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Laser assisted additive manufacturing of continuous fiber reinforced thermoplastic composites

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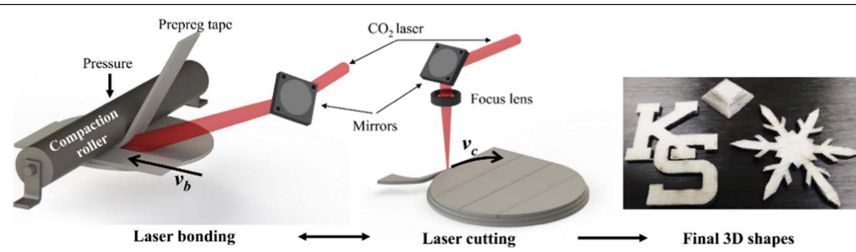
ABSTRACT

Herein, we proposed a novel laser assisted additive manufacturing (AM) methodology that utilizes prepreg composites (glass fiber-polypropylene) with continuous fiber reinforcement to fabricate 3D objects by implementing laser assisted bonding and laser cutting. The microstructure analysis demonstrated no visible void content and excellent interfacial bonding. The bonding strength of the proposed method was evaluated through lap shear strength and peel strength testing; resulting in 50% higher peel strength than hot compaction method, with lap shear strength up to 96% of compression molding benchmark data. Tensile properties of components printed by our method were superior to those of fused deposition modeling (FDM) printed short fiber composites with 300% and 150% of increase in tensile strength and modulus, respectively. Tensile strength of our printed components was comparable to compression molding and stamping, however, tensile modulus was 50% lower in average. Flexural strength of the laser assisted AM parts was also in the range of stamping and compression molding methods, with flexural modulus up to 100% higher than these methods. Overall, our proposed new technique offers an alternative direction in AM of continuous fiber reinforced thermoplastic polymer composites to solve the issues associated with current techniques.

GRAPHICAL ABSTRACT



1. Introduction

Continuous fiber reinforced thermoplastic polymer composites (CFRTPCs) exhibit superior properties, including mechanical performance, versatility, recyclability, and the potential for light-weight structures, that enable CFRTPCs as a substitute material for steel and conventional thermoset polymers in automotive, transportation, aerospace, and marine applications [1,2]. Continuous glass fiber (GF) and low glass transition temperature matrix systems such as polypropylene (PP) in combination provide ease of processing, lower associated manufacturing costs, high volume processing potential, and performance suited for high end uses. Additionally, these composites exhibit enhanced toughness, chemical-environmental resistance, damage tolerance, and an unlimited shelf life at relatively low cost. A large range of GF/PP composites is commercially available possessing these features [1,3]. High performance levels can be achieved with high fiber concentration and continuous fiber reinforcement; however, these attributes increase the processing complexity [4]. To date, numerous

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manufacturing methods for CFRTPCs have been developed, such as compression molding, stamping, vacuum forming, filament winding, pultrusion, and bladder-assisted molding. These manufacturing methods are often associated with expensive molds, and inability to produce complex construction with customized fibers alignment [5]. As a result, alternative manufacturing techniques for CFRTPCs are under great demand in order to bypass the long, expensive processing procedures, and add more complexity to manufactured structures.

Additive manufacturing (AM) or three-dimensional (3D) printing attracted popularity due to high customization and development of application-oriented parts [6]. AM is a promising technology that has not reached its full potential, particularly in the field of composites. Various researchers worked on applying AM to fiber reinforced thermoplastics in order to benefit from the vast flexibility in 3D composite manufacturing [7]. Most of the work done in this field have focused on fused deposition modeling (FDM), selective laser sintering (SLS), and stereolithography (SL) with short fiber reinforcement. Zhong, et al. [8] included short GFs in the filament for improved strength, however, extrusion force and potential tool wear were spotted during the process. Inclusion of short iron and copper fibers in acrylonitrile butadiene styrene (ABS) filament resulted in higher stiffness compared to printed pure ABS [9]. Shofner, et al. [10] compounded carbon nanotube and vapor grown carbon fiber with ABS in FDM 3D printing for improved mechanical properties. Tekinalp, et al. [11] developed a method to control the orientation of short carbon fibers in the matrix; reportedly, tensile strength and modulus of 3D printed samples exhibited 115% and 700% increase compared to pure thermoplastic matrix, respectively. However, FDM samples printed with this method showed significant pore formation between deposited filaments during 3D printing. Ning, et al. [12] reported that inclusion of 5 wt% carbon fiber content in ABS filament increased flexural strength, flexural modulus, and flexural toughness by 11.82%, 16.82%, and 21.86%, respectively. Short carbon fiber/ABS was also used for FDM 3D printing of 3D orthogonal preforms. Poor carbon fiber-ABS interfacial bonding and the high content of fibers under 100 μm in length (~50 wt%) were spotted indicating low reinforcing efficiency of short carbon fibers. The authors named continuous fiber reinforcement a highly desirable solution [13]. Carneiro, et al. [14] reinforced polypropylene with short GF for FDM and achieved 30% and 40% improvement for the modulus and strength, respectively. Compton and Lewis [15] employed a new epoxy-based ink for 3D inkjet printing of cellular composites with controlled alignment of multi-scale and high aspect ratio fiber reinforcement. These structures exhibited Young's modulus an order of magnitude higher than thermoplastics and photocurable resins utilized in commercial 3D printers. The SLS process has also been modified for fiber composites, with carbon fiber filled polyamide composite powder being commercially available for SLS. However mechanical mixing is not able to provide a uniform distribution of carbon fiber in the composite powder which can result in carbon fiber aggregates. Although efforts have been made to coat the fibers with nylon-12 through the dissolution–precipitation process to form suitable CF/PA composite powders, SLS is not capable of continuous or long fiber reinforcement [16–18]. Similarly, the SL process is able to fabricate 3D parts with short fiber reinforcement. Carbon fiber and glass fiber have been successfully applied to SL, however, carbon fiber can block the UV light and interferes with the curing process which can be resolved by thermal treatment [19]. Various fiber orientation and uniform fiber distribution were achieved by ultrasonic manipulation of the composite resin used in SL process [20].

The aforementioned methods for AM of short fiber composites reported improved strength relative to the thermoplastic matrix; however continuous fiber (CF) reinforcement has extra potential to be used in functional parts with more substantial effect on the mechanical properties. Maximum achievable stiffness and strength can only be obtained using CF, since most of the load in these composites is carried by the fibers oriented along the load direction [21]. Laminated object manufacturing (LOM) was one of the first developed AM methods capable of CF reinforcement. 3D parts in LOM are manufactured by cutting 2D cross-sections with a laser and sequentially laminating the sheets into 3D structures. Prepreg CF/epoxy composite sheets have been successfully utilized in LOM, however, additional heat treatment was required to fully cure the resin and consolidate the prepreg layers [22,23]. Furthermore, LOM is often associated with large amount of waste material and postproduction time is necessary to eliminate waste; in some cases secondary processes are required to produce accurately functional parts [24]. Lately, efforts have been made to modify FDM for CF polymers composites. Mori, et al. [25] proposed a FDM method in which continuous carbon fibers were sandwiched between lower and upper plastic plates, followed by heating of the plates for better bonding between layers. Although relatively higher strength was achieved, the usage of carbon fiber was limited in this method and porosity of composite structures had negative effects on the strength of the components. Lately, a new FDM method has been developed for continuous carbon fiber/polyactic acid (PLA). PLA and carbon fiber were supplied separately before heating and mixing inside the printing head [26–28]. However, this method, similar to other FDM techniques, suffers from bonding issues and void formation between printing beads.

On the other hand, there are other composite manufacturing methods with high potential to be customized for AM. Laser assisted tape placement (LATP) is one of the most promising techniques due to its flexibility and capability to achieve continuous fiber reinforcement. A significant advantage of this method is the ability to manufacture parts of essentially unlimited size in a rapid manner, potentially saving large capital and running costs associated with large autoclaves. In LATP the high temperature induced by the laser at the nip point combined with high compaction forces of the consolidation roller decrease the viscosity of the polymeric matrix, while the applied roller pressure promotes inter-ply bonding [29]. Recently, laser gained interest over alternative heat sources such as hot gas due to energy efficiency and precise control [30]. 94% of autoclave properties could be achieved for carbon fiber–polyether ether ketone (PEEK) using a diode laser processing head [31]. LAPT is associated with high cooling rates; high toughness was observed in LAPT parts with Polyphenylene sulfide (PPS) and PEEK matrix due to largely amorphous morphology [32–35]. Rosselli, et al. [36] studied the effect of process parameters on strength of thermoplastic composite rings manufactured by laser assisted on line consolidation. Comer, Ray, Obande, Jones, Lyons, Rosca, O'Higgins and McCarthy [29] investigated LATP in comparison with traditional autoclave methods for carbon fiber/PEEK manufacturing. LATP performed better in terms of interlaminar toughness, however flexural strength, interlaminar shear strength, flexural stiffness, and open-hole-compression strength were subpar to autoclave.

As discussed in the aforementioned literature review, there are various issues with the existing methods used for additive manufacturing of fiber reinforced thermoplastics, specially for continuous fiber reinforcement. The LATP process is able to manufacture 3D composite structures with minimum void concentration and continuous fiber reinforcement. Our proposed method implements a similar technique for adding prepreg composite tapes in successive layers and cutting each successive layer according to the CAD file. Prepreg tape is placed in parallel using LATP to cover each layer prior to laser cutting of the 2D shape associated with each layer with no post processing being required after the AM process. This method demonstrates the potential to solve the issue with interfacial bonding associated with FDM, while offering continuous fiber as reinforcement. In addition, when compared with LOM, our proposed method significantly reduces waste material because of the use of prepreg narrow tape instead of prepreg sheets; also, postprocessing is not necessary due to full consolation of prepreg tape. In the present work, interfacial microstructure and mechanical performance of the parts prepared with glass fiber/polypropylene (PP) prepreg by our newly proposed method were studied in assessment with other AM and traditional methods for fiber