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Author: Robert J. Hart

U.S. Army Combat Capabilities Development Command Ground Vehicle Systems Center
Detroit Arsenal
Warren, Michigan 48397-5000

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14. ABSTRACT

The current work explored the use of a compact tension method for testing interlayer crack resistance of additively manufactured polymers based on a modification of the ASTM E813 compact tension test. Test specimens were manufactured using PLA material on a fused filament fabrication 3D printer. Results showed that the peak load was consistent between specimens, however there was inconsistency in the load-point displacement curve, leading to variations in the calculated J-integral for the specimens. Based on the findings of this study, the compact tension specimen could be an effective tool for assessing the fracture-resistance of 3D printed polymers, because the overall geometry of the specimen allows crack formation to occur without excessive deformation or premature failure in low-stiffness, low strength polymers. Further investigation is required to develop greater consistency in the test data, particularly when it comes to measured load-point displacement and energy calculations.

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Introduction

Low density structural materials are crucial for developing lightweight components in commercial and military vehicle applications [1, 2, 3]. While additive manufacturing (AM) technology has evolved rapidly over the past several years, there is still limited understanding into the fundamental behaviors of as-manufactured AM materials. One fact, however, is well known: AM materials do not behave the same as traditionally manufactured parts. For instance, the most common AM processes, commonly referred to as Fused Filament Fabrication (FFF) or Fused Deposition Modeling (FDM), can produce parts with the same geometry and materials as injection molding, however the material properties of the as-manufactured parts can be significantly different. Since most AM parts are built from the bottom up in a layer-by-layer process, it is very common for the out-of-plane material properties to be weaker than the in-plane material properties. A previous study reported that the mechanical properties of the bond between layers (out-of-plane) can be 10-25% weaker than in-plane properties [4]. For fiber-reinforced AM materials, the out-of-plane strength can be orders of magnitude lower than the in-plane strength [5]. The anisotropy of AM polymer materials presents challenges in characterizing the mechanical properties in 3 dimensions [6]. While the anisotropy of AM polymer materials is reminiscent of the anisotropy of traditional fiber reinforced composite materials the relatively low stiffness and strength of AM polymer materials does not lend itself well to the standard test methods for high stiffness, high strength composite materials. For tensile properties, ASTM D638-14 *Standard Test Methods for Tension Testing of Plastics* and ASTM F2971-13 *Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing* can be used in a relatively straight forward manner. Due to the layer of layer nature that AM polymers are fabricated, the out of plane properties can suffer due to issues with layer adhesion. This study explores the use of a compact tension method for testing interlayer crack resistance of additively manufactured polymers.

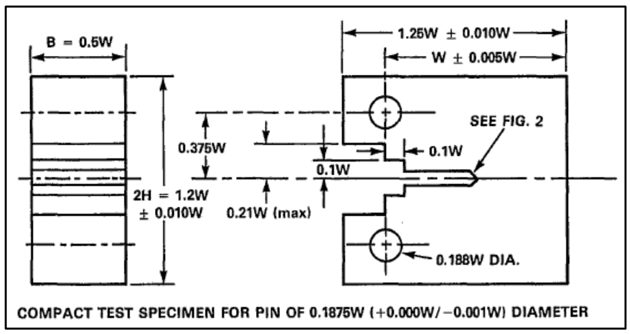
Description of Test Specimens

Test items were manufactured using a desktop FFF printer outfitted with a 1mm nozzle. The material used in this study was 1.75mm diameter polylactic acid (PLA). The follow printer settings were used:

- Nozzle diameter: 1mm
- Layer Height: 0.32mm
- Infill: Solid
- Material: PLA
- Printing Temperature: 200 °C
- Build Plate Temperature: 50 °C
- Build Plate Adhesion: Glue Stick

The compact tension specimen tested in this study was based on the suggested compact tension specimen in ASTM E813 in Figure 1 [7]. For convenience, a specimen with dimensions W = 25.4 mm and B = 0.5W = 12.7mm. The hole size of 2.5mm was selected to accommodate the 2.0mm steel pins in the clevis fixture. The hole was oversized by 2.5mm to account for tessellation of the stereolithography file and printing tolerances. While this dimension is smaller than recommended in ASTM D813, it is important to note that

D813 was intended for testing metals, and the loads for the PLA tested were expected to be much lower than the loads required for crack propagation in metals. Figure 2 shows stress contours from a finite element simulation of a PLA compact tension specimen, and the results indicate that crack propagation would occur prior to any failure at the clevis pins or excessive bending of the specimen. The printed test specimens were oriented so that the crack interface was aligned between the innermost two layers at the mid-plane of the specimen. The support material shown in Figure 3 (b) was needed to enable printing the overhanging structure, and prior to testing the support material was carefully removed with a serrated blade.

(a)


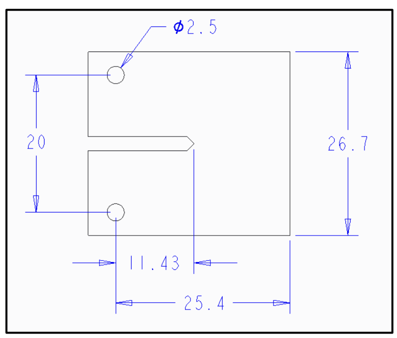
(b)


Figure 1: Geometry Of Compact Tension Specimen (a) In ASTM E813 [7] and
(b) The Compact Tension Specimen For The AM Polymers Tested In This Study. Dimensions are in millimeters.

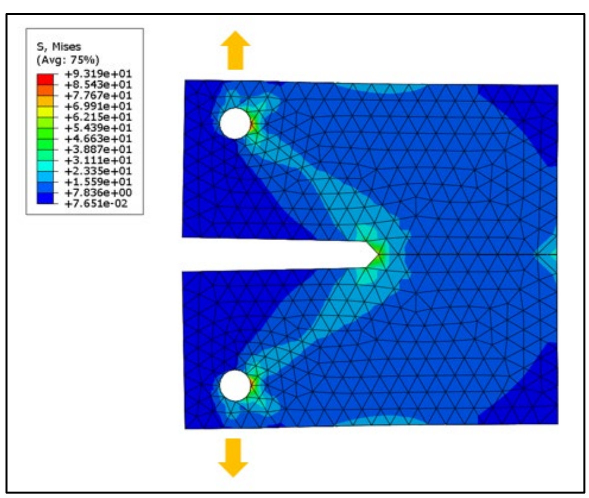


Figure 2: Stress contours for PLA compact tension

specimen subjected to 0.2mm load point displacement.

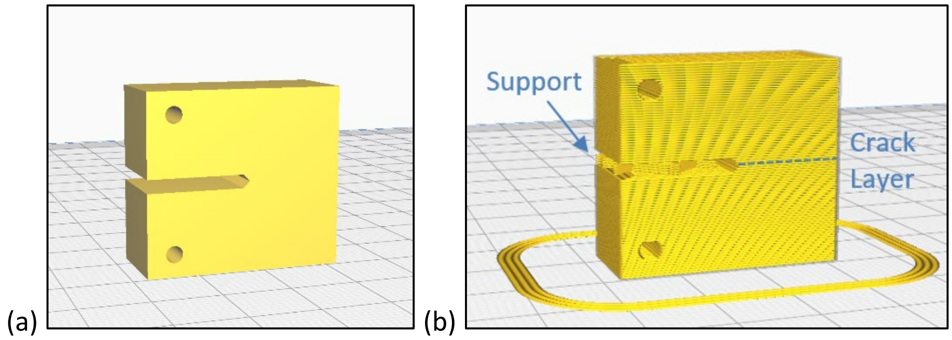


Figure 3: (a) Compact tension specimen oriented on build plate and (b) layer view showing the support material and interface where crack occurs during testing.

Methods

Compact tension specimens were tested using an Instron 5984 Tensile Tester with a 10 kN load cell and integrated video extensometer. In order to maintain a consistent angle at which the load was applied, 2.0mm steel pins were inserted through the holes in the specimen and held captive in a fixture that allowed the pins to rotate freely during the testing. The testing was conducted at extension rate of 2 mm/min which allowed sufficient time to monitor crack length and resulted in a total testing duration of 1-2 minutes per specimen. Crosshead displacement was used to determine load line displacement and video capture was used to monitor crack propagation in the specimen. Bluehill 3 software used data such as load and load line displacement. The specimens were tested until the load dropped to zero.

Results

The results for three PLA compact tension specimens are shown in Figure 4 and Table I. As seen in the results, the peak load observed was highly consistent with an average of 0.123 kN and a standard deviation of 0.0019 kN. Specimen #1 experienced greater load point displacement for an equivalent load, compared to specimen 2 and 3. This resulted in greater energy released during the test, since the J-integral calculation is determined by the area under the load versus load point displacement curve.

Table I: Test data for 3 PLA compact tension specimens produced via additive manufacturing

Specimen #	Peak Load [kN]	Load Point Displacement at Peak Load [mm]	J-Integral [J]
1	0.123	3.284	0.2305
2	0.124	2.424	0.2018
3	0.121	2.184	0.1983
Average	**0.123**	**2.631**	**0.2102**
Standard Deviation	**0.0019**	**0.5784**	**0.0177**

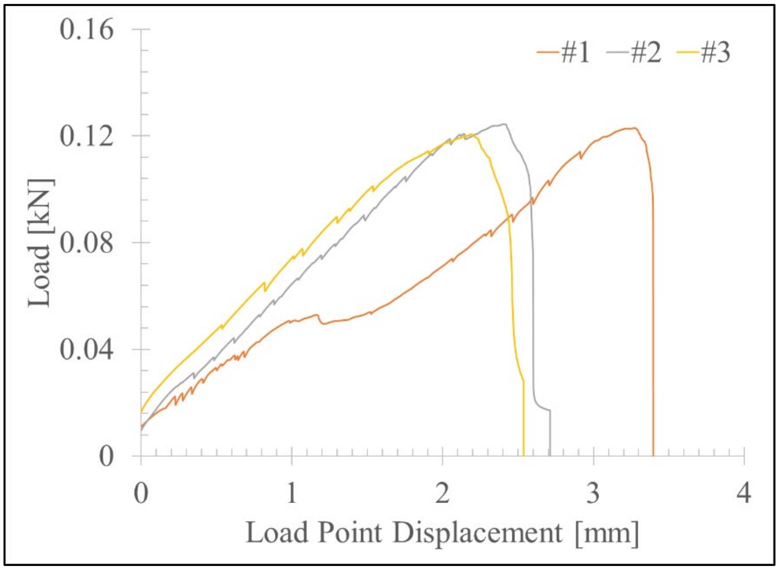


Figure 4: Load versus load point displacement for PLA compact tension specimens produced via additive manufacturing. The area under the load versus load point displacement curve gives the area for the J integral calculation according to ASTM E813.

Discussion & Conclusions

The current work explored the use of a compact tension method for testing interlayer crack resistance of additively manufactured polymers. Test specimens were manufactured using PLA material on a fused filament fabrication 3D printer. Results showed that the peak load was consistent between specimens, however there was inconsistency in the load-point displacement curve, leading to variations in the calculated J-integral for the specimens. Based on the findings of this study, the compact tension specimen could be an effective tool for assessing the fracture-resistance of 3D printed polymers, because the overall geometry of the specimen allows crack formation to occur without excessive deformation or premature failure in low-stiffness, low strength polymers. Further investigation is required to develop greater consistency in the test data, particularly when it comes to measured load-point displacement and energy calculations.

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