Composite Structures 185 (2018) 537–548

Contents lists available at ScienceDirect

Composite Structures

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

Characterization of 3D printed long fibre reinforced composites

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ARTICLE INFO

Keywords:
ALM
FDM
Long fibre composites
Mechanical characterization

ABSTRACT

Additive Layer Manufacturing (ALM) process is used in the present investigation to manufacture long fibre reinforced composite parts using the MarkOne® 3D-printer. In ALM, a continuous filament (including a tow of fibres) of composite material is injected by the printer, at high temperature, over a plain tool, forming the part while the material is cooled down. The used composite filament is formed by a PA (Nylon™) matrix and carbon or glass fibre reinforcements. Previous works have shown an improvement on the mechanical properties of a part, when some zones include a nylon based composite reinforcement using ALM. Nevertheless, the characterization of fully made nylon-based ALM composite material parts has not been reported. Thus, the aim of this investigation is the experimental characterization of composite nylon-based coupons. The plane strength and stiffness properties of the composites are obtained, both for tensile and compression load states. Results showed that the obtained mechanical properties for ALM composites are not yet comparable to those obtained by traditional methods (pre-pregs). This fact may be explained by the high porosity found in ALM coupons as well as a low fibre volume obtained. Nevertheless, the mechanical properties improvement in comparison to non-reinforced nylon parts is remarkable.

1. Introduction

The large number of complex processes involved in the manufacturing of composite materials regarding the traditional manufacturing techniques entail long production times and elevated costs. Furthermore, these techniques, due to the kind of raw materials used, imply the generation of scraps. New processes are explored to circumvent these problems. The very best way to do, it is to implement and automate all the steps in a single process. One alternative is the use of Additive Layer Manufacturing (ALM), usually named 3D printing, in which the material is laid up, compacted and cured at the same time. On the way the material is laid-up, it is cooled and solidified, achieving 3D geometries without using complex moulds. ALM technologies are experiencing an important rise in the production of aeronautical parts. In the past, its use has been dedicated to very low structural responsibility parts. In the last decade, there has been an increasing interest in introducing these technologies in the manufacturing of structural parts [1,2]. In fact, the use of ALM technologies in nanostructures was also studied, see [3]. Some of the advantages of ALM technologies compared to the traditional manufacturing procedures are: (i) the manufacturing of the parts does not require the use of moulds; (ii) there are almost no scraps after manufacturing; (iii) the manufactured parts require less post treatments (or even nothing); (iv) after the design of the part, all the process is automated, avoiding human mistakes.

Two kinds of materials are mostly used in ALM processes: metallics and plastics. The metallic materials offer high mechanical properties, capable to compete with metallic parts manufactured by casting or machining [4]. In the case of the plastic parts, its properties are very poor and they are not capable to directly substitute other materials for structural parts. In order to improve the properties of these parts, the introduction of fibre reinforcements was studied by several authors.

A review on different ALM techniques, applications and actual needs can be found in [5–8], while different techniques, specifically for fibre reinforced plastics, are summarized in [2,9–12]. The evolution on composites may start with one of the first attempts to improve the mechanical properties of 3D printed polymers (including continuous glass fibres and a photopolymer) presented in [13]. The technique used was 3-D photolithography, able to include around a 6% of fibre volume. Later on, using the same technique, carbon fibres were included and also the fibre volume was increased to approximately 30% in [14]. The effect of a dual (photo and thermal) curing for carbon reinforced photo polymer is studied in [15]. Glass (short) fibres were also used to reinforce a photopolymer in [16,17]. Moreover, a comprehensive study on the obtained mechanical properties using this kind of reinforcement can be found in [18,19].

Another ALM technique used to manufacture polymer composites is the so-called Laminated Object Manufacturing (LOM). In [20], LOM is used with glass fibre/epoxy matrix pre-pregs, a study on the different

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https://doi.org/10.1016/j.compstruct.2017.11.052
Received 11 July 2017; Received in revised form 16 October 2017; Accepted 20 November 2017
Available online 21 November 2017

interfaces appearing in the composite being also included in that investigation.

Nowadays, the Fused Deposition Modelling (FDM) is the ALM plastic technology considered adequate to combine the fibre reinforcements and a polymeric matrix. In the FDM technology, a thermoplastic filament is extruded through an injector, heated to the fusion temperature of the plastic, and placed over a plain mould. As the material is cooled down once placed, it turns into a solid and reaches its final shape. The final 3D geometries are manufactured from 2D layers [21].

For the FDM case, several possibilities for introducing the filament into the plastic have been considered [22,23]:

(i) Embbeding the fibre directly in the component: In this case, two injectors are needed, one for the resin and another for the fibre. The fibre and the matrix are mixed at the part, once injected.
(ii) Embedding the fibre in the injector: In this case, the fibre and the resin are mixed in the injector, just before the injection process.
(iii) Embedding the fibre previously to the injection: In this case, a preimpregnated filament containing both the fibre and the resin is used. It is interesting to notice that this kind of filament can be used in a traditional FDM machine, just with a modification of the injectors.

It is noticeable that FDM on composites has several common characteristics to well-established procedures as automated fibre placement [24] and filament winding. The latter has been used with carbon, glass and Kevlar fibres pre-impregnated with thermoplastic resins such as PEEK and polypropylene [25–27]. The main difference between those procedures and FDM, is that FDM does not need the use of a mould which follows the final shape of the part, as support columns (if needed) can be printed together with the desired part.

In [28], carbon fibre is included in ABS using a FDM technique, while PLA is used in [29,30]. Mechanical tests were performed to characterize the obtained composites. Finally, the effect of including glass fibres on some zones of nylon (NYL-AB-1K supplied by Mark-Forged®, Somerville, MA) coupons is studied in [31].

In the present investigation, fully reinforced coupons made of glass and carbon fibre filaments (supplied by MarkForged®, Somerville, MA), manufactured using FDM, will be characterized. The filaments include a tow of fibres which are embedded (previously to the injection) in nylon. First, some details of the 3D commercial printer MarkOne® [32] and the mechanical tests carried out are presented. Then, the results of the characterization tests are discussed.

2. Printer description

A MarkOne® 3D printer, manufactured by Markforged [32] has been the ALM/FDM system used in the present investigation. A picture of the printer can be seen in Fig. 1(a). The system can print two kind of materials independently and, for this reason, it has two extruders and two injectors, see Fig. 1(b). One of the injectors is used to print nylon (as the traditional 3D plastic printers can do) and the other one is used to print fibre reinforced thermoplastics. The nylon injector can be also used, in addition to print parts, to print supports when needed. The supports are material plies used to hold the printing in zones of the parts that have a cantilever configuration. Once the part is manufactured, the supports are discarded.

MarkOne® was considered as the first printer able to print composite parts. It was released by the end of 2014. Later, on February 2016 MarkTwo® printer was released and MarkOne® was discontinued. Nevertheless, both printers share similar technical characteristics. It should also be mentioned that updates are available for every printer model. MarkOne® uses its own software called Eigen®. 3rd party software cannot be used with the printer but the software allows to import .STL and .OBJ models. The orientation of the fibres can be controlled through the software. It allows to specify the fibre orientation on a layer-by-layer basis. The build size allows to print parts with the maximum following dimensions 320 mm × 132 mm × 160 mm.

MarkOne® printer is able to manufacture carbon, glass and arimidic (Kevlar™) fibre reinforced nylon parts. The used filaments are supplied by Markforged. These filaments consist on a mixture of a bundle of long fibres and resin, forming a preimpregnated-like material. A view of the glass fibre/nylon and carbon fibre/nylon filaments is shown in Fig. 2. The same filaments, after a calcination (where the resin has been removed), are also shown in the figure. Notice that the bundle of fibres can be clearly observed once the calcination is done. The aim of the calcination was to check the amount of fibres and resin present in the filament. Results showed an approximated 40% fibre weight for the carbon fibre filament and almost a 50% for the glass fibre case. Fibre volume fractions will be presented once the micrographs of the printed material are studied in the Discussion Section. In the following, the way the printer works with the fibre reinforced filament is described:

- The injector is heated up to the fusion temperature of the matrix.
- The fibre reinforcement filament is pushed through the injector.
- The resin is fused and the composite is placed over the printing bed, following a programmed pattern.
- The resin is cooled down just after having been laid up, obtaining the composite's final shape.
- Once the whole layer has been laid-up, the printing bed is moved down, allowing a new layer to be printed.

When printing nylon or glass fibre reinforced nylon, the geometry can be obtained following several printing patterns (rectangular and circular) making it possible to give orientations to the fibre in each layer (using the rectangular pattern). In the case of the carbon fibre reinforced nylon, due to the stiffness of the fibre, to print following a circular pattern is only allowed.

Notice that the printing system only allows the reinforcement to be

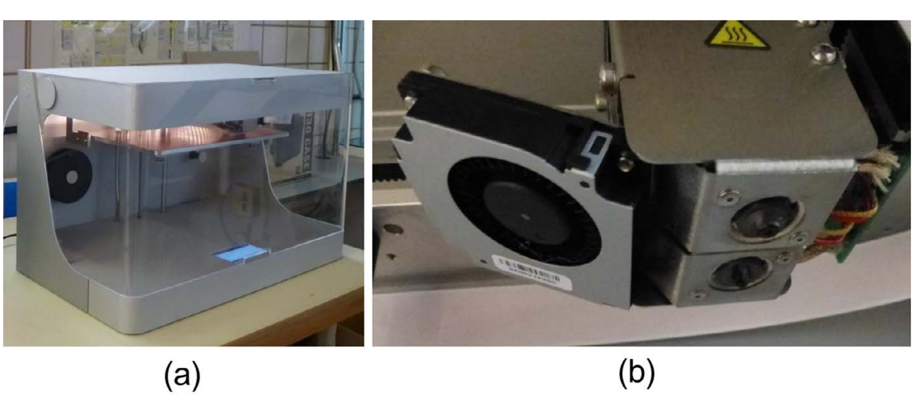

Fig. 1. (a) General view of the 3D printer. (b) Detail view of the two printer injectors.