of 4D printing, it is instrumental to establish the knowledge base needed to predict the behavior of 4D printed structures. Accordingly, this work is dedicated to study the stability and shape recovery properties of 4D printed honeycomb structures using thermoplastic shape memory polymer (SMP). In particular, the dimensional stability of samples subjected to heat at temperatures around the glass transition temperature of the SMP material was assessed. In addition, the local shape recovery properties were investigated in samples programed into various temporary shapes with highly heterogeneous stored strain fields. The as-printed samples experienced dimensional instability manifested through a time dependent and heat induced strain accumulation when subjected to temperatures of ± 10 °C around the SMP glass transition temperature. The rate of strain accumulation was temperature dependent and exhibited a high strain accumulation rate initially, followed by a relatively saturated response after about 10 min of temperature exposure. The total strain accumulation in the honeycomb samples was heterogeneous due to local variation in the deposition direction during printing. In the recovery experiments, despite the dissimilar levels of stored strain during programing, full local recovery was achieved independent of magnitude or nature of the stored strains. However, the local strain recovery rates varied in different regions and was attributed to different levels of stored strain and variation in the deposition direction. Overall, the work sheds important quantitative insight into the heterogeneous material response, dimensional stability and shape recovery of 4D printed structures manufactured using fused deposition and thermoplastic SMP.

1. Introduction

3D printing has revolutionized traditional manufacturing and is posed to enable significant breakthroughs in a broad range of applications and industries. The main advantage of this process is that it enables the fabrication of rather complex structures without the need for custom molds. For the most part however, and given the materials used for fabrication, the component will possess a rigid set of properties in terms of shape and functionality. 4D printing, which relies on 3D printing, deviates from that by enabling the fabrication of adjustable, tunable and programmable structures [1–6]. The ability to create complex structures, through the use of additive manufacturing technologies, with programmable or shape memory properties enables novel and unique designs for use in robotics [7], deployable structures [8], self-assembly [9] and biomedical applications [10]. Owing to the huge potential benefits of this technology, the emerging field of 4D printing is attracting significant attention from the research and development communities and is becoming a very active area of research. Current efforts span across all aspects of this process, including: suitable smart materials, additive manufacturing technology, design and structure, and stimulus methods. Among the various options of active materials currently being considered, thermoplastic shape memory polymers are particularly attractive due to their compatibility with the popular and widely used fused deposition (FD) 3D printers. Multiple studies have demonstrated the use of shape memory filaments in creating three dimensional structures with programmable shapes and heat activated recovery properties [11,12]. These studies provided a proof of concept but did not thoroughly investigate the dependence of the shape memory properties of 4D printed structures on structural complexity and the FD process parameters. Accordingly, detailed analysis and local measurements of the shape memory properties and how they relate to the fused deposition process (*i.e.,* 3D printing) is lacking. This work aims to provide a deep insight into the recovery properties of complex 4D printed structures with high levels of heterogeneity in

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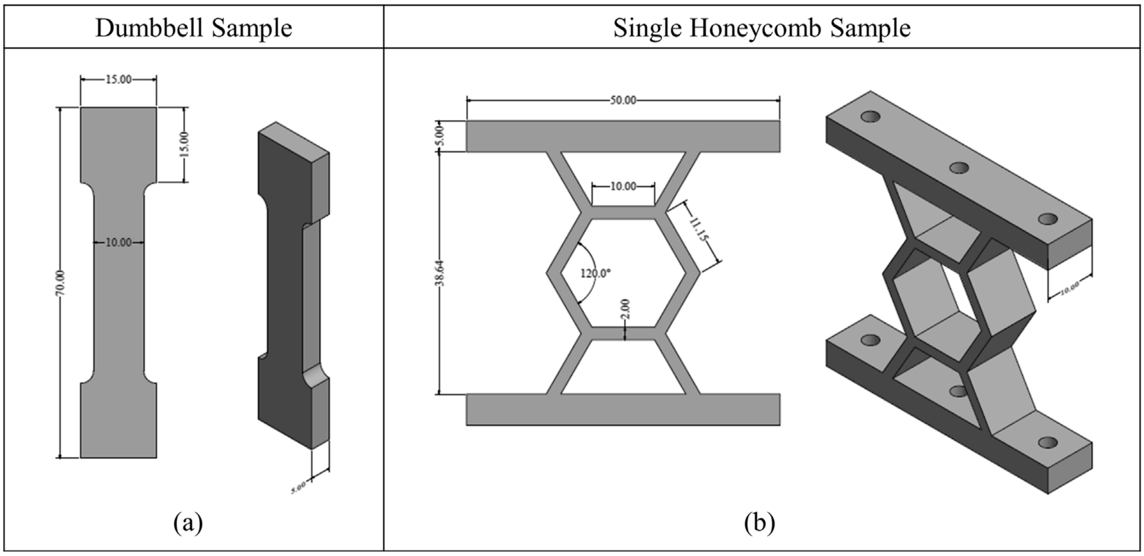

Fig. 1. 4D printed sample geometry (dimensions in mm). (a) Dumbbell tension sample. (b) Single cell honeycomb sample.

recovery strains.

Various parameters affect the quality of 3D printed parts using the FD process. For example, extrusion temperatures and speed, nozzle cooling, build plate temperature and build/deposition direction [13–15]. These parameters, among others, will affect the final print quality such as dimensional accuracy, density, surface finish, and strength [16–18]. The use of an active material (*e.g.,* shape memory polymer as considered in this work) introduces an additional level of complexity that relates to heat exposure during programing and recovery [6,19–22]. It is well known that thermoplastic polymers processed by FD, in general, shrink due to heat exposure, thus altering part dimensions [11,12]. In 4D printed components, heat exposure during programing and fixing a temporary shape results in an unintended dimensional change caused by shrinking in the polymeric material. This will be further amplified during the heat induced shape recovery phase. It is important to note that the shrinkage, and the resulting dimensional change, is not only affected by the material properties, but also by the FD process. For example, and as will be shown in this work, the deposition direction affects the amount of shrinkage in any given dimension. In this study, full field measurement techniques were employed to study the time dependent shrinkage properties of 4D printed structures at different temperatures and orientations relative to the deposition direction.

The temperature induced recovery process in thermoplastic shape memory polymers is a complex phenomenon that involves multiple variables such as stresses, strains and strain rates. Through macro-scale analysis in either tension or bending, this phenomenon can be investigated and the material dependent percent recovery, recovery rate and magnitude of recoverable strains can be quantified. On the structural/component level, studies have been mostly focused on demonstrating successful actuation of shape memory components to achieve the desired deployed shape or movement. Depending on the shape, the strain recovery field can be rather complex with high levels of heterogeneity. For example, a simple honeycomb structure subjected to tensile loading will develop a rather complex strain field with tensile and compression regions. The local recovery properties (*i.e.,* temperature induced SMP recovery) under such conditions is an area that generally requires further investigation to shed further insight into heterogeneous strain recovery. For example, and as will be shown in this work, the local strain recovery rate in honeycomb structures varies locally with different regions, reaching full recovery at different times. The complications arising in non-simple structures are further amplified in 4D printed parts due the FD printing direction. It remains unclear how the deposition direction, relative to the part dimensions, will impact on the local recovery properties. This aspect will also be a subject of investigation in the current study.

In this work, a thermoplastic shape memory polymer was used in a fused deposition process to create honeycomb structures (*i.e.,* 4D printing). Through full field measurement techniques, shrinkage properties of the printed parts were evaluated to provide insight into the relation between the time dependent shape change and printing/deposition direction. In addition, the honeycomb structures were programed into various temporary shapes induced by tension and compression forces to study the local recovery properties. In particular, the dissimilar and heterogeneous strain recovery in various local regions subjected to tension and compression was studied, and the correlation between the magnitude of recovery strain and deposition direction was evaluated. Overall, the work provides important quantitative insight into the properties of 4D printed parts using the FD process and thermoplastic shape memory polymer filament.

2. Materials and methods

Shape memory polymer filament with a diameter of 1.75 mm and a glass transition temperature (T_g) of 55 °C was obtained from SMP technologies, Japan. The filament was used in a FD 3D printer operating at 200 °C extruding temperature. Two types of samples were produced, standard dumbbell samples and single cell honeycomb structures, as shown in Fig. 1. Sample heating and programing were conducted using an Instron load frame equipped with an environmental chamber. Temporary shape programing was accomplished using a three step process: heating samples in the chamber to 55 °C, deforming them to the required shape (either in tension or compression) and finally allowing them to cool down to room temperature, which results in fixing the temporary/programed shape. For shape recovery, the chamber was stabilized at the recovery temperature (*i.e.,* 55 °C) before inserting the sample to initiate the shape recovery process. All recovery measurements were conducted on load free samples (*i.e.,* no applied load).

Two types of experiments were conducted; shrinkage and shape recovery (both on free samples with no loading applied). In shrinkage experiments, a fine speckle pattern was applied on the *as-printed* sample's surface using high temperature black paint. The pattern was stable at the temperatures considered in this study and suitable for local strain measurements using digital image correlation (DIC). The environmental chamber was heated to the desired temperature (45–65 °C) and allowed to stabilize before inserting the sample. Once the sample was inside the