# Additive manufacturing of multi-directional preforms for composites: opportunities and challenges

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**Current additive manufacturing methods present the potential to construct net-shape structures with complicated architectures, thus eliminating the need for multi-step processing and fasteners/joints. Combined with these features is the ability to ascribe material properties at the sub-millimeter scale, inspiring multi-material, functionally graded designs. These features make additive manufacturing an attractive option for composite materials development. In an effort to extend this family of technologies beyond nano- and micro-composites, we explore the additive manufacture of multi-directional composite preforms. This exercise has served to highlight the aspects of additive manufacturing critical to composite and general materials processing, as well as to demonstrate the high fidelity between modeled and additively manufactured structures. Within the scope of composites development, we review the state-of-the-art and discuss challenges facing the broad adoption of additive manufacturing for directionally reinforced composites processing.**

## Introduction

Traditional composites are composed of a reinforcement phase held together by a binder; their mechanical and physical properties can be tailored through proper selection of constituent materials and processing techniques as well as the design of micro-structural parameters [1–4]. Among the micro-structural parameters, reinforcements can be in the forms of discrete particles, continuous fibers, two-dimensional woven fabrics, or three-dimensional preforms. In 3D integrated preforms, the fibers/yarns are generally aligned along more than one directions [2–4]. Due to their unique characteristics, including out-of-plane mechanical properties, broad structural designability, improved structural integrity and damage tolerance, and cost-effectiveness, multi-directional textile preforms have found broad industrial applications [5]. Although a range of traditional textile forming techniques [6] have been developed to manufacture multi-directional preforms, there remain some fundamental technological barriers. As a result, the micro- and macro-structure of a manufactured preform may deviate from those of the designed/optimized model, leading to uncertainties in performance predictions.

The rapid advancements in additive manufacturing techniques have provided us with the impetus to examine the feasibility of manufacturing multi-directional preforms based on direct, layer-wise fabrication [7–9]. To this end, we have established model designs of an array of complex multi-directional preforms and demonstrated the fabrication of these preforms using an extrusion method with unreinforced acrylonitrile-butadiene-styrene (ABS) wires. To further examine the feasibility of additive manufacturing of reinforced performs, we have reviewed the advancements to date in reinforced composites where continuous fibers, short fibers, and particulates were utilized. Finally, the challenges in developing reinforced multi-directional preforms for composites are discussed.

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## Multi-directional preforms and conventional textile manufacturing technologies

Multi-directional textiles represent a class of preforms for composites in which reinforcing fibers are oriented in multiple directions, typically woven, braided, knitted or stitched together [2–4,10]. The broad application of textile structural composites [5] can be attributed to their unique characteristics, which include: (a) *Outstanding out-of-plane mechanical properties*: While 2D preforms mainly contribute to composites in-plane properties, 3D preforms provide reinforcement in the thickness direction [11], as well as in plane, leading to significantly improved out-of-plane performance. (b) *Broad structural designability*: The existing theoretical and experimental knowledge base [2–4,12–18] on multi-directional textile process-structure-property relationship provides a broad design space for preform structure and performance [3,16]. (c) *Improved structural integrity and damage tolerance*: Textile performing techniques enable net-shape or near-net-shape fabrication of composite parts with complex shapes, reducing or eliminating the need for joints [19]. The highly integrated fiber structure greatly enhances the tolerance to damage induced by matrix micro-cracks and delamination [20]. (d) *Cost-effectiveness*: The near-net-shape forming of composite parts [19,21] greatly reduces or eliminates the need for machining, cutting and assembling components.

There exists a broad array of conventional textile fabrication techniques for multi-directional preforms for composites [6]. (a) *Weaving*: In woven preforms, yarns are classified into warp, filling, and binder yarns. By interlacing different yarn groups in a predetermined pattern, 2D weaving creates a thin fabric with two-dimensional structure, while 3D weaving forms an integrated three-dimensional architecture [22]. (b) *Braiding*: In the braiding process, each yarn is attached to a carrier [23]; due to different carrier motion paths, the yarn groups intertwine with one another. For 2D braiding, yarn carriers move back-and-forth along undulating linear or circular paths; while in 3D braiding processes, yarn carriers move within a 2D braiding platform [16]. (c) *Knitting*: The knitting process generally leads to highly stretchable fabric preforms, in which adjacent yarns are looped through one another using hooks, to form a structure in which yarn orientation changes significantly over a small volume [24]. In a weft knitted preform, a single yarn is looped along the width-wise direction, while in a warp knitted preform, along the length-wise direction. (d) *Z-pinning* and *stitching*: Z-pinning and stitching are typically used to reinforce laminated structures in thickness/Z direction [18]. In the Z-pinning process, a group of pins oriented in the through-thickness direction is inserted into the laminated layers, while in the stitching process [25], a group of continuous stitch threads is utilized. Furthermore, Z-pinning and stitching can also help prevent the preform fabric plies from shifting under low shear forces associated with handling. (e) *Non-woven processing*: In non-woven preforms, reinforcements are generally in the form of staple/chopped fibers used often in combination with continuous fibers [26–31].

Although textile preforming technologies have greatly facilitated the development of advanced composites during the past quarter of a century, some fundamental technological barriers still exist. In conventional techniques, the precise control of preform structural parameters cannot be easily accomplished. As a result, the micro- and macro-structure of a manufactured preform may deviate from those of the designed/optimized model [32]. Any preform structural variation will, to some extent, induce an uncertainty in the mechanical and physical properties of the reinforced composites, hindering structural characterization, property prediction and design. Furthermore, because of the low level of automation in most of the existing textile preforming equipment, the cost of fabrication of multi-directional preforms, especially 3D preforms, remains high.

## Unique characteristics of additive manufacturing

Additive manufacturing, also broadly known as ‘rapid prototyping’ and ‘freeform fabrication’, embodies a novel class of manufacturing processes. According to ASTM-I F2792: Standard Terminology for Additive Manufacturing Technologies [33], additive manufacturing is ‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive methodologies’. The two fundamental features of additive manufacturing are direct fabrication (from design data to realistic product, without tooling and machining) and additive, layer-wise processing (from bottom section up to top section) (Fig. 1). These characteristics endow additive manufacturing the following unique capabilities unattainable using traditional manufacturing processes.

Additive manufacturing enables the fabrication of complex shaped objects [34–36]. In traditional processes, limited by tooling accessibility to nooks and internal surfaces, a complex part is often built by assembling separate simple parts, which often leads to premature structural failure at material joints. In additive manufacturing, however, regardless of their degree of complexity, objects are fabricated following the same procedure: slicing the designed model into a certain number of layers with a predetermined thickness and printing the sliced sections layer upon layer successively from bottom to top. This capability empowers very large geometric design freedom.

In addition to automation of the manufacturing process and elimination of manufacturing steps (in the case of composites, lay-up, infusion and curing), additive manufacturing facilitates the introduction of functional features [37–41], which are generally accompanied by structural complexity [42]. By changing material composition and location within a part at the processing stage [43], multi-material additive manufacturing makes it possible to create the features of multi-functionality and gradient functionality.

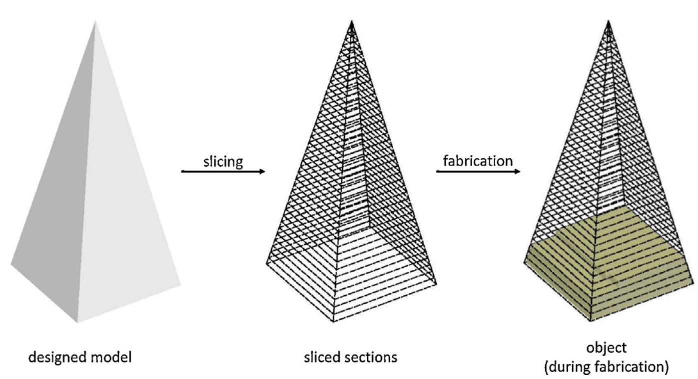


FIGURE 1

Flow chart of additive manufacturing. Additive manufacturing features direct fabrication and additive fabrication.

Additive manufacturing makes fabrication more flexible. By directly manufacturing an object from the design file, additive manufacturing greatly shortens the lead-time, facilitates efficient design demonstration, and makes the small lot-size (even one-piece) but complex shaped customization [44] very economical. Finally, in additive manufacturing, the material is placed just where it is needed and the residual material can often be readily recycled or reused, reducing material waste.

Specific advantages of additive manufacturing of multi-directional preforms over conventional textile forming techniques include:

### *High fidelity*
During traditional textile preform manufacturing, fibers/yarns must undergo multiple processing steps, during which they interact with each other and with the textile machine. The preforming process may give rise to micro- and macro-structural differences between a preform and its model in cross-sections, yarn paths, inter-yarn spacing, and overall preform sizes. In additive manufacturing, however, because of direct fabrication based on the preform design model, the resulting preform is almost identical to the original model. Thus, the consistency in preform quality is ensured.

### *Realization of complex structures*
In additive manufacturing, an object is made by building its constituent materials layer-by-layer, which enables achieving of desirable, optimal architecture parameters and the fabrication of highly complex structures. It should be noted that in traditional textile preforming techniques many desirable, optimal structures may not be feasible. For example, the increase of braiding angle of the 3D braided preform shown in Fig. 2 can be accomplished through additive manufacturing by simply shrinking the height of the model. However, to achieve the same goal using conventional techniques, it is necessary to calculate the required processing parameters first for each shrinkage step and sometimes the required parameters are not available from practical braiders.

### *Property predictability*
In conventional textile preforming, owing to the variability in preform micro- and macro-structures, the resulting physical and mechanical properties of preforms based on the same design may not be uniform. Thus, the precise prediction of preform property is difficult. However, in additive manufacturing, high fidelity of reproduction of preforms enables their properties to be predicted directly from the design model with high precision.

## Design of models for additive manufacturing of multi-directional preforms
In the previous section, we discuss the benefits of additive manufacturing as a direct fabrication process from digital data to final product. In order to fully take advantage of the high fidelity between model and object, it is particularly rewarding to pay attention to the design of preform architecture.

### *Basic features*
Because of the large number of yarn groups and their complex architecture in a multi-directional preforms, it is not feasible, if not impossible, to directly model the entire preform. Thus, the concept of 'representative volume element', RVE [14], has often been adopted by researchers for analysis and modeling [11–13,15,17]. This approach is based on the observation that in a multi-directional preform, yarns are assembled together according to a certain pattern, which endows the overall structure a feature of periodicity, in which the minimum, repeatable volume unit is defined as the representative volume element, also termed as a unit-cell. By repeating the basic volume element in the length, width and thickness directions, the total preform volume can be reproduced. The RVE concept not only facilitates the analysis and modeling of advanced textile composites but also greatly expands our capability in optimization of preform design for additive manufacturing (Fig. 3).

In a multi-directional preform, besides the periodical structural feature, its architecture could also show a multi-scale/hierarchical characteristic. At the macro scale, the entire preform can be

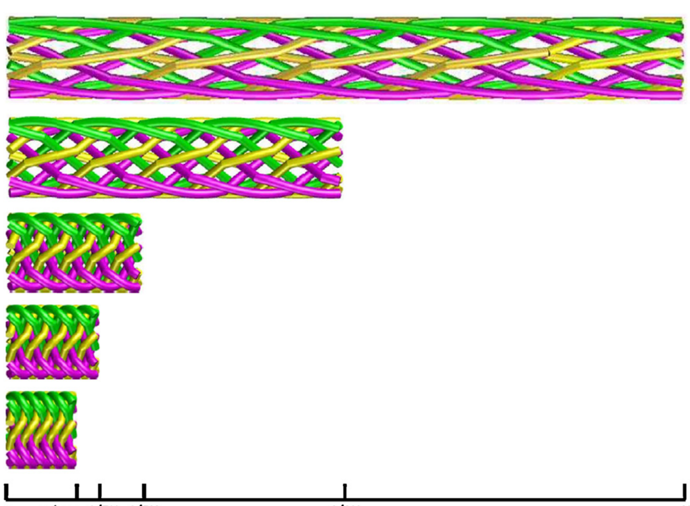


**FIGURE 2**

Preforms with different braiding angles. In additive manufacturing, braiding angle can be readily adjusted by shrinking/stretching the preform model length *H*.

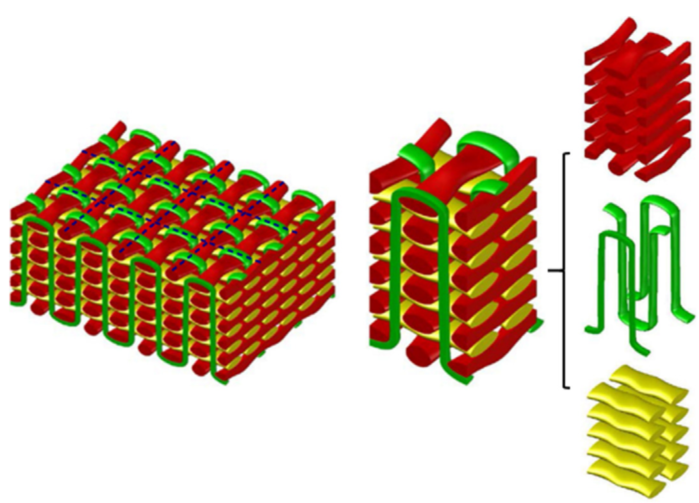

**FIGURE 3**

Unit-cell (right) of the through-the-thickness orthogonal interlock woven preform (left). According to yarn orientations, yarns within this unit-cell are further classified into 3 groups.

divided into a certain number of unit-cells; at the meso scale, a unit-cell can be regarded as composed of several groups of yarns; at the sub-meso scale, a yarn may be consisted of thousands of fibers; at the micro scale, a fiber possesses its own distinct structural characteristics. The multi-scale feature of a preform, although complicates model design, provides greater flexibility in manufacture not readily available in traditional fiber composites. The degrees of freedom achievable in the design of multi-directional preforms may include preform shape and size (macro scale), unit-cell architecture feature (meso scale), yarn geometry (sub-meso scale), and fiber size and property (micro scale).

### *Design of models*

The key factors in the model design of multi-directional preforms are discussed below.

#### Unit-cell architecture

Each type of unit-cell architecture has its unique characteristic in terms of physical and mechanical performance [2]. For example, woven architectures possess outstanding structural stability; braided preforms are known for their high structural integrity; and knitted preforms can sustain non-linear deformation. Therefore, the successful model design of a unit-cell architecture is fundamental to the application of a textile preform.

#### Constituent materials

Our ability in selecting different material constituents and placing them in different parts of the unit-cell will greatly enhance our option in designing the preform esthetic, physical and mechanical properties. The availability of multi-head/multi-material printer for additive manufacturing [45] enables the fabrication of multi-constituent and multi-functional preforms [46]. For example, using more than one kind of material with different colors as braid yarns may result in a more artistic braided part; using conductive and insulative materials as warp and weft yarns respectively may result in a unidirectionally conductive woven fabric; combining different material constituents among yarn groups may enable the fabrication of composites with functional gradient.

#### Structural parameters

The main structural parameters of a multi-directional preform include yarn size and shape, yarn orientation angle, yarn number, and preform size. Although in traditional textile manufacturing processes yarns are packed quite tightly due to the compaction step, in additive manufacturing of preforms, very thin yarns may result in unstable preform structure and yarn interpenetration occurs when thick yarns are used (Fig. 4). Yarn cross-section shape has a significant influence on preform void content. Also, yarn orientation affects both inter-yarn friction (through changing void volume content, Fig. 2) and preform anisotropy [14]. Attainable preform size is limited by nozzle size at the microscopic scale and by platform size at the macroscopic scale.

### *Model fabrication by additive manufacturing*

In order to explore their geometric feasibility in additive manufacturing, an array of models of multi-directional preforms for composites has been fabricated (Fig. 5) on an *uPrint*® *SE Plus* 3D printer (*Stratasys Inc.*, Minnesota, USA). This system is based on the fused filament fabrication (FFF) process, a material extrusion [33] approach of additive manufacturing. In fabricating these prototypes, acrylonitrile-butadiene-styrene (ABS) filament was used as the feedstock of model material, while a water-soluble filament was used as the feedstock of support material, which is necessary for the fabrication of 3D structures containing overhangs. As for printing resolution, each layer was nominally 0.254 mm (0.01 in.) thick, as dictated by the nozzle diameter of approximately 0.254 mm (0.01 in.). The printed objects were then immersed into a water solution to remove the support material.

In additive manufacturing, speed of fabrication and final part quality were determined by the following key factors:

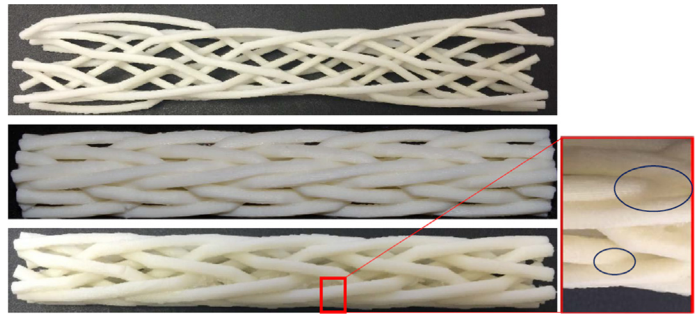

**FIGURE 4**

Braided preforms demonstrating yarn size effect in additive manufacturing: (top) The entire preform falls apart when yarns are too thin; (middle) For proper yarn size, yarns contact with one another without interpenetrate; (bottom) Yarn interpenetration occurs when the yarns are too thick (see circled areas).

#### Resolution

Resolution indicates the finest size/feature that can be printed by an additive manufacturing apparatus. It is generally described as spots per unit length [47] and limited by the nozzle size. Obviously, the higher the resolution is, the more spots per unit length need to be printed and the more detailed features can be realized. Thus, resolution plays an important role in the build time. A higher resolution implies a larger number of printing tracks and more detailed features, which also require more time to accomplish.

#### Layer thickness

Additively manufactured objects show a layer-wise feature; the layer thickness influences the build time and surface smoothness. For a given object height, a larger layer thickness means a less number of layers and a higher fabrication speed. However, a large layer thickness also leads to an obvious stair-step effect (Fig. 6).

#### Printing strategy

Printing path is another processing related factor which requires our attention. Previously, researchers printed ABS specimens and characterized their tensile response as a function of layer orientation [48]. They concluded that additive ABS solid samples display different tensile strengths, modulus of rupture, and impact resistance with different layer orientations. Specimens with 0° layer orientation, in which printing direction was parallel to the tensile direction, showed improved tensile strength and impact resistance over specimens with other layer orientations. The property anisotropy of additive specimens may result from interlayer porosity [49]

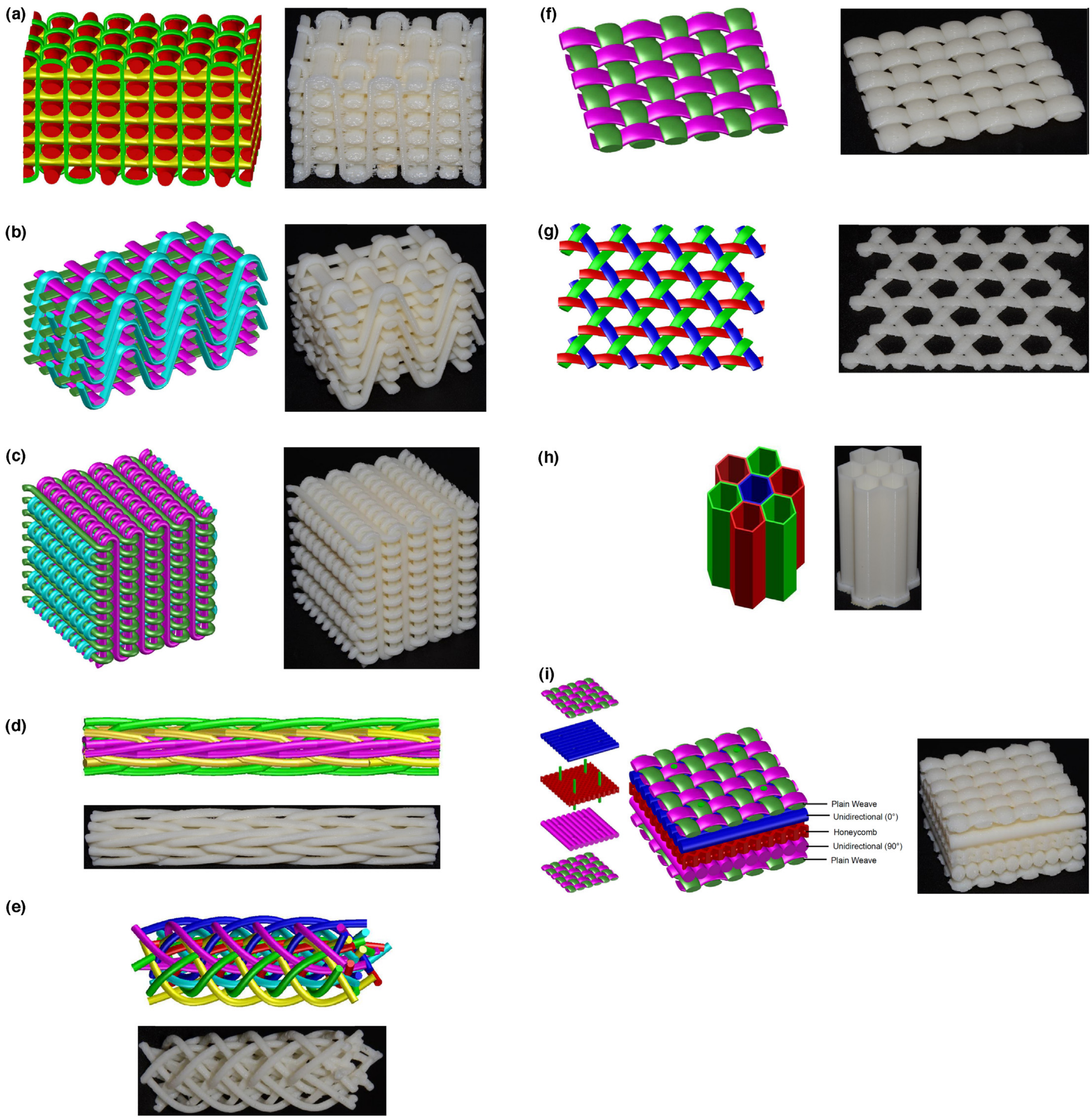


**FIGURE 5**

Typical multi-directional preforms for composites, showing designed models (left) and photos of fabricated object (right): (a) 3D through-the-thickness interlock woven preform, (b) 3D layer-by-layer interlock woven preform, (c) 3D orthogonal woven preform, (d) 3D rectangular 4-step braided preform, (e) 3D cylindrical 4-step braided preform, (f) 2D plain woven preform, (g) 2D triaxial woven preform, (h) honeycomb preform with hexagon cells, and (i) Z-pinned sandwich preform consisting of 5 layers (top plain weave, 0° unidirectional lamina, honeycomb with rectangular cells, 90° unidirectional lamina, and bottom plain weave).

and weak interlayer bonding [48]. Therefore, adopting a scan methodology to minimize the former is critical.

It should be noted that, although the multi-directional preforms shown in Fig. 6 were fabricated by FFF for demonstration purposes, they could be readily manufactured by other additive manufacturing techniques.

## Advances in additive manufacturing of reinforced composites

The figures discussed in the previous sections demonstrate the capability to design multi-directional preforms for additive manufacturing, validated through the fabrication of polymeric preforms using FFF. In the subsequent sections, we will focus on

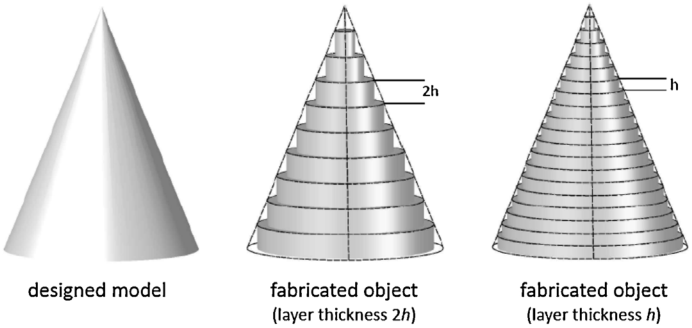


**FIGURE 6**

Schematic of stair-step effect resulting from layer-wise fabrication.

the opportunities and challenges facing the development of additive manufacturing based *reinforced* multi-directional preforms.

To realize the full potential of additive manufacturing as an effective, versatile fabrication method of multi-directional preforms for composites in load-bearing structural components, imbedding reinforcements such as continuous or short fibers, particles, and nanomaterials into the preform may be necessary. Recently, some promising results in additive manufacturing of composites reinforced by fibrous/high-aspect-ratio fillers have been demonstrated. These are summarized in Table 1 and briefly discussed below.

As a type of *material extrusion* based additive manufacturing process [33], the fused filament fabrication (FFF) technique builds structures through the melting and extrusion of thermoplastic filaments, which cool and solidify upon placement. To improve the mechanical properties of FFF based additive parts, researchers have incorporated reinforcing materials into their thermoplastic feedstock [49–53]. Typically, acrylonitrile-butadiene-styrene (ABS) and polyamide (PA) are used as matrix materials; reinforcement is in the form of short/chopped fibers (such as carbon or glass fibers). This approach requires (1) selection of a fiber and matrix such that good adhesion can be achieved between the two, (2) optimization of fiber length distribution and (3) identification of an ideal mixing process which will not damage the fibers yet will achieve a well-blended suspension. The fiber/matrix suspension is extruded into continuous filaments, which are wound into spools to be used as model material for FFF. Tekinalp et al. [49] and Love et al. [50] fabricated short carbon fiber reinforced ABS composites; Zhong et al. [51] incorporated short glass fiber into ABS; Shofner et al. [52,53] combined vapor-grown carbon fibers with ABS to reinforce additive composites. The authors investigate the effects

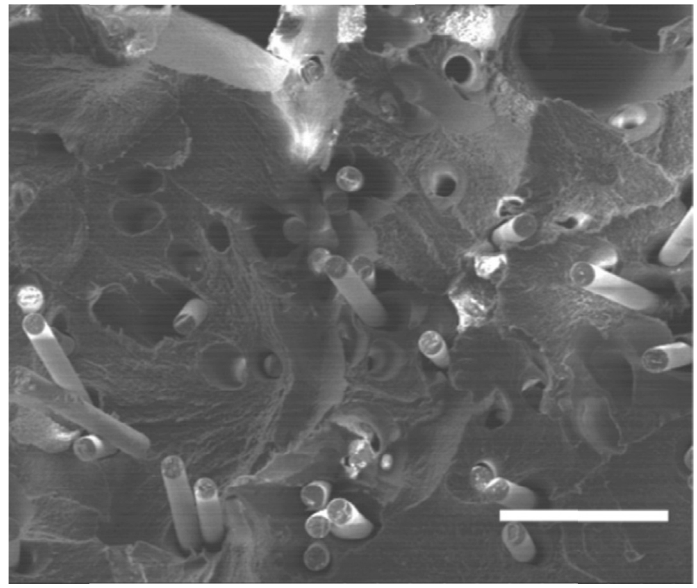

**FIGURE 7**

SEM micrographs of failure surfaces of FFF carbon fiber/ABS composites [49].

of fibers on the composites microstructure (Fig. 7), mechanical properties, and distortion (Fig. 8). It is noted that fibers tended to orient along the printing direction in the composites due to the shear stress induced in the extrusion process.

Recently, researchers adopted the FFF process for continuous fiber based printing [54,55]. Ref. [54] reported that a continuous fiber reinforced composite part was incorporated into a sandwich construction, consisting of two polyamide skins and a polyamide honeycomb core surrounded by continuous carbon fiber as reinforcement. Instead of using reinforced thermoplastic as the feedstock material, the part was fabricated by a dual-head printer – one head printed the polyamide, while the other head printed the continuous carbon filament. In contrast, Namiki et al. [55] adopted a 'co-extrusion' process (Fig. 9) to fabricate continuous carbon fiber-reinforced poly-lactic acid (PLA) composites. The authors supplied carbon fibers and PLA filaments separately, commingling them in a heated extrusion head. In both methods, due to the mechanical pulling and placement, continuous fibers were orientated along the printing direction.

Another *material extrusion* based additive manufacturing method, known as 'direct ink writing' (DIW) [56], has been used to process composite materials by extruding thermoset resins from a

**TABLE 1**

**Summary of additive manufacturing of fibrous/high-aspect-ratio fillers reinforced composites.**

| AM process | Specific approach | Filler form | Filler alignment | Alignment mechanism |
|---|---|---|---|---|
| Material extrusion | Refs. [49–53] | Short fiber | Along printing direction | Shear stress (*during preparation of feedstock spool*) |
| | Refs. [54,55] | Continuous filament | Along printing direction | Mechanical pulling and laying |
| | Ref. [57] | Short fiber, whisker | Along printing direction | Shear stress (*near nozzle*) |
| Powder bed fusion | Ref. [58] | Single-layer graphene oxide | Perpendicular to cross-section | Evaporation of dispersing agent |
| | Ref. [59] | Nanofiber | Random orientation | – |
| Vat photopolymerization | Ref. [60] | Micro-particle | Along electric-field direction | Polarization effect |
| Binder jetting | Ref. [61] | Short fiber | Along printing direction | – |

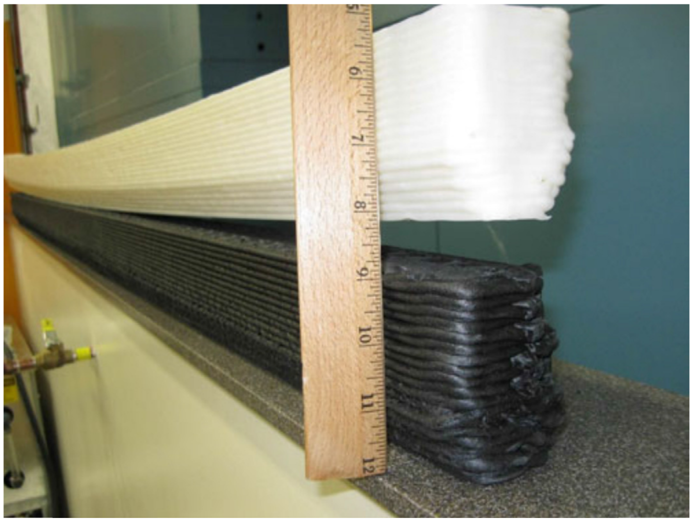

FIGURE 8
Additively manufactured bars based on FFF: with (bottom) and without (top) carbon fiber reinforcement [50]. The one with carbon fiber reinforcement showed no distortion, while the one without carbon fiber curled to near 1 in.

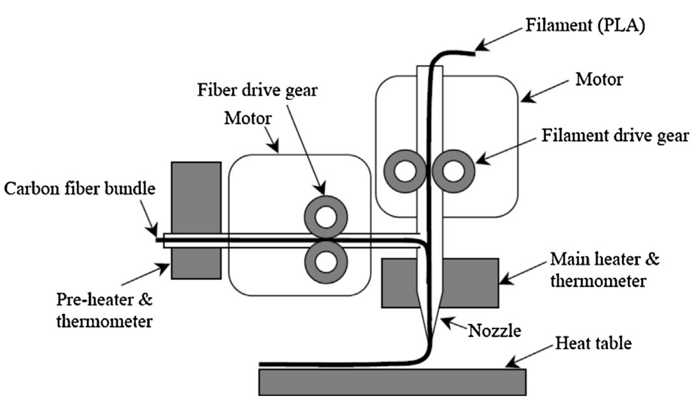


FIGURE 9
Schematic of the co-extrusion process for additive manufacturing of continuous fiber reinforced composites [55].

syringe in a specified pattern, thus building up a structure in a layer-wise manner. This approach requires precise rheological control, typically achieved through the use of filler particles, to prevent flow post extrusion and a loss of net shape. Compton and Lewis [57] used this method to produce reinforced epoxy structures (Fig. 10). They selected silicon carbide whiskers (with a diameter of 0.65 $\mu$m and a mean length of 12 $\mu$m) and short carbon fibers (with a diameter of 10 $\mu$m and a mean length of 220 $\mu$m) as reinforcement fillers. The authors achieved a sufficiently high yield strength ink through the incorporation of dimethyl methyl phosphonate (DMMP) and nano-clay platelets as rheological modifiers. Compton and Lewis demonstrated a significant increase in Young's modulus upon addition of the fiber reinforcement in their cellular structures. Due to the shear stress around the print nozzle, the whiskers and fibers were aligned along printing direction.

Laser sintering (LS), a *powder bed fusion* process, is another option for the additive manufacturing of reinforced composites. Lin et al. [58] demonstrated the reinforcement of an iron matrix

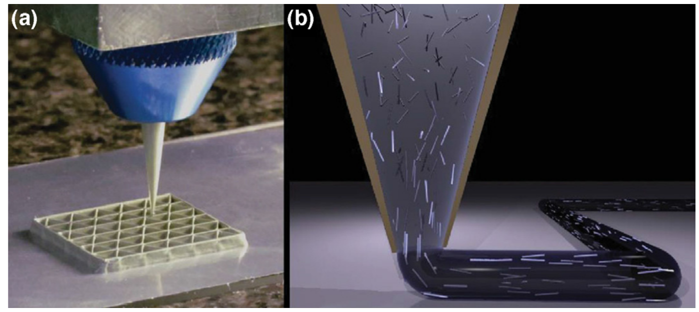


FIGURE 10
(a) Image of 3D printing process. (b) Schematic of fiber orientation within resin [57].

by single-layer graphene oxide (GO) powders. Before sintering, to evenly mix single-layer GO powders with iron matrix powders, polyvinyl alcohol (PVA) was used as a dispersing agent. The effects of GOs on the micro-structure and mechanical properties of the resulting composites were studied and the GOs were reported to be aligned vertically in the cross-section due to the evaporation of PVA during sintering (Fig. 11).

Also based on LS, Goodridge et al. [59] investigated the additive manufacturing of carbon nanofiber (CNF) reinforced polyamide-12 (PA12) composites. First, they mixed CNFs with PA12 powders and compression molded the mixed powders into a sheet, which was cryogenically fractured into CNF/PA12 compound powders (Fig. 12) and then laser sintered. They reported increases in both storage and loss modulus of the reinforced composites.

Based on stereolithography (SL) technology, a *vat photopolymerization* additive manufacturing method [33], Holmes and Riddick [60] took advantage of the polarization effect and used electric fields to align aluminum micro-particles (with an aspect ratio of around 1 and a diameter of 20–50 $\mu$m) within an UV curable acrylate photopolymer system into chain-like structures, referred to as 'pseudo fibers' (Fig. 13). By changing electric field direction, they demonstrated the feasibility of orienting 'pseudo fibers' perpendicular to the build platform.

Using a *binder jetting* process where model materials are glued together by a selectively deposited binder/glue material, Christ et al. [61] also explored the additive manufacturing of fiber reinforced composites. They used four kinds of short fibers (denoted as polyacrylonitrile fiber (PAN), polyacrylonitrile short cut fiber (PAN-sc), polyamide fiber (PA), and alkali resistant zirconium silicate glass short cut fiber (glass fiber)) to reinforce a matrix of cellulose-modified gypsum powder and investigated their effects on the mechanical properties of reinforced composites.

In addition to the above mentioned fibrous/high-aspect-ratio fillers, other kinds of reinforcements such as nanotubes [53], particles [62–64] have also been used in the additive manufacturing of composites. A relevant review article can be found in [65].

## Challenges in additive manufacturing of multi-directional preforms for composites

Despite the exciting opportunities and potentials of additive manufacturing of multi-directional preforms for composites, there exist many challenges and difficulties, as delineated below.

(1) Even though the availability of 3D printing facilities is expanding rapidly, the range of materials used is fairly

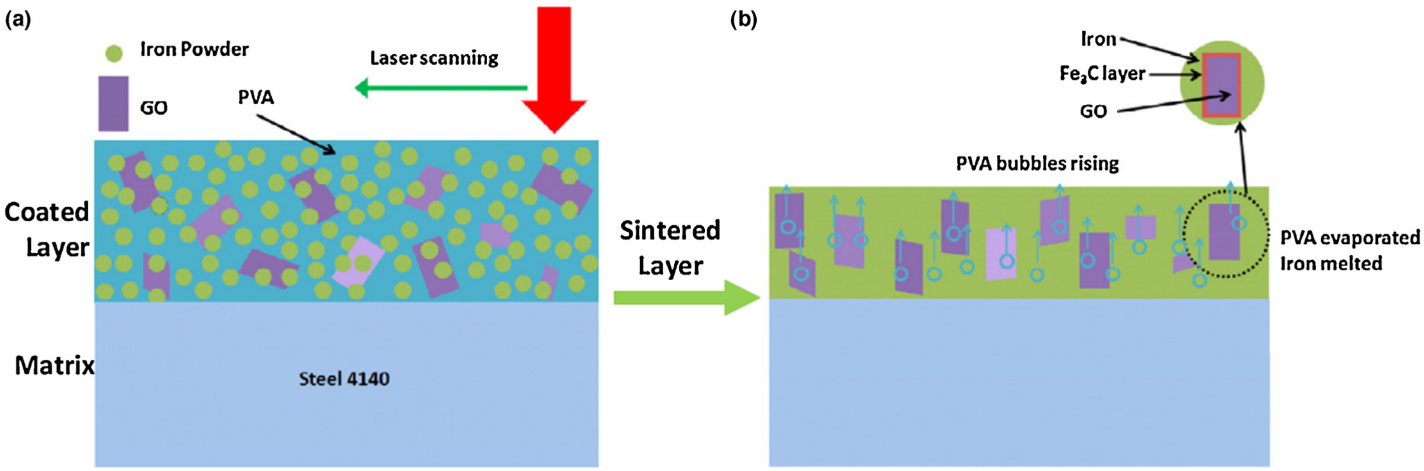


FIGURE 11
Schematic of the laser deposition of GO/iron layer on steel 4140: (a) after coating, and (b) after laser sintering [58].

limited. They mainly include thermoplastics (such as acrylonitrile-butadiene-styrene, polyamide, polycarbonate, polyphenylsulfone), metals (such as aluminum [66], bronze [67], titanium [68], iron [69]), and ceramics (such as $Al_2O_3/ZrO_2$ [70]). Thermoset polymers, commonly used in load-bearing composites, have not yet been widely and commercially adopted for additive manufacturing.

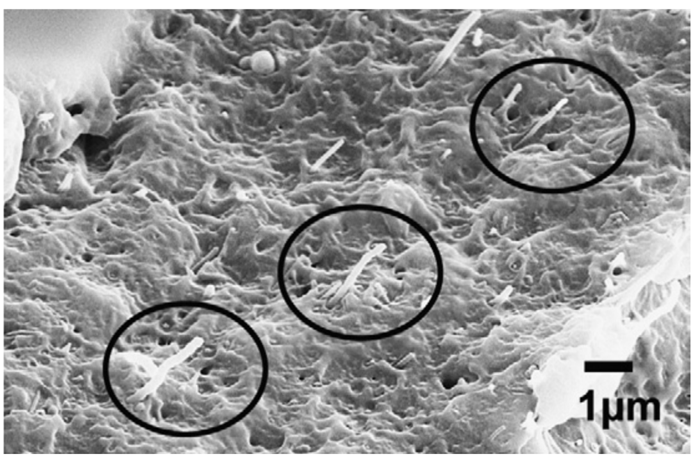


FIGURE 12
SEM image of CNF-mixed polyamide-12 matrix. CNFs are shown as the fibrous bright objects in the circles [59].

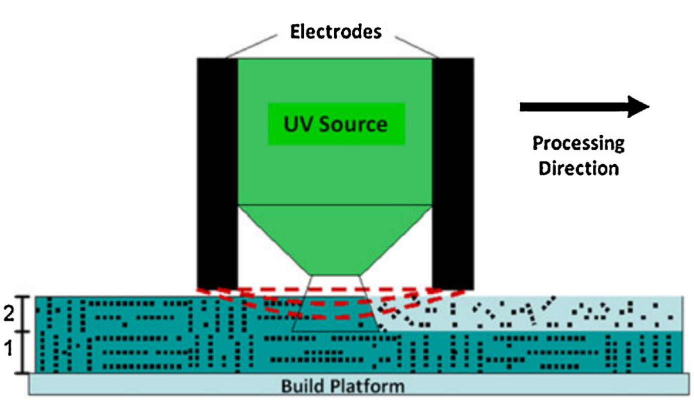


FIGURE 13
Schematic of electric field aided additive manufacturing of aligned-particle reinforced composites [60]. The chains of particles were oriented by the electric field created by the electrodes. UV light was used to cure the resin immediately after particles being oriented.

(2) Although additive manufacturing is well suited for fabricating objects of complex and intricate architecture, the availability of printing resolution (e.g. nozzle size for the material extrusion based processes) imposes a limitation on the printing accuracy, layer thickness, and surface smoothness. Furthermore, most additive manufacturing facilities have a closed fabrication platform which limits the size of objects to be printed. So far, the reliable minimum wall thickness of additively manufactured structures is limited to the millimeter scale and minimum layer thickness to the sub-millimeter scale.

(3) To expand the design space for additive manufacturing, a more suitable and powerful design tool may be necessary. So far, most of the computer-aided design (CAD) software implemented in additive manufacturing processes was originally developed to support conventional fabrication methods, where one model is generally obtained by adding/subtracting/combing regular objects such as cubes, cylinders, spheres, and simple cones and pyramids. When building anfractuous and porous architectures such as textile assemblies, which generally consist of several groups of intertwining yarns, and cellular architectures, the existing CAD tools may be inadequate [34].

(4) The rapid adoption of additive manufacturing may be limited by the lack of engineering standards [47,71]. So far, several basic standards for additive manufacturing, such as ASTM F2792, ISO 17296, ISO/ASTM 52915-13, and ISO/ASTM 52921-13, are available. However, future developments, for instance, in standards for design, material selection, processing and test methods are imperative for advancing additive manufacturing from prototype development to industrial application [72].

(5) Also, the lack of reliable *in situ* monitoring [73] and feedback loop for control of the fabrication process [74,75] and product quality [76] hinder the development and application of additive manufacturing technology [77]. Due to the direct fabrication nature of additive manufacturing, close *in situ*

monitoring and controlling of starting materials (such as powder size, powder shape, and size distribution), processing parameters (such as deposition temperature, constituent location, and melt-pool size), and product qualities (such as part dimension, detail accuracy, porosity, and inter-layer bonding strength) are necessary. Additive manufacturing will facilitate further structural complexity (multi-material, functionally graded) driving developments in non-destructive evaluation methods as well.

(6) For additive manufacturing of reinforced multi-directional preforms in particular, incorporating reinforcing fillers (such as short/continuous fibers, particles, and nanomaterials) presents further challenges to the materials development. For example, considering material extrusion based processes, the introduction of reinforcing fillers raises the chance of nozzle clogging, which limits the filler volume content of the resulting composites. Thus, knowledge of the rheological properties of printing materials and the control of volume content and size distribution of voids are essential.

(7) In traditional multi-directional continuous fiber preforms, the local orientation of a fiber varies throughout the preform structure, which is responsible for the outstanding out-of-plane properties. However, as reviewed above, in existing additive manufacturing approaches to reinforced composites, fillers are mainly orientated in the plane of the layer-by-layer printing. Extending the existing additive manufacturing approaches to spatially oriented fibrous/high-aspect-ratio fillers or even continuous fibers will be a major challenge. The layerless additive manufacturing process [78,79] and multi-axial, omnidirectional additive manufacturing methods may be desirable solutions to these issues.

(8) In addition to the out-of-plane orientations of fillers and fibers, the simultaneous and synchronized printing of the matrix material for composites is highly desirable, as this would eliminate the resin infiltration step which introduces further process complexity. This one-step approach requires the implementation of multi-print-head processes.

(9) Another exciting challenge lies in the scale-up of composites additive manufacturing, which presents the opportunity to extend this family of processes to major industries, such as automobile, infrastructure, aerospace and aeronautics. While several promising results have been reported [80–82], a major barrier lies in the competition between high structural resolution and fast printing speed for cost-effective fabrication. A possible solution may come from layerless additive manufacturing technologies [78,79].

## Summary

Additive manufacturing provides unique opportunities for the manufacture of multi-directional preforms which have so far been produced only by traditional textile forming techniques. In order to facilitate the implementation of additive manufacturing, key factors in the model design of multi-directional preforms have been identified and the successful design and printing of several major multi-directional preforms has been demonstrated. These additive manufactured preform architectures show a high degree of fidelity from model to object, which is generally lacking in the conventional manufacturing techniques. Also, we have reviewed the possible approaches for additive manufacturing of fiber-reinforced preforms, which are desirable, especially for composite parts relevant to aerospace and biomedical components, for which high-performance and small lot-size may be required. Finally, we have discussed the challenges facing the broad adoption of additive manufacturing and its application for the fabrication of fiber-reinforced preforms, in particular.

## Conflict of interest

The authors declare no actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations.

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