Composite Structures 184 (2018) 11–17

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

3D-printed multimaterial composites tailored for compliancy and strain recovery

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ARTICLE INFO

Keywords:
Deformation mechanism
3D-printed multimaterial composites
Compliancy
Strain recovery
Load-bearing capacity
Instability

ABSTRACTS

Co-continuous multimaterial composites are novel types of multifunctional structures. This study focuses on numerical and experimental investigation of the mechanical behavior of 3D periodic single-material cellular D-structure and the corresponding co-continuous composite. Different volume fractions of desired geometry were fabricated by multimaterial fused deposition modeling (FDM) technology and compressive mechanical properties of the samples were obtained by mechanical tests. It was observed that embedding a hyperelastic material to the cellular structure dramatically hindered the shearing bands in localized regions to develop, thereby made it feasible for composite material to undergo larger deformations without failure. Furthermore, it was demonstrated that the soft phase in multimaterial composite induces a homogeneous deformation to cellular structure, which enhances the load-bearing capacity and flexibility of the whole composite. In this paper, it was shown that the co-continuous multimaterial composite provides a well-balanced approach between desired flexibility and load-bearing which is referred to as compliancy. A strain recovery between 82 and 93% was also measured when unloading for multimaterial composite. These integrated properties could be valuable to various engineering applications such as synthetic limbs, soft robotics, and wearable structures as shoes and splints.

1. Introduction

Multimaterial additive manufacturing techniques offer a compelling alternative fabrication approach, allowing materials with various mechanical properties to be placed selectively within a structure, and enabling complex multi-part design iterations to be rapidly fabricated with trivial effort. Due to the enhanced mechanical properties of co-continuous multimaterial composites in comparison to constituent material properties, they have been of great interest to material scientists. The co-continuous composites with interpenetrated phases are known for multifunctionality [1–3], efficient mechanical properties [4–6], mathematically defined morphology [7], thermal and electrical extremals [2]. Moreover, the ability of these structures to provide various stiffness in one configuration holds great promise in the multifunctional design of robots [8,9] in which for some especial applications such as soft grippers, a spatial change in material stiffness is potential to provide valuable engineering solutions. As another multimaterial structures, high performance energy absorption structure which exhibit superelasticity with reversible compression strain up to 0.9 [10] as well as high performance energy absorption structures [11] can be mentioned. There has been also studies in the fields of damage and failure process in interfaces and void growth [12,13] for non-uniformly interpenetrated multimaterial composites by FEM.

There have been four main methods for fabrication of multimaterial structures: stereolithography (SL), selective laser sintering (LS), 3D printing (3DP), and fused deposition modeling (FDM). Recently, the Stereolithography method has been the main fabrication approach of many multimaterial structures [4,6,8,9,14]. Despite many advantages of this method such as precise way to lay down layers about 16 μm [15], the material library limits to only UV-cured photopolymers. Furthermore, currently available printable photopolymers are not capable of sustaining the high material strains, desirable mechanical strength, and susceptible for failure under cyclic loadings [14,16]. Fused deposition modeling or briefly FDM method, instead, is a low-cost technology and can use a wide range of materials. About all the polymers that can be melted through a hot nozzle can be 3D printed by this method. As an important advantage, some FDM printers have made it feasible to produce multimaterial 3D parts.

Co-continuous multimaterial composites have recently attracted a huge attention which their characteristics making them distinct from

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http://dx.doi.org/10.1016/j.compstruct.2017.09.049
Received 8 December 2016; Received in revised form 7 September 2017; Accepted 19 September 2017
Available online 25 September 2017
0263-8223/

the conventional composites. Eliminating stress concentration in interfaces, smooth transition of stiffness, reduction in number of applied materials, and strong bonding between printed materials are contributions which has not been obtained generally until now by conventional multimaterial composites. A frontier example for conventional multimaterial composites is a variable stiffness prosthetic socket for a transtibial amputee [8] manufactured by multimaterial 3D printing, using SL method. The printed socket reduces the peak contact pressure on the interfaces between body and socket by 17%. However, the conventional morphology is not without its drawbacks: (i) discontinuity of stiffness through socket, (ii) weighted body caused by the poor mechanical properties of printed structure, (iii) and the use of several materials with different stiffness to meet compliancy. Furthermore, in the area of robotic design, the most recent research was implemented on the 3D printing of a rigid/soft robot with stepwise gradient of nine materials [9], creating a structure that transits from highly flexible (rubber-like) to fully rigid (thermoplastic-like), using SL technology. Considering the above-mentioned defects for conventional multimaterial composites, it becomes important to explore the mechanical behavior of new multimaterial composites. The work presented here makes two new contributions to the study of co-continuous multimaterial composites. First, we presented the mechanical behavior of a 3D periodic single-material cellular D-structure and corresponding co-continuous composite. We showed that this composite provides a controllable balance between flexibility and load-bearing, or namely compliancy. Second, we introduced that the multimaterial composite is highly capable to provide a perfect strain recovery. These properties offer optimal support and flexibility in robotics and synthetic constructs that resemble biological materials or structures which are closely in contact with parts of body.

2. Experimental

2.1. Materials and methods

In this paper, the combination of multiple materials with different properties into a single structure is explained. The 3D periodic single-material cellular D-structure and corresponding co-continuous composite are manufactured by FDM method. The potential to combine hard thermoplastic materials, which is referred to as Bayblend having less than 6% rupture strain (Fig. 1b), with very soft rubbers with the rupture strain of more than 500% (Fig. 1c) is investigated. The Bayblend material is a blend based on polycarbonate (PC) and ABS, and the soft rubbers were made of thermoplastic polyurethane (TPU). Yet, none of the available 3D printing methods of materials could provide such mechanical properties as obtained using FDM method for constituents of 3D printed structures.

In this work, we impose a controlled material distribution into the composite material based on co-continuous architectures, which are constructed by triply periodic minimal surfaces for a D-structure (see Fig. 2a). Triply periodic minimal surfaces are basically implicit functions representing cellular surfaces in the space, the equation of which is expressed in the form of sinusoidal terms with an offset value of C determining the fraction of material composition. D-surface was defined with the implicit function of $\cos(2\pi x)\cos(2\pi y)\cos(2\pi z) - \sin(2\pi x)\sin(2\pi y)\sin(2\pi z) = C$, where C was manipulated to give the Bayblend internal volume fractions ($\varphi < C$) of 30, 50, and 70%. Then, STL files were generated through an image-based method according to the 2D cross sectional images of a replica of unit cells. The same approach was utilized to design hexagonal meshes as an input to CAE software for the sake of conducting finite element simulations. The aforementioned STL files were imported into a FDM 3D printer [17]. Bayblend and TPU hyperelastic filaments were inserted into the machine and the materials were injected according to the input STL models.

2.2. Characterization

The uniaxial testing of TPUs as soft phase and Bayblend as hard phase are carried out using a universal testing machine (shown in Fig. 1). The hyperelastic constants of TPUs were determined based on the correlation between values of strain energy density rebuilt from test data and the theory [18]. Applying this method, the constitutive model proposed by Mansouri and Darijani with respect to other models reports the least residual sum of squares about RSS = 0.05 and RSS = 0.91 for 3D printed TPU3660 and TPU3695 materials, respectively. The discrepancy between the model results and the experimental data, commonly referred to as residual sum of squares (RSS), is defined as

$$RSS = \sum_{i=1}^{n} W_{data} - W_{model}^{2} \tag{1}$$

A perfect fit would yield a residual sum of squares of 0.0. The constitutive model is in the form

$$W = A_1[\exp(m_1(I_1-3))-1] + B_1[\exp(n_1(I_2-3))-1] \tag{2}$$

where A_1 and B_1 are material parameters, m_1 and n_1 are non-dimensional values and I_1, I_2 are invariants of the right Cauchy – Green strain tensor. The initial shear modulus, μ_0, is computed through the relation $\mu_0 = 2(A_1 m_1 + B_1 n_1)$. During the fitting procedure of uniaxial extension data from Fig. 1a, the initial shear modulus $\mu_0 = 33.27$ MPa and $\mu_0 = 7.92$ MPa are reported for TPU 3660 and TPU 3695 materials, respectively. The TPU 3660 and TPU 3695 have also density about 1050 kg/m^3. The set of material constants for hard phase, Bayblend as elastic-plastic material, are Young's modulus $E = 1.7$ GPa, Poisson's ratio $\upsilon = 0.35$, and density $\rho = 1100$ kg/m^2.

A set of compression tests are conducted on samples consist of $4 \times 4 \times 4$ cells up to strain about 0.35. The cubic sample height is $l_0 = 40$ mm. These cubic samples include as cellular topology with

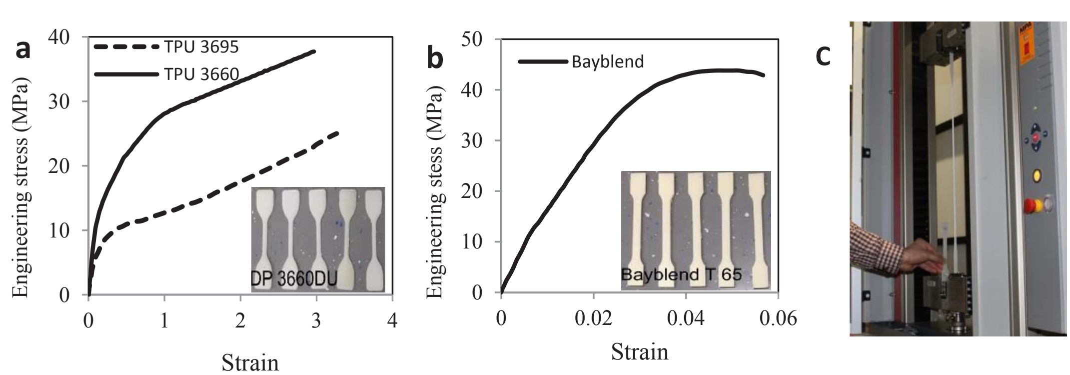

Fig. 1. (a) Stress – strain responses of two TPUs subjected to uniaxial tension. (b) Uniaxial tension response of Bayblend. (c) Comparison of an un-deformed sample of TPU with deformed one up to strain of 500% before breaking.