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The effect of crack insertion for FDM printed PLA materials on Mode I and Mode II fracture toughness

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Abstract

The paper presents mode I and II fracture toughness results for polylactic acid material obtained via fused deposition modeling. The tests were performed using Single Edge Notch Bend specimens loaded in four point bending: symmetric for mode I, asymmetric for mode II, respectively. The notch was inserted by 3D printing, and by milling, respectively. Fracture toughness values measured for the specimens with 3D printed notch resulted to be higher than those obtained by milling. The effect of notch insertion is more evident in mode I while it is less important for mode II.

Keywords: Additive Manufacturing, Fused deposition modeling, PLA, mode I, mode II, fracture toughness

1. Introduction

Fused deposition modeling (FDM™) or 3D-printing is an extrusion additive manufacturing technique, which allows the building of complex parts, Gibson et al. (2015). The process is based on the extrusion of a thermoplastic filament transported by two counter-rotating driving wheels into a hot die melting the plastic material. Parts are generated by

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the material deposition through a nozzle that is moving according to a pre-defined CAD structure in a layer-by-layer manner, Gibson et al. (2015).

Polylactic acid (PLA) is a bio-based and bio compostable thermoplastic widely used in different industries due to its superior mechanical strength. Unlike the high strength and high stiffness of this material, its brittle behavior and low temperatures responsible for the material geometric distortion, have been pointed out to be its limitations in real life, Sennan et al. (2014). Due to the mentioned characteristics, PLA is the most used material in FDM printing. Consequently, the fracture toughness of this material is an important parameter to be precisely known.

The influence of printing parameters on the tensile properties of PLA such as: printing direction and orientation, types of infill, layer thickness, color of the filament, specimens, was investigated by Gordon et al. (2016), Kiendl and Gao (2020), Yao et al. (2020), Vălean et al. (2020). The FDM parts produced by PLA filaments tend to provide mechanical properties comparable to the ones made from bulk PLA, Gordon et al. (2016), Farah et al. (2016), Yao et al. (2020), Vălean et al. (2020).

In addition, fracture properties determined using a significant number of AM specimens were determined by Ahmed and Susmel (2018, 2019) and by Arbeiter et al. (2018). However, only few results are reported in the literature regarding the mode II fracture toughness and mixed mode fracture of PLA, Khan et al. (2019).

Nomenclature

a	crack length
b_1, b_2	supports positions
B	specimen thickness
K_{IC}	mode I fracture toughness
K_{IIC}	mode II fracture toughness
P_{max}	maximum applied load
W	specimen width

The Single Edge Notched Bend (SENB) specimen under symmetric and asymmetric loading was adopted in this study in order to determine the Mode I and Mode II fracture toughness. Particularly, the asymmetric loading was employed to determine mode II fracture toughness for a wide range of brittle materials (Aliha et al. (2019)). Among these, it is worth mentioning: concrete, Yin et al. (2019); granite, Razavi et al. (2017) and Wang et al. (2017); wood, de Moura et al. (2018); polyurethane foam, Marsavina et al. (2016) and Apostol et al. (2016a, b); extruded polystyrene, Yoshihara and Maruta (2019); polyamide, Linul et. al. (2020); bi-material PMMA – Aluminium, Marsavina and Piski (2010).

This paper experimentally investigates the influence on the mode I and II fracture toughness of PLA specimens obtained through FDM technology, of notch insertion by 3D printing or machining.

2. Materials and manufacturing process

The Prusa MK3 printer was used for fabrication of the test specimens. The printer was equipped with an HFE300 extruder for printing parts with filaments of 2.85 mm diameter. A 3D printing software was used to set the printing parameters such as raster angle, head speed, extrusion temperature and so on. To ensure the quality of the printed part, the temperature of the nozzle and the built platform was controlled to be at around 60°C and 220°C, respectively. A 100% infill density was defined with raster angles of ±45° for the infill. A 0.15 mm layer thickness was considered for printing. Previous studies show that the higher mechanical properties in tensile for 3D printed PLA were obtained for specimens printed in the horizontal plane and for 0° orientation, Vălean et al. (2020). Accordingly, the specimens were printed in horizontal plane considering the direction angle of printing equal to 0°.

The single edge notch bend specimens (SENB) were printed with and without notch, Fig. 1. The notch in the un-notched specimens was introduced by milling, Fig. 1.

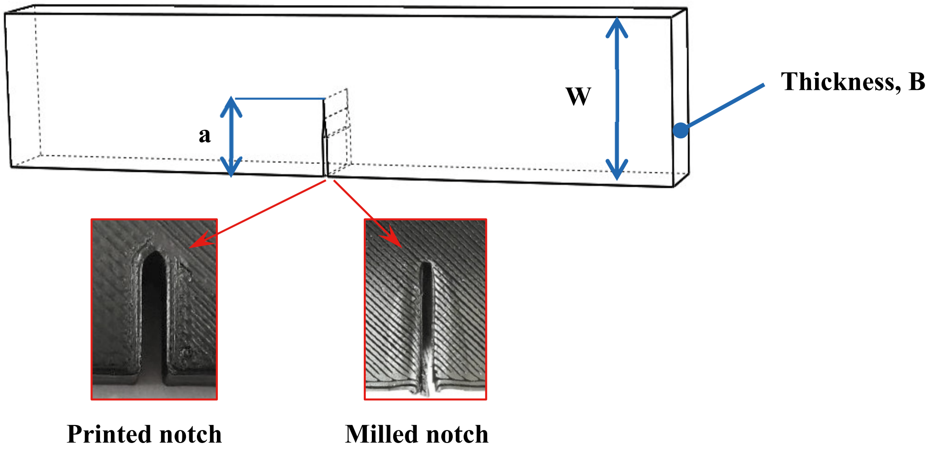

Fig. 1. The SENB specimen dimensions

The tests were performed by using Walter+bay 10 kN testing machine with a load speed of 2 mm/min at room temperature (T=22°C). Two loading configurations were considered:

- symmetric four point bending for the determination mode I fracture toughness, Fig. 2.a;
- asymmetric four point bending for the determination mode II fracture toughness, Fig. 2.b.

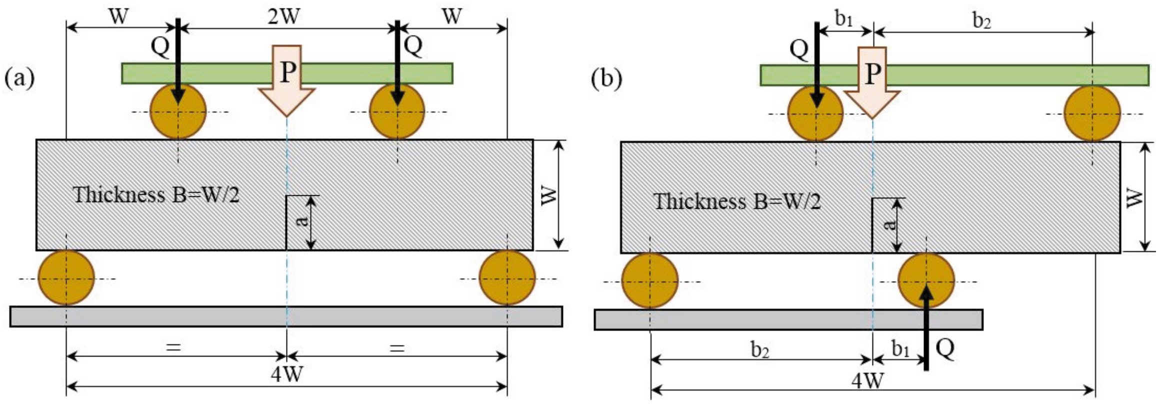

Fig. 2. Loading configurations: (a) Symmetric four point bending; (b) Asymmetric four point bending.

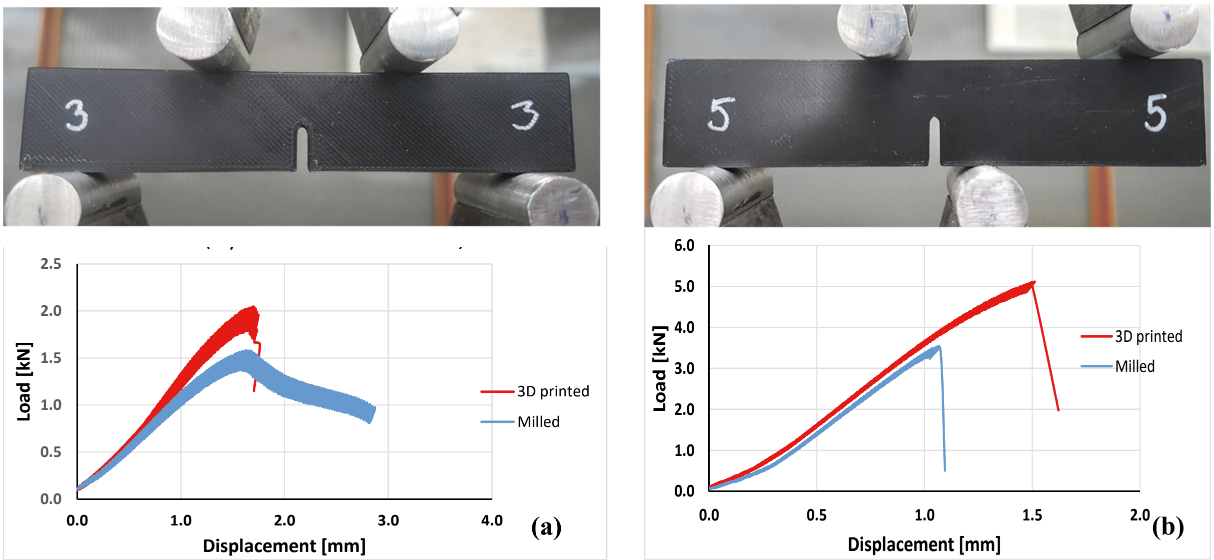

Fig. 3. Typical load – displacement curves: (a) Symmetric four point bending; (b) Asymmetric four point bending.

Quasi-brittle behavior was observed during testing with an abrupt decrease of force after reaching the maximum load value, particularly for the asymmetric four point loading case.

3. Results

The maximum load P_{max} determined from the load-displacement curves was used to calculate the fracture toughness.

The fracture toughness of the two loading cases were determined according to Murakami (1987):

- for mode I:

$$K_{IC} = \sigma\sqrt{\pi a} \cdot f_I\left(\frac{a}{W}\right) \tag{1}$$

with $$\sigma = \frac{3\,P_{max}}{B\,W} \tag{2}$$

$$f_I\left(\frac{a}{W}\right) = 1.122 - 1.121\left(\frac{a}{W}\right) + 3.74\left(\frac{a}{W}\right)^2 + +3.873\left(\frac{a}{W}\right)^3 - 19.05\left(\frac{a}{W}\right)^4 + 22.55\left(\frac{a}{W}\right)^5 \tag{3}$$

where a, B, W are the specimen's dimensions.

- for mode II:

$$K_{IIC} = \tau\sqrt{\pi a} \cdot f_{II}\left(\frac{a}{W}\right) \tag{4}$$

where $$\tau = \frac{Q}{B\,W} \tag{5}$$

$$Q = P_{max}\frac{b_2 - b_1}{b_2 + b_1} \tag{6}$$

$$f_{II}\left(\frac{a}{W}\right) = -0.2915 + 6.3229\left(\frac{a}{W}\right) - 9.12\left(\frac{a}{W}\right)^2 + 6.057\left(\frac{a}{W}\right)^3 \tag{7}$$

b_1 and b_2 are the positions of the supports for asymmetric loading, Fig. 2.b.

The fracture toughness results are shown in Fig. 4.a for mode I and in Fig. 4.b for mode II, respectively. It could be observed that higher fracture toughness were obtained for the 3D printed notches comparing with the milled ones. The results also show that the ratio between mode II and mode I fracture toughness is 0.55 for the 3D printed notch and 0.59 for the milled notch, respectively. Moreover, for both mode I and mode II loading, the specimens with printed notches highlights a lower dispersion of results (small scatter) compared to the milled notches. This aspect can be associated with the better accuracy of the 3D printer compared to that obtained by using the milling machine.

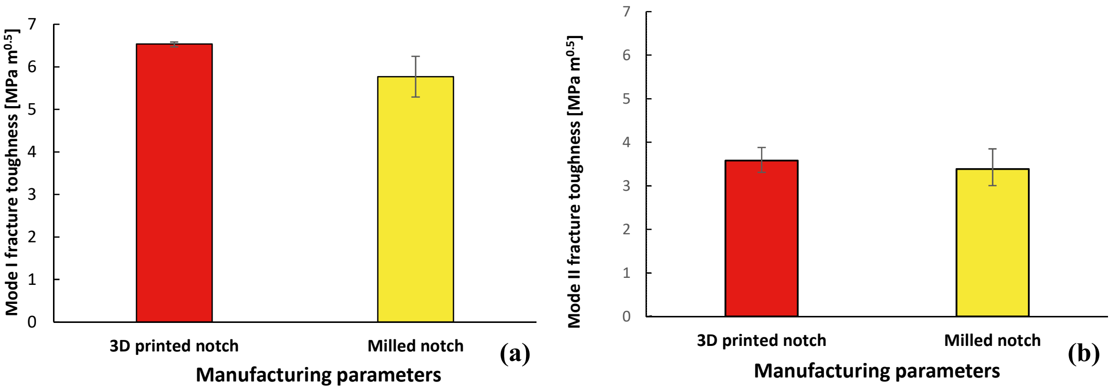

Fig. 4. Fracture toughness results: (a) K_{IC}; (b) K_{IIC}.

4. Conclusions

The paper presented the influence of different ways of inserting a notch on the mode I and mode II fracture toughness of PLA material obtained via FDM technology. SENB specimens were 3D printed with and without notch. The notch was inserted by milling in the un-notched specimens. Symmetric and asymmetric four point loading was applied in order to obtain the mode I and mode II fracture toughness, respectively. The average value obtained for the mode I fracture toughness was 6.5 MPa·m$^{0.5}$ for the 3D printed notch and 5.8 MPa·m$^{0.5}$ for the milled notch, respectively. These values fall in the same range reported by other published data ranging from 5 to 6.5 MPa·m$^{0.5}$ at 0° orientation, Arbeiter et al. (2018), and higher than 3.7 MPa·m$^{0.5}$ provided by Ahmed and Susmel (2018). It could be concluded that higher fracture toughness can be reached if the notch is directly 3D printed. As a practical recommendation, for complex structures, is better to create all geometrical features during 3D printing, without further machining.

The measured mode II fracture toughness was 3.6 MPa·m$^{0.5}$ for the 3D printed notch and 3.4 MPa·m$^{0.5}$, respectively, showing less influence of the notch insertion by machining for mode II. The ratio between mode II and mode I fracture toughness has been found to be between 0.55 and 0.59.

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References

Ahmed, A.A., Susmel, L., 2018. A material length scale–based methodology to assess static strength of notched additively manufactured polylactide (PLA), Fatigue and Fracture of Engineering Materials and Structures, 41(10), 2071–2098.

Ahmed, A.A., Susmel, L., 2019. Static assessment of plain/notched polylactide (PLA) 3D-printed with different infill levels: Equivalent homogenised material concept and Theory of Critical Distances, Fatigue and Fracture of Engineering Materials and Structures, 42(4), 883–904.

Aliha, M. R. M., Mousavi, S. S., Ghoreishi, S. M. N., 2019. Fracture load prediction under mixed mode I + II using a stress based method for brittle materials tested with the asymmetric four-point bend specimen, Theoretical and Applied Fracture Mechanics, 103, 102249.

Apostol, D.A. Stuparu, F., Constantinescu, D.M., Marsavina, L., Linul, E., 2016a. Experimental and XFEM Analysis of Mode II Propagating Crack in a Polyurethane Foam, Materiale Plastice, 53(4),685-688.

Apostol, D.A. Stuparu, F., Constantinescu, D.M., Marsavina, L., Linul, E., 2016b. Crack length influence on stress intensity factors for the asymmetric four-point bending testing of a polyurethane foam, Materiale Plastice, 53(2), 280-282.

Arbeiter, F., Spoerk, M., Wiener, J., Gosch A., Pinter, G., 2018. Fracture mechanical characterization and lifetime estimation of near homogeneous components produced by fused filament fabrication, Polymer Testing, 66, 105–113.

Ayatollahi, M.R., Aliha, M. R. M., 2011. On the use of an anti-symmetric four-point bend specimen for mode II fracture experiments, Fatigue and Fracture of Engineering Materials and Structures, 34, 898–907.

de Moura, M. F. S. F., Silva, M. A. L., Morais, J. J. L., Dourado, N., 2018. Mode II fracture characterization of wood using the Four-Point End-Notched Flexure (4ENF) test, Theoretical and Applied Fracture Mechanics, 98, 23-29.

Farah, S., Anderson, D.G., Langer, R., 2016. Physical and mechanical properties of PLA, and their functions in widespread applications – a comparative review. Advanced Drug Delivery Reviews 107, 367-392.

Gibson, I., Rosen, D., Stucker, B., 2015. Additive Manufacturing Technologies, Springer New York, New York.

Gordon, A.P., Torres, J., Cole, M., Owji, A., Zachary DeMastry, Z., 2016. An approach for mechanical property optimization of fused deposition modeling with polylactic acid via design of experiments, Rapid Prototyping Journal, 22(2), 1-18.

Khan, A.S., Aaqib Ali, A., Hussain, G., Ilyas, M., 2019. An experimental study on interfacial fracture toughness of 3-D printed ABS/CF-PLA composite under mode I, II, and mixed-mode loading, Journal of Thermoplastic Composite Materials, 1-24.

Kiendl, J., Gao, C., 2020. Controlling toughness and strength of FDM 3D-printed PLA components through the raster layup, Composites Part B 180, 107562.

Linul, E., Marsavina, L., Stoia, D.I., 2020. Mode I and II fracture toughness investigation of Laser-Sintered Polyamide. Theoretical and Applied Fracture Mechanics, 106, 102497.

Marsavina, L., Constantinescu, D.M., Linul, E., Stuparu, F.A., Apostol, D.A., 2016. Experimental and numerical crack paths in PUR foams, Engineering Fracture Mechanics, 167, 68-83.

Marsavina, L., Piski, T., 2010. Bimaterial Four Point Bend Specimen with Sub-Interface Crack, International Journal of Fracture, 164, 325–332.

Murakami, Y., 1987. Stress Intensity Factors Handbook, Pergamon Press, New York.

Razavi, S.M.J., Aliha, M.R.M., Berto, F., 2017. Application of an average strain energy density criterion to obtain the mixed mode fracture load of granite rock tested with the cracked asymmetric four-point bend specimens Theoretical and Applied Fracture Mechanics, 97, 419-425.

Sennan, P., Pumchusak, J., 2014. Improvement of mechanical properties of poly(lactic acid) by elastomer. The Malaysian Journal of Analytical Sciences 18(3) 669-675.

Stoia, D.I., Marsavina, L., Linul, E., 2020. Mode I Fracture Toughness of Polyamide and Alumide Samples obtained by Selective Laser Sintering Additive Process. Polymers, 12, 640.

Vălean, C., Marșavina, L., Mărghitaș, M., Linul, E., Razavi, J., Berto, F., 2020. Effect of manufacturing parameters on tensile properties of FDM printed specimens, Procedia Structural Integrity, 26, 313-320.

Wang, C., Zhu, Z.M., Liu, H.J., 2016. On the I-II mixed mode fracture of granite using four-point bend specimen, Fatigue and Fracture of Engineering Materials and Structures, 39(10), 1193-1203.

Yao, T., Ye, J., Deng, Z., et al., 2020. Tensile failure strength and separation angle of FDM 3D printing PLA material: Experimental and theoretical analyses. Composites Part B 188, 107894.

Yin, Y., Qiao, Y., Hu, S., 2019. Four-point bending tests for the fracture properties of concrete, Engineering Fracture Mechanics, 211, 371-381.

Yoshihara, H., Maruta, M., 2019. Mode I J-integral of extruded polystyrene measured by the four-point single-edge notched bending test, Engineering Fracture Mechanics, 222, 106716.