Composite Structures 182 (2017) 36–53

Contents lists available at ScienceDirect

Composite Structures

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

Review

A review on additive manufacturing of polymer-fiber composites

Pedram Parandoush, Dong Lin *

Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

ARTICLE INFO

Article history:
Received 7 January 2017
Revised 25 July 2017
Accepted 29 August 2017
Available online 1 September 2017

Keywords:
Additive manufacturing
Fiber reinforce polymer composite
4D printing
Mechanical properties

ABSTRACT

Additive manufacturing (AM) of polymer-fiber composites has transformed AM into a robust manufacturing paradigm and enabled producing highly customized parts with significantly improved mechanical properties, compared to un-reinforced polymers. Almost all commercially available AM methods could benefit from various fiber reinforcement techniques. Recent developments in 3D printing methods of fiber reinforced polymers, namely, fused deposition modeling (FDM), laminated object manufacturing (LOM), stereolithography (SL), extrusion, and selective laser sintering (SLS) are reviewed in this study to understand the trends and future directions in the respective areas. In addition to extra strength, fibers have also been used in 4D printing to control and manipulate the change of shape or swelling after 3D printing, right out of the printing bed. Although AM of fiber/polymer composites are increasingly developing and under intense attention, there are some issues needed to be addressed including void formation, poor adhesion of fibers and matrix, blockage due to filler inclusion, increased curing time, modelling, simulation, etc. Nonetheless, numerous innovative techniques were spotted amongst recent work trying to overcome these challenges with new material or manufacturing techniques.

Contents

1. Introduction

Additive manufacturing (AM), also known as 3D printing, is defined as a process of adding materials to fabricate objects from three-dimensional (3D) models (CAD models) in successive layers, versus traditional subtractive manufacturing methods. Numerous novel AM processes have been developed over the span of more than 20 years of AM development with applications in aerospace,

* Corresponding author at: Department of Industrial and Manufacturing Systems Engineering, Kansas State University, 2080 Rathbone Hall, 1701D Platt St. Manhattan, KS 66506, USA.

E-mail address: dongl@ksu.edu (D. Lin).

http://dx.doi.org/10.1016/j.compstruct.2017.08.088
0263-8223/

automotive, biomedical, digital art, architectural design, etc [1]. There has been an exponential increase in AM technology in recent years and it continues to grow due to its versatility and low cost for rapid prototyping and manufacturing applications. All of these features, combined with AM's customizability to fabricate complex monolithic structures and geometries, with micrometer resolution, helped AM grow to a multibillion-dollar industry [2,3].

To date, the dominant part of the 3D printing industry has immensely relied on single material printing. This issue, paired with limited choices of available resins compatible with commercial printers, has severely limited variations in the physical and chemical properties of 3D printed objects. These limitations have led to development of multi-material printers with partial control on material composition and properties, offering layered composite materials. Furthermore, multiple printing heads have allowed printing blended composites with functional and variable features. 3D printing of fiber reinforced composites is currently conducted by stereolithography (SL), laminated object manufacturing (LOM), fused deposition modeling (FDM), selective laser sintering (SLS), and extrusion. This is one of the hottest topics in the field of additive manufacturing and is under intense attention. This also offers significant improvement in mechanical properties, however, it requires a complex procedure to be manufactured and is difficult to be incorporated into processing. Implementing the traditional methods of composite manufacturing in AM is not practical and new technologies are needed to assist with the development of new AM methods [4].

Advances in development of composite 3D printers have not prevented development in pre-blended materials with fillers such as nanoparticles, carbon nanotubes, fibers and graphene in order to achieve unique characteristics and capabilities [5]. Fiber reinforcement, in particular, appears to be an attractive filler to improve the properties of polymers. Pre-blended materials using discontinuous fibers as an additive have been under intense investigation as a suitable alternative to multi-head printers with complex and costly designs. These additive based materials exhibit unique characteristics and capabilities, depending on the additive used. Suitable mechanical, electrical, or thermal properties can be accomplished in an inexpensive manner.

Polymers, in particular, have been the center of attention due to ease of production and availability. The 3D printing industry primarily involves polymers in various forms, such as reactive, liquid solutions, and thermoplastic melts [6,7]. These benefits, joined by enhancements from fiber reinforcement, offer a favorable combination for future development of AM technology. In addition, almost all of the existing AM methods can be benefited from fiber reinforcement.

Although fiber reinforcement in 3D printing sounds promising, there are numerous issues which need to be resolved. Namely, the effect of fibers on resolution, agglomerate formation, heterogeneous composite formation, blockage of printer heads, non-adhesion, and increased curing times [5]. This paper reviews recent advances in AM of polymer based fiber reinforced composites and potential methods for modelling and analysis of these 3D printed structures. Latest development and improvement to existing methods will be reviewed in detail, in order to understand the challenges in 3D printing of polymer composites with fiber reinforcement.

2. 3D printing of fiber reinforced polymer composites

Fiber reinforcement can greatly improve the properties of 3D printed parts with polymer matrix. Fiber orientation and void content of composites are the main concerns in 3D printing of these composites. Most of the commercially available 3D printing techniques would benefit from fiber reinforcement. In this section, all of these techniques for 3D printing of polymer-fiber composites are reviewed in detail to demonstrate their strengths and weaknesses in additive manufacturing of polymer-fiber composites. These methods are FDM, LOM, SL, extrusion, and SLS.

2.1. Fused deposition modeling (FDM)

FDM is currently the most applied AM technology, according to Wohler's Report from Stratasys, Inc. Commercial FDM machines held 41.5% of the market share, with the total of 15,000 FDM machines sold by the end of 2010. The key elements of the FDM system include material feed mechanism, liquefier, print head, gantry, and build surface [8]. Several process parameters are essential in FDM, including bead width, air gap, model build temperature, and raster orientation. The effects of raster orientation on tensile and compression test results have been investigated in detail [9]. The temperature distribution during the FDM process can be monitored by IR camera [10]. The surface roughness and cross section shape of the FDM fabricated parts are under intense study. Figs. 1 and 2 illustrate the bonding mechanism in the FDM of polymer composites along cross-section of printed parts [11,12]. Several building rules have been proposed to improve the strength and accuracy of the FDM printed parts, such as build parts to ensure tensile loads are carried axially along printed directions, deal with the stress concentration at corners, use negative air gap to increase both strength and stiffness, consider that small bead width leads to extra printing time and better surface quality, be aware the part accuracy affected by the build orientation, and

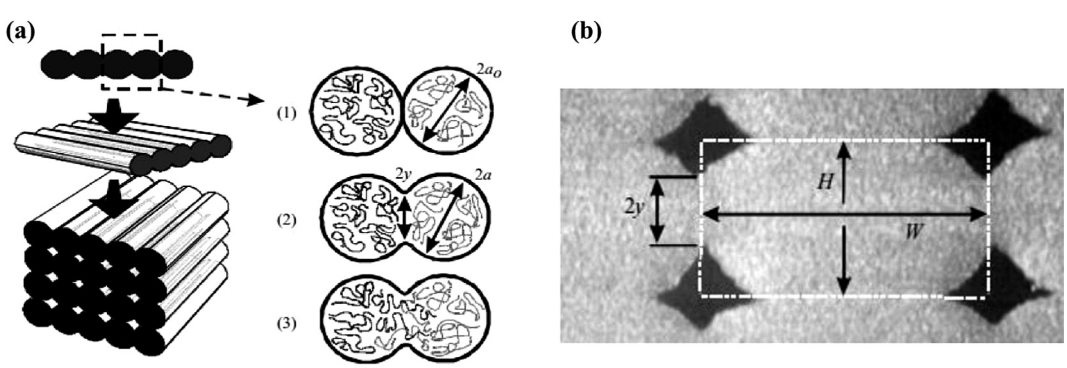

Fig. 1. (a) Bond formation process between two filaments: (1) surface contacting; (2) neck growth; (3) molecular diffusion at interface and randomization, (b) microphotograph of the cross-sectional area of a FDM part: W is the filament's width, H is the filament height; 2 y is the neck length between adjacent filaments (Reprinted with permission from [11]).