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Thickness effect on the fracture behavior of structural components fabricated via Fused Deposition Modeling

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Abstract

In general, the mechanical properties of components produced with additive manufacturing (AM) are dependent on both the geometry and thickness of fabricated parts. Any change will influence the underlying fabrication process and inherent characteristics. Therefore, it is vital to understand the dependency of mechanical behavior of produced components to improve the designability and applicability. In this study, the thickness effect on fracture behavior of PLA specimens fabricated via FDM technology has been investigated. Overall, 15 double edged notched tension (DENT) specimens were produced layer by layer with three different thicknesses of 1mm, 3mm and 5mm. Fracture properties such as fracture load and critical stress intensity factor (SIF) were determined and analyzed from the experimental fracture tests and numerical simulations. 2D digital image correlation (DIC) analyses were performed to evaluate the full-field displacement and strain distributions around crack tips of the specimens. The experimental results indicated that there is a strong correlation between the building thickness and critical SIF. Specimens with larger building thickness experience lower critical SIF due to the fact that thicker specimens have a smaller plastic deformation zone which can lead to both smaller energy dissipation and smaller critical SIF. Furthermore, thinner specimens have higher possibility of developing fracture trajectories along the raster angles.

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1. Introduction

The terminology 'additive manufacturing' refers to the manufacturing process of layering material to create a component. Unlike the conventional technique such as subtractive manufacturing (SM), in which the material is subtracted from the solid in order to create the required component (Hibbert et al. 2019). AM is often treated as the next industrial revolution and a fast-growing technology in a variety of industrial applications such as biomedical implants, automotive, architecture, and aerospace (Zhai, Lados, and Lagoy 2014). It has the capacity of converting design files into fully functional components. Fused deposition modeling (FDM) or fused filament fabrication (FFF) is a manufacturing process that employs a moveable head to deposit the molten thermoplastic material onto a building platform. The filament is generally heated approximately several degrees above the melting point, which causes it to solidify immediately after extrusion.

A fracture occurs when a specimen is subjected to a static load that causes that specimen to break into two or more pieces. Polymers may fail in several ways depending on the type of stress and the material's mechanical properties. In general, fracture specimens have an existing notch or crack, and the fracture occurs as a result of crack propagation through the specimen. Overall, there are three modes of fracture, which refer to the decomposition of crack tip stress into three distinct loading conditions. Mode-I refers to the stress which is orthogonal to the crack surface's local plane. Mode-II is the sliding mode in which the stress is parallel to the crack surface but orthogonal to the crack front and Mode-III is the tearing mode in which the stress is applied out of plane and parallel to the crack surface and front (Dame 2013). Only Mode-I fracture behavior will be considered and investigated in this article.

Numerous literature studies have already been reported on the thickness and scale effect on the fracture behavior of various materials. For instance, Wong et al. (Wong, Baji, and Gent 2008) investigated the fracture toughness of hydroxyapatite-filled polycaprolactone lamina of different thicknesses using the technique of essential work of fracture. The specific essential work of fracture was discovered to decrease as the specimen thickness increased. In addition, Bell et al. (Bell and Siegmund 2018) investigated the size effect of 3D-printed polymeric specimens under three-point bending tests and discovered that the strength and the fracture toughness of the specimens are size-dependent, especially for smaller specimens. In addition, the experimental results also revealed that large specimens can be characterized as quasi-brittle while the smaller ones exhibited a softening behavior before failure. However, there is no sufficient amount of research articles on the thickness effect of fracture behavior of components fabricated via FDM technology.

Nomenclature

AM	additive manufacturing
CAD	computer-aided design
CNC	computer numerical control
DENT	double edged notched tension
DIC	digital image correlation
FDM	fused deposition modeling
FFF	fused filament fabrication
LEFM	linear elastic fracture mechanics
PLA	polylactic acid
SENB	single edge notched bending
SIF	stress intensity factor
SM	subtractive manufacturing
UTS	ultimate tensile strength

2. Experimental Procedures

2.1. Materials and fabrication process

All the specimens were produced by using an Original Prusa i3 MK3 printer via FDM method with a filament diameter of 1.75mm. Color of natural PLA filament was selected as a feedstock due to the fact that colors were reported to have significant influences on the mechanical properties such as ultimate tensile strength and elongation at failure (Wittbrodt and Pearce 2015). A slicing software Ultimaker Cura 4.8.0 was used to generate G-codes. It is worth mentioning that all the specimens were fabricated with 100% infill density in order to approach the optimal mechanical properties of completely dense material as close as possible (Torres et al. 2016). Furthermore, the raster angles (infill line directions) were selected to be ± 45 degrees for alternative layers. Some other detailed important printing process parameters are listed in Table 1. These process parameters were determined based on the experimental results to fabricate acceptable specimens with the minimum possible internal voids while maintaining accurate measurements and smooth layers.

Table 1. Printing process parameters for all the specimens.

Building parameters	Parameter value	Building parameters	Parameter value
Infill density	100%	Nozzle temperature	215 °C
Wall line count	2	Raster angles	± 45 degrees
Wall thickness	0.8mm	Initial layer printing speed	30mm/s
Infill line distance	0.4mm	Printing speed	45mm/s
Layer height	0.1mm	Build plate temperature	75 °C

2.2. Fracture tests

Three different geometries of testing specimens with a thickness of 1mm, 3mm, 5mm were fabricated as illustrated in Fig. 1. The dimensions used for DENT specimens were based on the specimens for tensile tests according to the ASTM standard. The overall crack length to width ratio, $2a/w$ was determined to be 0.5, which indicates a single crack length of 6.5mm (i.e. the length of pre-notch and pre-crack together) for all the specimens with various thicknesses. All the specimens were fabricated without the notch and pre-crack initially. Five specimens were fabricated all at once with a parallel printing sequence for each case as illustrated in Fig. 2. The notch was produced with an Epilog Fusion M2 laser cutter. The speed, power, and frequency of the laser were adjusted to each thickness to ensure a clean cut without melting. A pre-crack was then fabricated with the use of a razor blade in order to create a sharp pre-crack as recommended in reaching a total crack length of 6.5mm on each side of the specimens. For this aim, the specimens were placed on one side out of the vice stand and protective plates so that the distance from the vice stand to the end of the specimen corresponded with the length of the notch and pre-crack. The razor blade was then knocked into the specimen through the notch with a hammer. The pre-crack was set to be 1.5mm for all the specimens. Then the fabricated specimens were tested under a displacement rate of 2mm/min until failure and the gripping area was set to be 25mm for each side during the tests.

Fracture tests were conducted using DIC, which is an optical measurement technique that allows a comprehensive field investigation of a materials or structure's deformation, displacement, and strain. A high-speed fixed camera system was used to capture frames at a predetermined sampling of 200ms (5 images per second). In order to provide a strong contrast, all the DENT specimens from each thickness were painted with matte white background and speckled with black dots.

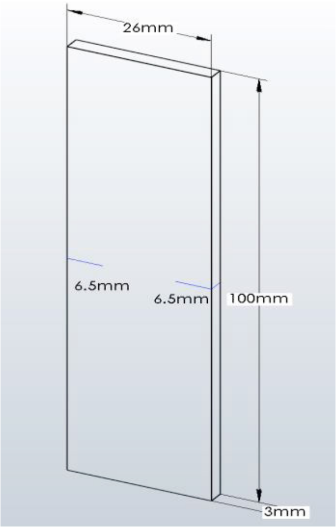

Fig. 1. Dimensions of one DENT test specimen

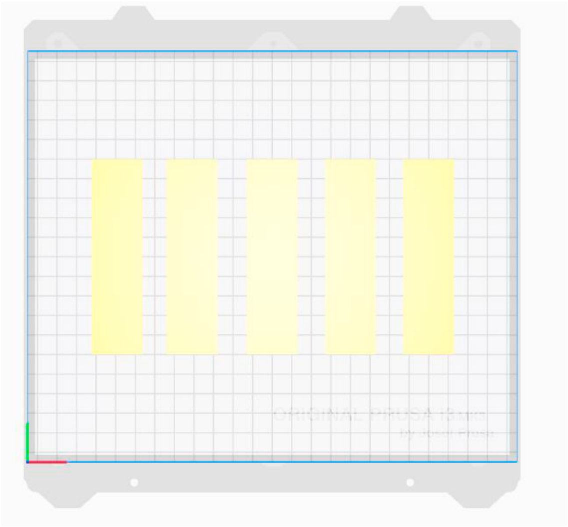

Fig. 2. Printing orientation of the test specimens on a building platform (Top view)

3. Results and Discussions

The purpose of these fracture tests is to investigate the thickness effect on the fracture behavior of DENT specimens fabricated from PLA. Load versus displacement curves for each thickness were plotted as illustrated in Fig. 3. It can be discovered that the specimens with higher building thickness experience both higher fracture load and higher scatter. Fracture load and critical SIF were computed for each thickness and listed in Table 2. Specifically, a three-dimensional linear elastic fracture mechanics (LEFM) analysis was performed to obtain the values of critical SIF (Nagarajan, Mohanty, and Misra 2019). Various values of young's modulus and Poisson's ratio corresponding to each thickness obtained from uniaxial tensile tests were used for the material properties in the simulation (Xu et al. 2021). Furthermore, fracture loads with the unit of MPa were calculated based on the gross cross-section of the specimens. DIC was also used to obtain the full-field strain distributions around the damage zone of the specimens as illustrated in Fig. 4. The experimental results revealed that the specimens with higher building thickness experience lower critical SIF values. To further evaluate this tendency, the fracture surfaces of the tested specimens were evaluated.

It is worth mentioning that specimens with larger thickness experience fewer possibilities of having slant fracture surfaces and more possibilities of having flat fracture surfaces. It can be observed that thinner specimen have a higher critical SIF value accompanied by noticeable slant fracture, which requires a higher amount of energy for fracture (Ralph et al. 2001). Therefore, the proportion of shear lips or slant fractures decreases as the thickness increases, which is in correlation with the observed trend of critical SIF value. Another conclusion discovered from a literature study matches with the experimental results as well. It was reported that the fracture toughness of relatively thinner aluminum sheets is higher than the thicker sheets (Shinde et al. 2012). This is a well-known phenomenon in the field of fracture mechanics, where the thinner cracked components that are in a plane stress condition, experience a larger plastic deformation zone around the crack tip which results in higher energy dissipation and consequently leads to a higher critical SIF in the fracture moment.

Furthermore, the experimental results indicated that there is a strong influence of building thickness on the bonding between the raster angles as a source of different fracture trajectories for different building thicknesses. Specimens with relatively lower thicknesses experience higher possibilities of having fracture trajectories along the raster angles as illustrated in Fig. 4. It should be stated that the raster bonding of the first layers in the print shows a lower quality regarding the air gaps between the rasters compared to the rest of the layers. In this scenario, the thinner specimens with a fewer number of layers can be more affected by the quality of the first layers, making the crack propagation more influenced by the raster angles. On the other hand, thicker parts include a higher number of deposited layers, reducing the possible influence of the initial layers on the fracture properties. In addition, the possible influence of reheating of the layers in thicker parts should be pointed out, which may improve the bonding between the raster lines in the previous layers. The crack propagation along the raster lines in thinner parts can cause two different sources of variation in the mechanical properties. First, crack propagation along rasters indicates that the crack is breaking through only half of the rasters (i.e. 45° or -45° rasters). In this case, the full strength of all rasters may not be used for load-bearing, resulting in an expected lower failure load. Secondly, the deviation of the crack from its initial plane would result in a local mixed-mode fracture of the material, possibly increasing the size of the damage zone around the crack tip and causing higher energy dissipation in the material. These two points are now under investigation to evaluate their impact on the fracture strength and the thickness dependency of the fabricated FDM parts. In addition, in order to better distinguish the thickness effect based on the fabrication quality and the stress state around the crack tip, additional testing on conventional (non-printed) PLA specimens with different thicknesses should be performed and the trend of thickness dependency of the fracture strength should be compared with the FDM specimens of the same thickness range.

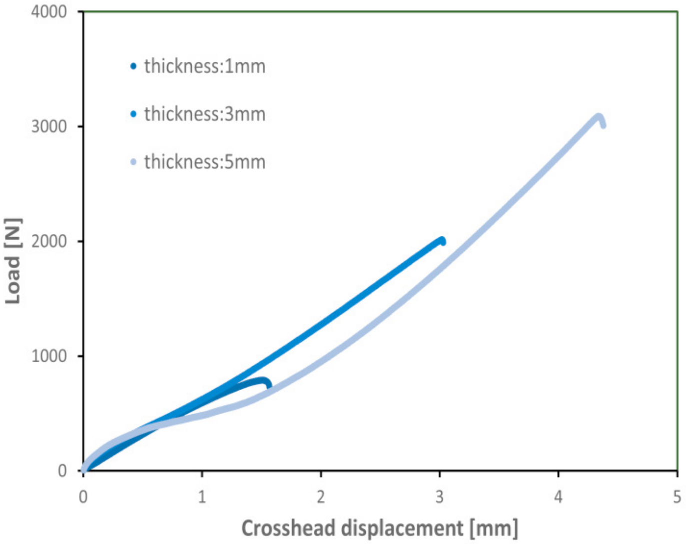

Fig. 3. Load displacement curves for fracture tests with the thickness of 1mm, 3mm, and 5mm

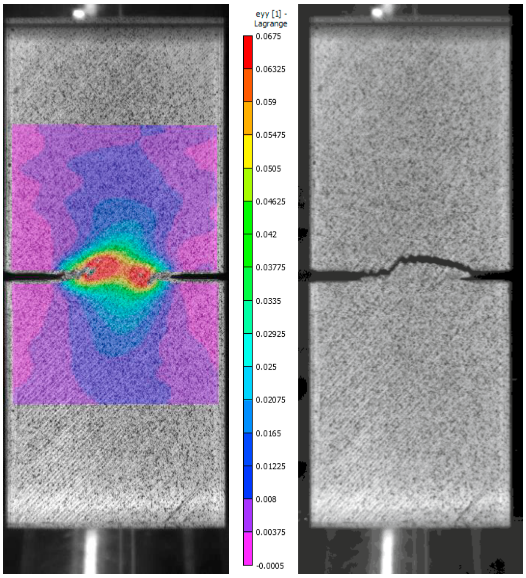

Fig. 4. The damaged zone around the crack tip in DIC compared with real fracture trajectory with the thickness of 1mm

Table 2. The calculated value of fracture load and critical SIF for various thicknesses (Xu et al. 2021)

Property: thickness	1mm	3mm	5mm
E [Gpa]	3.2	3.1	3.1
Poisson's ratio	0.275	0.316	0.342
Fracture load [N]	783.75 ± 12.61	2071.90 ± 123.74	3068.42 ± 140.39
Fracture load [MPa]	30.14 ± 0.49	26.56 ± 1.59	23.60 ± 1.08
K_C_critical SIF [MPa$\sqrt{m}$]	170.3	150.0	134.7

4. Conclusions

Overall, the thickness effect on fracture properties of PLA specimens fabricated via FDM technology on their mechanical properties has been investigated in this study. Fracture tests were performed under uniaxial static loading, and DIC was used to visualize the strain distributions of the specimens. The experimental results indicated that there is a high degree of association between fracture properties and thickness. Specifically, specimens with larger building thickness experience lower critical SIF. One of the reasons is that thinner specimens have a greater plastic deformation zone around the crack tip, resulting in increased energy dissipation and a greater critical SIF in the fracture moment. It was found that relatively thinner specimens have a greater chance of developing fracture trajectories along the raster angles because of the weaker bonding strength between the layers in these specimens. Further studies should be conducted to better understand the interlayer bonding in the specimens of different thicknesses and evaluate the possible sources of the variation in the interlayer and inter-raster bonding strength.

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