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Full Length Article

Evaluation of compressive and flexural properties of continuous fiber fabrication additive manufacturing technology

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ABSTRACT

This study focuses on the characterization of additive manufacturing technology based on composite filament fabrication (CFF). CFF utilizes a similar method of layer by layer printing as fused filament fabrication but is also capable of reinforcing parts with layers of various continuous fibers into a polymer matrix. Due to the orthotropic characteristics of additive manufacturing based on fused filament fabrication, 3D printed parts may present different mechanical behavior under different orientations of stress. Furthermore, technologies such as CFF allow a range of configurations to fabricate and reinforce the parts. In this study, mechanical characterization of polyamide 6 (PA6) reinforced with carbon fiber was conducted by design of experiment as a statistical method, to investigate the effect of reinforcement pattern, reinforcement distribution, print orientation and percentage of fiber on compressive and flexural mechanical properties. CFF technology 3D print stronger parts than conventional additive manufacturing technologies. Maximized compressive response was achieved with a 0.2444 Carbon Fiber volume ratio, concentric and equidistant reinforcement configuration, resulting in a compressive modulus of 2.102 GPa and a stress at proportional limit of 53.3 MPa. Maximized flexural response was achieved with 0.4893 Carbon Fiber volume ratio, concentric reinforcement and perpendicular to the applied force, resulting in a flexural modulus of 14.17 GPa and a proportional limit of 231.1 MPa.

1. Introduction

Additive Manufacturing (AM) technologies have become a new paradigm in design due to product geometric, fabrication and customization possibilities. ASTM classifies AM processes into different categories: binder jetting, material jetting, direct energy deposition, sheet laminations, material extrusion, powder bed fusion, and vat photopolymerization [1–3]. Each category contains different technologies and use of materials. Those technologies have been evolving rapidly, changing the application possibilities and capabilities in terms of time, quality, design and performance. Material extrusion process category includes Fused Filament Fabrication (FFF) technology and the use of different polymers, being one of the most used and proliferated technologies, due to its low cost and ease of use; FFF form 3D geometries depositing layer by layer extruded thermoplastic filament, utilized for rapidly produced prototypes and functional components [4]. However, due to the nature of layer by layer deposition, FFF parts can present mechanical disadvantages such lower elastic properties than injection molded components and possible delamination effects, resulting in premature failure [4,5]. These disadvantages limit FFF parts applications and leave prototyping as the main one [6].

An important factor that allows new design and innovative approaches for AM applications is the advance in materials [3]. Recent studies focuses on the improvement of mechanical properties in FFF parts by defining optimal printing parameters configuration [7–9], modifying fabrication parameters - treatments [10] and reinforcing parts using composite materials [5,11–17]. Addition of fibers to polymers in additive manufacturing technologies has been studied and concluded that increase the mechanical properties of 3D printed parts [5,14,15], sometimes even surpassing aluminum alloys [6,11]. Also anisotropic and orthotropic characteristics of layer by layer AM technologies have been well studied [5,7,18] determining that there are significative effects of printing part orientation in the mechanical response.

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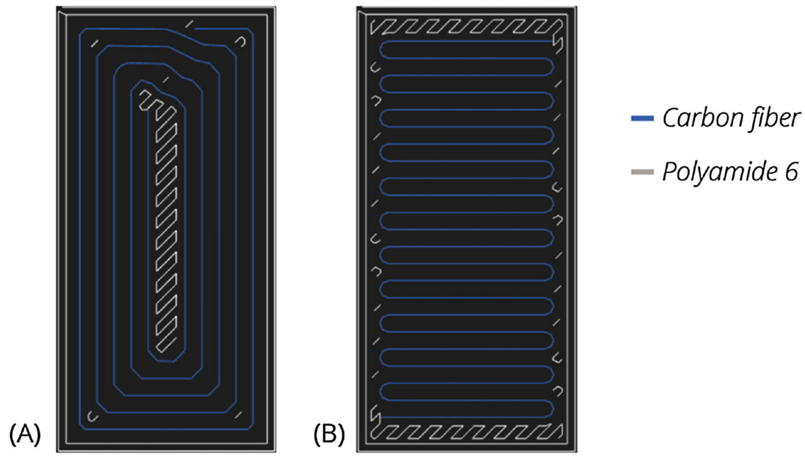

Fig. 1. Fiber reinforcement types, concentric (A) and isotropic −0° layer (B).

An example of improvement in mechanical properties of FFF parts is Continuous Filament Fabrication (CFF) technology, developed by the company Markforged. CFF produces functional FFF 3D printed parts reinforced by continuous fiber (carbon fiber, fiberglass and Kevlar) embedded into a polymeric matrix of PA6 or a mixed PA6 with micro shopped carbon fiber, commercially known as Onyx, resulting in high strength 3D printed parts. This research is focused only in carbon fiber reinforcement properties on a matrix of PA6. Some authors have evaluated the tensile [4,6] and flexural [6] properties of 3D printed parts with CFF technology. These studies are focused and limited in some parameters of the technology such as material and fiber-laydown pattern. However, there are more parameters to be tested and reported to extend this technology characterization and design input parameters for functional parts.

In this study mechanical characterization of CFF technology was conducted by design of experiment (DoE) as a statistical method, to investigate the effect of fiber pattern, reinforcement distribution and print orientation on compressive and flexural mechanical properties of polyamide 6 (PA6) reinforced with continuous carbon fiber (CF). Then the effect of fiber percentage was studied implementing ideal parameters combinations from the DOE.

2. Materials and methods

2.1. Statistical methodology

To evaluate the main factors that may present an influence in CFF technology mechanical properties, Design of Experiments (DOE) was implemented as statistical method for both compressive and flexural testing, these tests were named Test A. The factors analyzed for compressive test were reinforcement pattern and reinforcement distribution in a full factorial design 2^2 with 4 base runs and 2 replicates – 8 total runs, as shown schematically in Fig. 3. The factors analyzed for flexural testing were reinforcement type and printing orientation in a multilevel factorial design with 6 base runs and 2 replicates – 12 total runs, as shown schematically in Fig. 4. For statistical analysis Minitab 17 Statistical software was used.

Then Analysis of Variance (ANOVA) was used as statistical method to analyze the effect of fiber percentage on the mechanical response of the specimens in both compressive and flexural tests, using the optimized combination of factors resulting from Test A. These ANOVA tests were named as Test B.

2.2. Mechanical testing

Specimens for compressive and three-point flexural testing were fabricated using a Mark Two 3D printer (Markforged, Watertown, MA, USA). The specimen's geometry was created according to ASTM D695-15 and ASTM D790-15 for compressive and flexural testing respectively. The test specimen geometry was created using a computer aided design (CAD) software (SolidWorks 2016, Dassault Systems), exported as a stereolithography file (STL) and imported into the slicing software Eiger (Markforged, Watertown, MA, USA) to reinforce and fabricate them. The specimens were fabricated with PA6 matrix and reinforced with continuous carbon fiber filament, both materials supplied by Markforged. The polymer was stored into a moisture-sealed Pelican 1430 modified dry box to avoid moisture absorption [6].

The Mark Two 3D printer fabricates FFF parts reinforced with continuous fiber deposited by a dual extruder nozzle. It is possible to extrude fiber along the printing layer with a plastic matrix. The fiber extruded by the second nozzle has a PA6 thin film layer in order create an interphase between the matrix and fiber layer during printing [19]. The fiber reinforcement fill type is configured in the Eiger software, which can have a concentric or isotropic fiber -laydown pattern. Concentric reinforcement allows a concentric ring pattern of the fiber and deposits a free number of rings limited by the part geometry. Isotropic reinforcement allows a unidirectional pattern that can be rotated each layer. By default, Eiger software embeds the fiber with a 45-degree rotation each layer, but it can be freely defined manually. Both configurations are represented in Fig. 1.

Fiber volume fraction can be modified by the number of fiber layers in the isotropic configuration and by the numbers of rings in the concentric pattern. Like most 3D printing technologies, the fill density can be modified, which affects the density of matrix material. It is possible to create to a completely solid part (100% infill) or a partially filled part with any infill greater than 10% [19]. The fiber volume ratio for each sample was calculated from the fiber and PA6 volumes reported by the Eiger software.

The reinforced specimens were evaluated by performing compressive and flexural tests as it is shown in Fig. 2. A universal machine Tinius Olsen (50 kN load cell) was used to apply and measure the loads into the specimens.

2.2.1. Compressive testing

An initial compressive Test A was made to analyze the 3D printing factors: reinforcement type with 2 levels and reinforcement distribution with 3 levels. The reinforcement types analyzed were isotropic pattern (0°, −45°, 90°, +45°) and concentric pattern. The reinforcement distributions analyzed were in the specimen borders, in the borders and center of the specimen, and equidistant reinforcement as it is shown in Fig. 3 (B), (B + C) and (E) respectively. The specimens were printed with an average 0.1 Carbon Fiber volume ratio. Two specimens (12 mm × 12 mm × 24 mm) of each factor combination were fabricated and tested in accordance with standard ASTM D695. Crosshead