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Microstructural design and additive manufacturing and characterization of 3D orthogonal short carbon fiber/acrylonitrile-butadiene-styrene preform and composite

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ABSTRACT

In contrast to conventional preforming techniques, additive manufacturing features direct and layer-by-layer fabrication, which provides viable new capabilities for the fabrication of reinforced composites. In this article, we explore the microstructural design as well as additive manufacturing and characterization of 3D orthogonal, short carbon fiber/acrylonitrile-butadiene-styrene (ABS) preforms and composite. First, an array of 3D orthogonal preforms is designed based on topological consideration and validated by fused filament fabrication of pure ABS wire; high fidelity between models and preforms is accomplished. Then, short carbon fibers are introduced into the designed 3D orthogonal preforms as reinforcement, using a short carbon fiber/ABS wire. Lastly, the compressive behavior of a 3D orthogonal, short carbon fiber/ABS preform and that of its silicone infused composite are characterized. The preform design methodology developed in this research as well as the preliminary effort made in composite fabrication and characterization demonstrates the feasibility of additive manufacturing of 3D orthogonal preform based fiber composites.

1. Introduction

3D orthogonal preforms [1,2], which are composed of yarn assemblies in three mutually orthogonal directions, have traditionally been fabricated only by the 3D weaving process [3], a textile preforming technique. Because of the outstanding structural integrity and superb mechanical performance of 3D woven products, especially the out-of-plane properties, textile preforming technology has found significant applications in aeronautics [4–6], automotive [7] and infrastructures [8] as well as other industries [9–12]. However, the lack of precise control of preform microstructures during fabrication remains a barrier to accurate performance prediction of 3D orthogonal performs fabricated by textile technologies [13].

Furthermore, due to the nature of existing weaving equipment, the availability of topological design for 3D orthogonal preforms is fairly limited. In contrast, additive manufacturing, emerging as a global revolutionary technology since its inception in the 1980s [14–17], provides new opportunities for the design and fabrication of composite materials [18–29]. According to ASTM-I F2792: Standard Terminology for Additive Manufacturing Technologies, additive manufacturing is “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive methodologies” [30]. Additive manufacturing embodies several distinct advantages over conventional fabrication techniques, such as improved structural designability and complexity, realization of mass customization, and reduced capital investment and production cost via simplification (or even elimination) of tooling and finishing [31,32]. In a recent review [29], Quan et al. examined the opportunities and challenges in additive manufacturing of multi-directional preforms for composites. Although the authors demonstrated the additive manufacturing of

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an array of multi-directional preforms for composites for the first time, the fabricated preforms, additively manufactured using fused filament fabrication (FFF) of pure ABS materials, were not reinforced.

Among a variety of reinforcements used to improve the mechanical performance and size stability of additively manufactured parts, short carbon fiber has often been adopted [26,33–35]. Tekinalp et al. [26] reinforced ABS using short carbon fibers 0.2–0.4 mm in length and reported increases in tensile strength and modulus of dog-bone samples by 115% and 700%, respectively. Love et al. [35] reported that short carbon fiber additions can radically reduce distortion and warping of the resulting composites during deposition. Shofner et al. adopted carbon nanofibers to reinforce additively manufactured ABS parts and also observed desirable results [33,34].

In this article, we report the following research efforts in the microstructural design as well as additive manufacturing and characterization of 3D orthogonal, short carbon fiber/ABS preforms and composite. First, three types of 3D orthogonal preforms were designed in terms of the Cartesian, cylindrical and spherical coordinate systems, respectively, and the model designs were validated by fabricating the preforms using FFF of pure ABS. Next, additive manufacturing of reinforced 3D orthogonal preforms has been demonstrated by using a short carbon fiber/ABS wire. Lastly, the compressive behavior of a composite based on the 3D orthogonal, short carbon fiber/ABS preform and a silicone elastomeric matrix has been characterized.

2. Microstructural design of 3D orthogonal preforms

3D orthogonal preforms, traditionally fabricated by 3D weaving techniques, signify a class of integrated textile structure, in which yarns are intertwined with one another (See Fig. S1 in Supplementary Information), endowing the composites with desirable structural stability.

2.1. Topological design

The topological design of 3D orthogonal preforms can be conducted step-by-step in terms of orienting yarns with respect to the reference axes, aligning yarn sheets, combining sheets of different alignments and checking equivalency among possible combinations. The design procedure based on Cartesian coordinate system is demonstrated in the following.

2.1.1. Yarn orientation

By choosing a Cartesian coordinate system and aligning the yarns along the principal axes, the yarn orientation can be identified as shown in Fig. 1a. Here, the yarns along the X, Y and Z axis are termed as *X-yarn*, *Y-yarn* and *Z-yarn*, respectively.

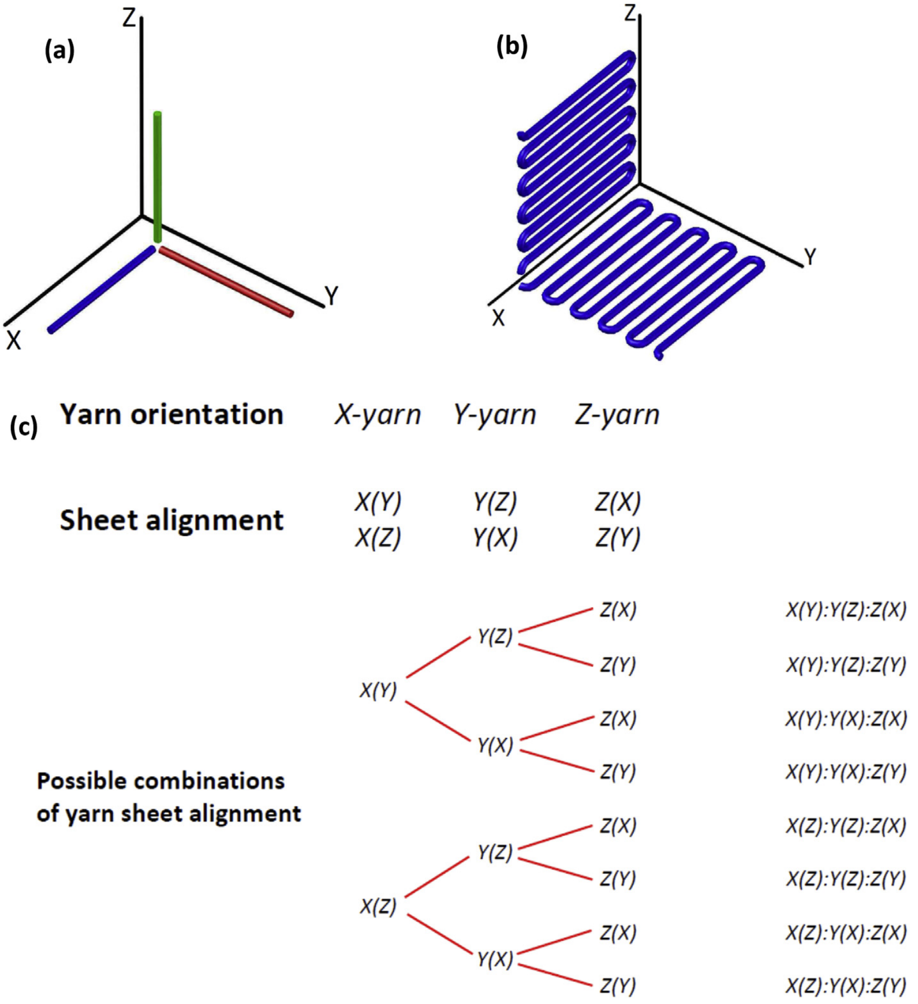

Fig. 1. Topological design of 3D orthogonal preforms in Cartesian coordinate system: (a) yarn orientation, (b) two possible alignments of the X-yarn sheet, and (c) eight possible combinations of sheet alignments.