Additive Manufacturing 22 (2018) 883–890

Contents lists available at ScienceDirect

Additive Manufacturing

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

Interlayer fracture toughness of additively manufactured unreinforced and carbon-fiber-reinforced acrylonitrile butadiene styrene

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ARTICLE INFO

Keywords:
Additive manufacturing
Interlayer fracture toughness
Fused filament fabrication
Fused deposition modeling
Acrylonitrile butadiene styrene

ABSTRACT

This study presents development of a test method for characterization of interlayer, mode-I fracture toughness of fused filament fabrication (FFF) materials using a modified double cantilever beam (DCB) test. This test consists of DCB specimen fabricated from using unidirectional FFF layers, an 8 μm Kapton starter crack inserted in the midplane during the printing process, and reinforcing glass/epoxy doublers to prevent DCB arm failure during loading. DCB specimens are manufactured with a commercially available 3D printer using unreinforced Acrylonitrile Butadiene Styrene (ABS) and chopped carbon-fiber-reinforced ABS (CF-ABS) filaments. To examine the effect of the FFF printing process on fracture toughness, additional ABS and CF-ABS specimens are hot-press molded using the filament material, and tested with the single end notch bend (SENB) specimen configuration. The fracture toughness data from DCB and SENB tests reveal that the FFF process significantly lowers the mode-I fracture toughness of ABS and CF-ABS. For both materials, *in situ* thermal imaging and post-mortem fractography shows, respectively, rapid cool-down of the rasters during filament deposition and presence of voids between adjacent raster roads; both of which serve to reduce fracture toughness. For CF-ABS specimens, fracture toughness is further reduced by inclusion of poorly wetted chopped carbon fibers. Although this study did not attempt to optimize the fracture performance of FFF specimens, the results demonstrate that the proposed methodology is suitable for design and optimization of FFF processes for improved interlayer fracture performance.

1. Introduction

Additive manufacturing by fused filament fabrication[1] (FFF) holds promise for on-demand manufacturing of tailored objects for a wide variety of applications, including rapid prototyping, part replacement, and tooling for composite layup, to name a few. Despite the apparent advantage over more traditional manufacturing methods (e.g. manufacturing by subtraction, injection molding), FFF parts often suffer from poor mechanical characteristics, limiting their broader adaptation for end-use, load-bearing components. The poor performance of FFF parts often results from the use of polymeric base materials that are selected based on rheological properties to improve the extrusion process, instead of materials that exhibit exceptional mechanical properties. Additionally, the quality of final fully-formed FFF parts is affected by part intricacy and the corresponding print path, and the differential cool-down and solidification of the individual rasters, among other factors. The complexity of the FFF process results in parts that are often highly anisotropic with properties that are difficult to characterize, let alone predict.

To date, limited research has been conducted to systematically relate properties of FFF base materials, the printing process, the resulting structure, and the mechanical performance. A few studies have found that optimizing parameters like extrusion and print bed temperatures, print speed, layer height, and infill percentage can increase tensile strength and stiffness of FFF parts [1–3]. However, regardless of parameter optimization, FFF parts still exhibit lower properties compared to those obtained by conventional polymer processing methods such as compression or injection molding [1,4–8]. A few recent studies have attempted to increase strength and stiffness of FFF parts by combining polymeric filaments with chopped glass [9] and carbon fibers [10–12], carbon nanotubes [10,13], zinc oxide nanorods [14], and Jute plant fibers [14]. In most cases, the addition of reinforcement resulted in marginal increase in mechanical properties, that are still well below properties of metallic alloys and continuous-fiber reinforced polymers.

In addition to poor mechanical performance, FFF parts exhibit low interlayer and intralayer fracture properties. In the context of this work, interlayer fracture is defined as decohesion of adjacent layers of an FFF part, and is similar to delamination between plies of a tape-laminate

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[1] Fused Filament Fabrication is a material extrusion technology as per ISO/ASTM 52900.

https://doi.org/10.1016/j.addma.2018.02.010
Received 15 November 2017; Received in revised form 7 February 2018; Accepted 21 February 2018
2214-8604/

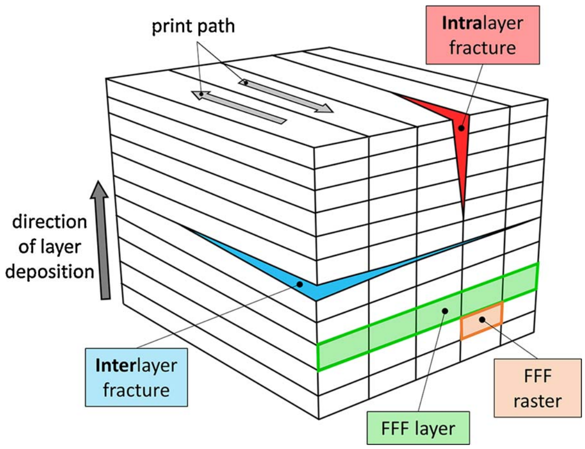

Fig. 1. Definition of interlayer and intralayer fracture in FFF manufactured unidirectional components.

composite. Intralayer fracture is defined as decohesion between adjacent raster roads, and is analogous to intralaminar ply cracking. The difference between the two fracture types in unidirectional FFF components is shown in Fig. 1. To date, characterization of fracture properties of FFF components has been attempted indirectly using tensile testing [9,15]. A recent study utilized several double cantilever beam (DCB) and T-peel test configurations to measure adhesion between two Polyjetted photopolymer layers [16]. Currently, there are no viable fracture toughness tests that can be applied to a broad range of FFF materials.

In light of the above discussion, this study aims to develop a test methodology for characterization of interlayer fracture toughness properties of FFF materials. This test has the potential to be used in optimization of FFF processes for improved interlayer fracture toughness, evaluation of new FFF materials, or assessment of novel interlayer inclusions (e.g. sensors, antennas) and their effect on fracture performance. The test geometry used in this study is based on a DCB test described in ASTM D5528 test standard for unidirectional fiber-reinforced polymer matrix composites [17]. Given the maturity and straightforward nature of D5528, the specimen geometry, test procedures, and data reduction are adopted as closely as possible. The suitability of the test described herein is evaluated by testing specimens manufactured from Acrylonitrile Butadiene Styrene (ABS), and ABS reinforced with short carbon fibers (CF-ABS). All specimens are manufactured using a commercially available 3D printer. To examine the effect of the FFF printing process, fracture toughness was also measured using ABS and CF-ABS filaments that were hot-press molded (HPM). The HPM materials were tested using the single end notch bend (SENB) specimen configuration according to ASTM standard D5045 [18]. In what follows, a description of the specimen manufacturing process is presented, including printing of DCB specimens, adhesion of reinforcing doublers, and insertion of interlayer starter cracks during the printing process. The test procedure is presented, followed by results from fracture toughness testing, fractography, and *in situ* thermal imaging.

2. Specimen design and manufacturing

2.1. DCB specimens

The DCB specimens were designed based on the guidelines provided in the ASTM D5528 standard with one notable exception. Given the low stiffness of ABS and CF-ABS materials relative to fiber-reinforced composites, the FFF-manufactured DCB specimens were stiffened with composite doublers. This was done to reduce the overall specimen deflection at the onset of fracture, and to prevent flexure-induced failure of the arms. Based on previous experience with fracture-toughness testing of thin adhesives, 3.1 mm thick G10 glass/epoxy laminates were used as the doubler material. The actual ABS and CF-ABS specimens were manufactured by printing twenty 0.2 mm thick layers. Similar to the D5528 standard, an 8 μm Kapton film (SPEX SamplePrep; Metuchen, NJ, USA) was placed between the 10th and 11th layer during the printing process to create a sharp starter crack. The resulting DCB specimen geometry is depicted in Fig. 2. As seen in this figure, total specimen thickness was approximately 10.3 mm, total length was 152 mm, and initial starter crack length was 50.8 mm. After final machining the average specimen width was 22.5 mm, which corresponds to approximately 46 raster roads for ABS specimens and 23 raster roads for CF-ABS specimens.

The FFF specimens were manufactured in pairs by printing a 48 mm × 158 mm × 4 mm plaque as shown in Fig. 3. In this figure, the heavy lines correspond to the outline of the entire plaque, while the dashed lines show the cut lines for each specimen. The light-orange region corresponds to location of the Kapton insert. To ensure that the crack faces remain closed during the print and doubler adhesion, a 13 mm section was printed between the end of the Kapton film and the right edge of the plaque. To reduce the effect of thermal residual stresses, the four corners of the plaque were filleted to a 2 mm radius. Each layer was printed using a rectilinear fill pattern with the raster orientation aligned along the direction of the expected crack growth. This was done to prevent possible crack migration caused by the undulations between the rasters. To minimize the internal void content, the infill percentage was set to 100%. In the context of FFF, infill percentage is defined as the degree to which the internal volume is filled with raster roads. Although an infill of 100% implies no gap between adjacent rasters, some voiding is usually observed due to the elliptical cross-section of the solidified rasters. Thus 100% infill minimizes void content but does not fully eliminate it.

The ABS specimens were fabricated using Polylac® PA-747 natural ABS filament (Village Plastics; Barberton, OH, USA). The extrusion was performed using a 0.35 mm dia. circular nozzle at 235 °C. The print bed was set to 95 °C throughout the printing process. The CF-ABS specimens were fabricated using 3DXTech CarbonX™ carbon-fiber reinforced filament (3DXTech; Byron Center, MI, USA), which has a reported fiber volume fraction of 15% [19]. Based on resin digestion and optical microscopy, the average fiber length in CarbonX™ filament is approximately 81 μm, with standard deviation of ± 20 μm. The CF-ABS

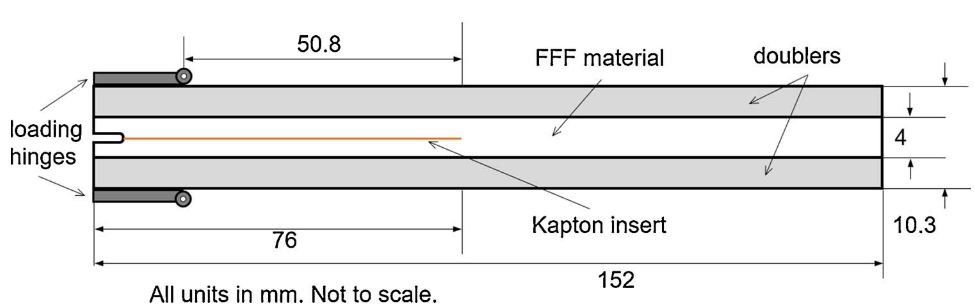

Fig. 2. Geometry of the modified DCB specimen.