OPTIMIZING FUSED DEPOSITION MODELING 3D PRINTING PROCESS FOR FRACTURE RESISTANCE

N. Aliheidari, J. Christ, A. Ameli*, Advanced Composites Laboratory, School of Mechanical and Materials Engineering, Washington State University Tri-Cities, WA

R. Tripuraneni, S. Nadimpalli, Department of Mechanical and Industrial Engineering, New Jersey Institute of Technology, Newark, NJ

* Corresponding author: a.ameli@wsu.edu

Abstract

The quality of fused deposition modeling (FDM) 3D printed parts are primarily influenced by the process conditions and mesostructural features. This study aims to establish the relationships between the process parameters/mesostructural features and the fracture resistance of printed parts. Double cantilever beam specimens of ABS were printed at different nozzle and bed temperatures, and with different layer height and layer width and then fracture-tested to measure the fracture resistance using J-integral in a finite element model. The result indicated that nozzle temperature and layer height had the most significant effects on the fracture resistance. The fracture resistance increased by ~30% with 20°C increase in the nozzle temperature. The bed temperature and the layer width appeared to be less significant factors, compare to the nozzle temperature. The results of this work establish insight and guidance in the design of printed materials for structural and functional applications.

1. Introduction

Additive manufacturing (AM) is a commonly known process by which objects are manufactured directly from computer-aid design (CAD) model by the gradual deposition/addition of material [1]. Under the umbrella of AM, there are a large number of technologies that employs layer-by-layer method for part fabrication. These methods are stereolithography, selective laser sintering, inkjet printing, and fused deposition modeling (FDM). Amongst all, FDM is receiving exceptional attention because it is simple, clean and environmental friendly for a vast range of applications [2,3].

In the FDM process, a feedstock, usually a thermoplastic material is heated above the glass transition temperature and driven as a flowable material onto a build platform. A single layer is formed as the nozzle deposits thermoplastic in discrete lines next to each other in the X-Y plane; creating a thin 2-D layer. Once the planar layer is complete, the bed, or sometimes the nozzle, moves in the Z direction and the subsequent layer is then deposited onto the previous layer. This process is repeated until the part is completed [4]. The ability to rapidly prototype functional parts makes FDM a very versatile and desirable AM process. With increasing popularity, FDM is being utilized in many cutting edge applications in automotive, aerospace and medical industries. Due to the vast and promising applications of FDM printed parts, there has been an increasing number of investigations into new characterization techniques and properties of end-use parts, particularly mechanical properties.

Using standard mechanical testing methods such as tensile and bending, a large number of studies have been conducted based on stress-strain characteristics to characterize the tensile, compressive, and bending properties of FDM printed parts [4–7]. These studies provide information only about the steady-state performance of printed materials; in the majority of real-world applications, these methods cannot be directly used in the strength evaluation and/or failure prediction of printed materials. In the applications such as scaffold, medical devices, sensors, flexible electronics, and robotics [8,9], printed structure experiences repeated mechanical and thermal loads, creep loads, etc. Such loadings can result in crack-growth-dominant failure modes not seen in static loadings. To design under such circumstances demands the understanding of the fracture behavior and properties of the printed material. When cracks or defects in materials reach a certain critical length, they can propagate even though the nominal stress may be much lower than the static strength, resulting in an unpredicted catastrophic failure. Stress-strain based test methods presented in the literature cannot predict the fracture properties of FDM parts and there has been no research attempt to characterize the fracture properties of FDM printed materials.

In a recent work, the authors have presented a fracture-mechanics-based approach to characterize the apparent and interlayer fracture resistances of FDM 3D printed polymers [10]. Using a fracture mechanics approach, this paper investigates how the fracture properties of 3D printed materials are controlled by the process parameters and mesostructural features which is inner structure resulting from neck growth between adjacent filaments. To this end, double cantilever beam...
(DCB) specimens of acrylonitrile butadiene styrene (ABS) are designed and loaded in opening mode. Four different parameters including nozzle temperature, bed temperature, layer height, and layer width are varied in the printing of DCB specimens. A finite element model is utilized as part of data reduction and the apparent fracture resistance is calculated using J-integral method. The relationships between these parameters and the fracture resistance are then characterized and discussed.

2. Experimental procedure

2.1. Fracture specimen fabrication

Because of its widespread use in FDM and excellent printing capability, acrylonitrile butadiene styrene (ABS) filament with a diameter of 1.75 mm (BuMat, USA with a CAS number of 9003-56-9) was selected as the feedstock. Beam-type fracture samples are the most common specimen geometry used for fracture characterization of layered materials and are well established for adhesive joints [11,12]. Therefore, DCB samples were adapted for this work and printed using a Felix-pro I printer (Netherland) with compatible software, Simplify 3-D. The DCB specimen was designed such that the arms do not experience any plastic deformation during loading. The DCB specimen geometry was 32.5 × 13.5 × 10 mm for length, height and width of the samples respectively (Figure 1 and Table 1).

![Figure 1. a) DCB specimen design b) an actual FDM 3D-printed DCB sample.](image)

Table 1. Dimensions of the DCB specimen. The symbols are the same as in Fig.1a.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Specimen length</td>
<td>32.5</td>
</tr>
<tr>
<td>h</td>
<td>Arm height</td>
<td>6.0</td>
</tr>
<tr>
<td>t</td>
<td>Precrack thickness</td>
<td>1.5</td>
</tr>
<tr>
<td>a₀</td>
<td>Precrack length</td>
<td>19.5</td>
</tr>
<tr>
<td>d</td>
<td>Pin hole diameter</td>
<td>1.0</td>
</tr>
<tr>
<td>w</td>
<td>Specimen width</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The specimens were printed by varying four different parameters while holding the other three parameters constant. The variable parameters were nozzle temperature, bed temperature, layer height, and layer width. Layer width and height are controlled by the independent adjustments of the nozzle feed rate and the distance between the nozzle tip and the layer via the software. As listed in Table 2, for each parameter, three different levels were considered. Also, print nozzle diameter was 0.35 mm and printing speed was set at 60 mm/s, and a 100 percent infill with solid linear pattern with no perimeter was used to print the longitudinal layers. Each planer layer was composed of continuous lines parallel in the printer’s x-axis, which resulted in the specimens with all the layers oriented in the longitudinal direction of the DCB.

![Figure 2. Experimental setup for fracture testing of printed DCB specimens.](image)

Table 2. Variable parameters of FDM 3D printing

<table>
<thead>
<tr>
<th>Nozzle temperature (°C)</th>
<th>Bed temperature (°C)</th>
<th>Layer height (mm)</th>
<th>Layer width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>85</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>230*</td>
<td>95*</td>
<td>0.2*</td>
<td>0.35*</td>
</tr>
<tr>
<td>240</td>
<td>105</td>
<td>0.3</td>
<td>0.45</td>
</tr>
</tbody>
</table>

*Fixed values when other parameters were varied.

2.2. Fracture test set-up

DCB fracture specimens under steady state loading were used to determine the crack growth resistance of FDM structures with unidirectional layers. The specimens were subjected to a uniaxial opening load (resulting in mode I loading), using a MTS tensile testing set up (Fig. 2). TSW Elite software was used to apply and record displacement and load data. Load-displacement data and captured images of samples using 5 megapixel monochromatic CCD camera were synchronized by a LabVIEW program. Initiation of crack growth was determined from the captured images and the corresponding load was taken as a critical load for fracture resistance calculation. Four to five specimens were tested for each condition.

3. Data reduction

The resistance of specimens to crack initiation is characterized using the J-integral method. J-integral represented by Rice as a path-independent integral around the crack tip and described as:

\[
J = \int_c W dy - \int_c (t_x \frac{\partial y}{\partial x} + t_y \frac{\partial y}{\partial y}) ds
\]
where $\Gamma$ is any path surrounding the crack tip, $W$ is strain energy density, $t_x$ traction vector along $x$ axis, $t_y$ traction vector along $y$ axis, $n$ unit outer normal vector to path $\Gamma$, $u$ displacement vector and $s$ distance along the path $\Gamma$.

The load corresponding to the first observable crack initiation during DCB loading together with the measured elasticity modulus of 1.924 GPa [10] and Poisson’s ratio of 0.35 [13] was used in a finite element model using ANSYS 16.2 coupled with J-integral method to find the apparent fracture resistance. Figure 3 shows the plane strain finite element mesh of the DCB specimen with the corresponding boundary conditions. The crack initiation load was applied at the end of the arms to mimic the loading condition during testing. ABS was assumed linear elastic for all the J-integral values reported in this study.

![Figure 3. Plane strain finite element mesh of DCB with magnified crack tip. The arrow points to the node with $y=0$ coordinate that was fixed in all directions to avoid rigid body motion.](image)

4. Results and Discussion

Figure 4a and 4b depict the representative load-displacement curves of the DCB specimens printed at various nozzle temperatures and bed temperatures, respectively. Figure 5a and 5b also show the DCB’s load-displacement curves for varying layer height and layer width, respectively. In all the cases, the load increased relatively linearly with an increase in the crosshead displacement, until the crack growth started. It is noted that after the crack initiation, during the crack growth, the load still continued to increase, but at a nonlinear decreasing rate, up to a maximum value, where the catastrophic failure occurred by an unstable and sudden crack growth. The load increase in this range may be associated with the toughening or damage zone development ahead of the crack tip, resulting in an increase of the fracture energy before the final failure.

The critical load used for the fracture energy (apparent fracture resistance) calculations was the load corresponding to the onset of crack growth, and obtained from Figs. 4 and 5 synchronized with the optical images. Therefore, the reported fracture energy values account for the critical energy at the crack initiation.

![Figure 4. Load-displacement curves for DCB samples printed at different (a) nozzle temperatures and (b) bed temperatures.](image)

![Figure 5. Load-displacement curves for DCB samples printed at different (a) layer height and (b) layer width.](image)
enhanced interlayer bond, or a more favorable mesostructure, or both.

Figure 6 shows that both the crack initiation load and the corresponding apparent fracture resistance increase with an increase in the nozzle temperature. The minimum apparent fracture resistance (1981.15±40.8 J/m$^2$) was obtained for the samples printed at 220°C, while that for the samples printed at 240°C was measured to be the highest (2731.87±119.94 J/m$^2$). Critical load was also increased from 136±1.41 N to 160±2.94 N when the nozzle temperature was raised from 220 to 240°C. When the filament is extruded from the nozzle onto the previous layer, localized diffusion and re-melting occurs due to the heat conduction between the two layers. The overall temperature gradient has a critical effect on the bond formation and bond quality. Therefore, increasing the nozzle temperature has a dominant effect on the fracture resistance.

Figure 6. The variation of apparent fracture resistance and critical load with nozzle temperature.

Figure 7 shows the impact of the bed temperature on the critical load and the apparent fracture resistance. It is seen that both the apparent fracture resistance and the critical load proportionally increase with an increase in the bed temperature. The apparent fracture resistance values for 85, 95 and 105°C were measured to be 2063.82±129.37, 2172±60.77 and 2419.675±129.97 J/m$^2$, respectively.

Figure 7. The variation of apparent fracture resistance and critical load with bed temperature.

Overall, the fracture resistance increased as the temperature was raised, irrespective of the nozzle or bed. This is attributed to a better fusion quality at higher temperatures. When either nozzle or bed temperature increases, the interlayer temperature at the fusion location is also increased. The fusion process is a strong function of temperature and time. At higher temperatures, the polymer molecules have more mobility (less viscosity) and thus the inter-diffusion of molecules between the two layers can occur more easily. At the same time, once the temperature at which the fusion process begins is higher, the polymer molecules have more time for inter-diffusion before reaching to a temperature that they cannot further effectively move (glass transition temperature). Consequently, when the fusion temperature is higher, a large necking ratio (more inter-diffusion, greater fused region) with a more number of entangled molecules (stronger adhesion) between the layers is formed, which translates into greater fracture resistance.

Moreover, the comparison of the results in Figures 6 and 7 show that the nozzle temperature has a stronger effect on the fracture resistance, compared to that of the bed temperature. The fracture resistance changed with the rates of ~36 and ~18 J/m$^2$/°C when the nozzle temperature and bed temperature were varied, respectively. This is expected from the heat transfer perspective. The bed heat source is generally far from the fusion location at the interlayer, while the nozzle heat source is in the close vicinity of the fusion location and moves with it. Therefore, the temperature gradient between the nozzle source and fusion location may be smaller than that between the bed heat source and fusion location. Another reason can be related to the magnitude of these temperatures. The nozzle temperature is much higher than the bed temperature and noting that the quality of the fusion process has a nonlinear relation with the temperature, a temperature change at the higher level of temperatures (nozzle temperature range) would result in a greater impact compared to the same temperature change at the lower temperature range (bed temperature range).

Figure 8 shows the apparent fracture resistance and the critical load as a function of layer width. The fracture resistance increased from 1993.5±305.6 to 2364.0±196.2 J/m$^2$ and the critical load increased from 136.12±10.36 to 148.36±6.13 N when the layer width was increased from 0.25 to 0.45 mm. Once the layer width increases, the continuous adhesion area increases. At the same time, the total number of layers in the crack plane decreases, which in turn results in a decreased number of inter-layer voids. Consequently, the overall interfacial adhesion between the two crack faces increases and the fracture resistance is improved, as the layer width is increased. An infinite...
crack width should correspond to a bulk continuous specimen.

![Figure 8](image_url)

Figure 8. The variation of apparent fracture resistance and critical load with layer width.

The effect of layer height on apparent fracture resistance and applied load was also shown in Figure 9. No significant difference was observed between the fracture resistances of the samples with 0.1 and 0.2 mm layer heights, having 2130.73±108.37 J/m² and 2170.0±60.77 J/m², respectively. However, when the layer height was increased to 0.3 mm, the apparent fracture resistance drastically dropped to 731.82±47.22 J/m². This is an unexpected result. One possible reason might be the technical limitations of the used printing machine in accurately and effectively controlling such a large layer height. Further investigations are needed for better understanding of this trend as well as varying scatter range.

![Figure 9](image_url)

Figure 9. Effect of layer height on the apparent fracture resistance and applied load

Overall, within the ranges of the parameters examined, using 240°C, 105°C, 0.2 mm and 0.45 mm as the nozzle temperature, bed temperature, layer height and layer width bring the highest fracture resistance. A future work can be designed to study any possible interactions between these factors for a comprehensive understanding and optimization of fracture resistance.

Conclusions

The fracture resistance of FDM 3D Printed DCB specimens was characterized as a function of several printing and mesostructural parameters. Mode-I loading was applied to the DCB specimens and the apparent fracture resistance were obtained using an FE model by applying J-integral method. The effects of four major printing parameters including nozzle and bed temperatures, layer height and layer width on the apparent fracture resistance was characterized and discussed. The result showed that the samples printed at higher nozzle temperatures had significantly higher fracture resistance. The layer height was another dominant factor. The effect of the bed temperature and layer width were less significant.

References