Consequence of the industrialized considerations on the flexible and splintering stuffs of FDM 3D-printed PLA samplings

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ABSTRACT

Fused Deposition Modeling (FDM), also known as material extrusion, is currently one of the most popular Additive Manufacturing (AM) technology on the market. In this study, two commercial FDM printers were used for layer-by-layer manufacturing of polylactic acid (PLA) Dog Bone (DB) and Single Edge Notched Bend (SENB) specimens, aimed at investigating the in influence of the manufacturing parameters on the tensile and fracture properties of PLA elements obtained by FDM technology. The effects of growing direction (horizontal and vertical), building orientation (0◦, 45◦ and 90◦), printer type, layer thickness (0.15 and 0.40 mm), specimen thickness (4 and 10 mm) and lament color (purple, white, black, gray, red, orange) are discussed in detail. Tensile tests were performed on DB specimens, while fracture mechanics tests on SENB specimens. Both the tensile and fracture properties of FDM 3D-printed PLA specimens have been found to be dependent on the investigated manufacturing parameters. From the microstructural analyses of the SENB fracture surfaces, it has been observed that the fracture mechanisms and crack propagation is a step-wise process. Finally, the material properties charts (Young's modulus and mode I fracture toughness versus tensile strength) are plotted.

KEYWORDS: Fracture Mechanics, Structural Integrity, Hydrogen Embrittlement, Nondestructive Evaluation

1.0 INTRODUCTION

Additive manufacturing (AM) is a process in which components are created layer-by-layer on a special platform through computer- aided design (CAD) and manufacturing and enables the production of components with a complex geometry. The AM technology is able to print almost any material (e.g. metals and their alloys, ceramics, polymers, biological materials, etc.), offering a wide range of products in different ranges of engineering applications, such as the automotive, aerospace, civil, medical, energy, sport industries [1 - 24]. AM technology can be clearly into different manufacturing processes including selective laser sintering (SLS), stereo- lithography (SLA), power fused deposition modeling (FDM), bed and inkjet head 3D printing (PIP) and liquid frozen deposition manufacturing (LFDM) [25 - 46]. The FDM technology, one of the most widely used in additive manufacturing, is based on the extrusion technique; its success is mainly due to its cost-effective way of printing and the ease of obtaining parts [46–58]. In FDM process, the 3D printing machine contains a plastic wire spool feeding a print head (nozzle) which extrudes a thin lament of melted plastic, forming, layer-by-layer according to a CAD le, the component [59–71]. Previous researches have shown that the main process parameters in the mechanical properties are the raster orientation, and the layer thickness and nozzle temperature [16–18]. It was also observed that, in addition to the mentioned printing parameters, the color of the lament, the in type, the building orientation and the printing direction have all a major in on the tensile properties of PLA parts [72–80]. In addition, several studies have reported that FDM components manufactured by using PLA laments show properties comparable to those made of bulk PLA [1–22]. The investigation of the tensile behavior of PC and ABS parts aimed at determining the degree of the anisotropy in 3D printed components, was carried out by Cantrell et al. [23-39]. They found that the raster orientation of the PC specimens leads to an anisotropic behavior, resulting in a directional variation of up to 20% of the strengths and elastic modulus. On the other hand, the authors observed that the values of Poisson's ratio and Young's modulus for ABS are slightly in by the raster and build orientation. et al. [40-57] investigated the in of the layer thickness and extrusion nozzle type on the strength of 3D-printed ABS parts. They noticed that the small thicknesses of the layers allow to obtain the best mechanical properties. They also found that an increase in nozzle temperature provide better melting between adjacent layers. In addition, the authors observed that the crack paths regularly occurred along the layer interface. Rodríguez-Panes et al. [58-67] investigated the tensile behavior (modulus of elasticity, tensile strength, tensile yield stress and rated tensile stress) of various PLA and

ABS components produced by the FDM technique. Specimens made of PLA were found to be stiffer and with higher tensile strength than ABS. On the other hand, the results obtained with ABS showed a lower variability than those obtained with PLA. Due to its superior strength/stiffness properties, bio-based, bio-compostable, and bio-compatibility PLA thermoplastic elements are widely used in various advanced applications. Nonetheless, in addition to the high strength and stiffness of this polymeric material, its brittle behavior has been shown to limit its lifespan [68-80]. Due to all the above-mentioned properties, PLA material is nowadays the most used in FDM printing. A reliable and con dent use of PLA elements thus requires the mechanical properties to be precisely known; among them, the fracture toughness of the components made of this material is an important parameter to study. However, the literature reports only a few results for mode II and mixed mode fracture toughness of PLA parts [1-33]. The Single Edge Notched Bend (SENB) was adopted for the determination of Mode I and Mode II fracture toughness using a symmetric and an asymmetric loading conjurations, respectively [34-56]. Particularly, the asymmetric loading was employed to determine mode II fracture toughness for different types of brittle materials [1-35] such as concrete [36-53], granite [54,69], wood [7-26], polyurethane foam [40–54], extruded polystyrene [43-52], polyamide [56-70], bi-material PMMA-Aluminum [44]. Starting from the published data, which are often affected by some ambiguities related to the in fence of certain process parameters [70-80] on tensile and fracture toughness properties, this paper experimentally investigates the tensile and fracture properties of PLA printed specimens. In particular, this study considers the assessment of the mode II fracture toughness, a parameter not yet investigated in the literature, of FDM printed PLA elements.

2.0 EXPERIMENTAL

The test specimens were fabricated via FDM using two different printers namely The G-codes for FDM process were generated with the help of slicer which results to be compatible with both the adopted printers; this allows obtaining more comparable specimens for sake of experimental results comparison. The constant process parameters for fabricating the test specimens are provided in Table 1. It should be noted that PLA lament (manufacturer PRUSA) of two different diameters (1.75 and 2.85 mm) were used for mentioned and 3D platform printers. It should be noted that the main goal of the current research is not to perform a direct comparison of the two utilized printers, as few process parameters (i.e. nozzle diameter and layer thickness are different) are not identical when producing samples using the two printers (see Table 1). All the printed specimens were fabricated through the thickness for producing SENB specimens, while both through the thickness and through the width printing have been assumed for preparing SENB specimens. For the tensile and fracture experiments, dog-bone (DB) and single edge notch bend (SENB) specimens were prepared, respectively.

Table 1
Process parameters for manufacturing test specimens for tensile tests by using the two different printers.

Process parameter	Prusa® i3 MK3	3D Platform® WN400
Nozzle diameter	0.4 mm	1 mm
Infill density	100%	100%
Nozzle temperature	220 °C	220 °C
Bed temperature	60 °C	60 °C
Raster angle	+45°/-45°	+45°/-45°
Build direction	Flat, printed through the thickness	Flat, printed through the thickness
Layer thickness	0.15 mm	0.40 mm

Fig. 1 illustrates the basic features of these two geometries. To compare the fracture resistance of the FDM parts in as-fabricated condition and in the case where the crack is introduced to the bulk material, two different sets of SENB specimens were considered. In the first type of SENB specimens, the notch was introduced in the CAD model which was used for FDM fabrication. In this case, the notch geometry has been introduced throughout the thickness and the two outer walls surround the notch area as well as the rest of the circumference. In the second type of SENB specimens, prisms with the same global dimensions as the SENB specimens were fabricated and the notch geometry was introduced by milling by using a tool of 0.6 mm thickness (see Fig. 1b). During the milling process, the coolant was continuously used to prevent excessive heating of the specimen in order to reduce the change of melting and prevent recrystallization in the notched area. Microscopic investigation of the notch tip show similar shape and dimensions of the notch for both printed and milled notch, the only difference is that for printed notch the contour of the specimen is continuum, while for the milled one the deposited laments in the notch area are cut.

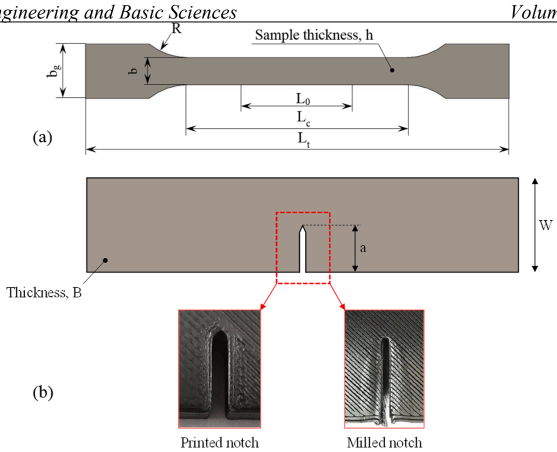

Fig. 1. Schematic illustration of PLA-FDM specimens: DB (a) and SENB (b) specimens.

3.0 RESULT

All quasi-static tests were carried out at room temperature under displacement control, with a displacement rate of 2 mm/min. Clip-on extensometers with 30 mm measuring length were used to record the displacements used to calculate the Young modulus, in accordance with ISO 527–1 standard. The tensile strength was estimated by dividing the maximum load to the cross section of the DB specimen. Five specimens were tested for each set of manufacturing parameters. The reported results are the average values. Two growing directions of horizontal (Fig. 2a) and vertical (Fig. 2b) were considered for fabrication of the test specimens.

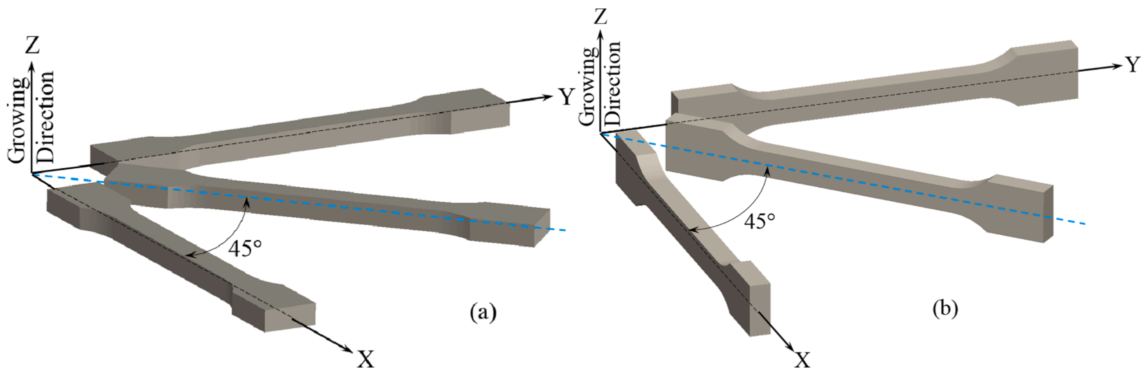

Fig. 2. Printing direction and orientation: Horizontal (through the thickness) (a) and Vertical (through the width) (b) growing. 4

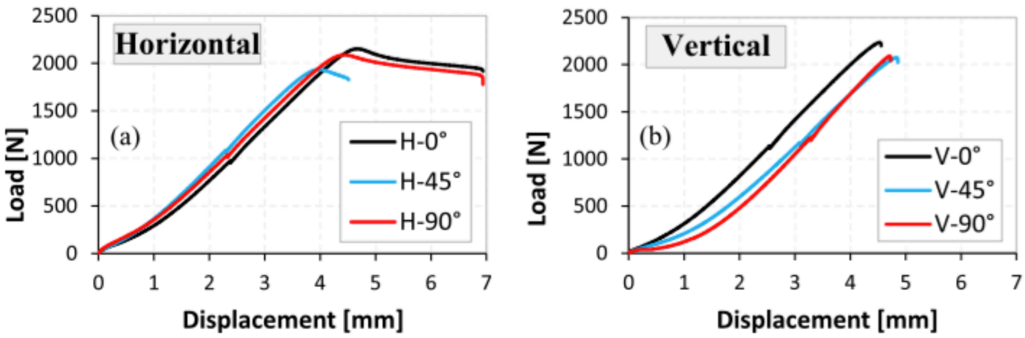

Fig. 3. Load - displacement curves obtained from the tensile tests: horizontal (a) and vertical (b) growing direction.

Typical load–displacement curves recorded during tensile testing are shown in Fig. 3. A quasi-brittle fracture can be observed for the specimens grown in the vertical direction (through the width) and in the horizontal direction. The results of Young modulus and tensile strength obtained for the specimens manufactured with printer for specimens with a thickness of 4 mm, and width of 10 mm are shown in Fig. 4. Higher Young modulus values were obtained for all three considered orientations for the vertical grown specimens; compared with the values related to the horizontal ones, it has been found an increase of about 3.6% for 45 orientation and approximately 6% higher for 0 orientation. Also, it could be observed that Young modulus values are not significantly in nuanced by the orientation, the results are in the scatter of experimental determination for both horizontal and vertical directions. Broken DB specimens after tensile tests for both vertical and horizontal growing directions are shown in Fig. 4. It could be observed that the fracture plane for horizontal growing direction is at 45 for 0 and 90 specimen orientation, while for the 45 specimen the orientation the fracture surface is normal to the loading direction. In the case of vertical growing direction, the fracture plane is normal to the loading direction for all growing orientations. Typical load–displacement curves recorded during tensile testing are shown in Fig. 3. A quasi-brittle fracture can be observed for the specimens grown in the vertical direction (through the width) and in the horizontal direction.

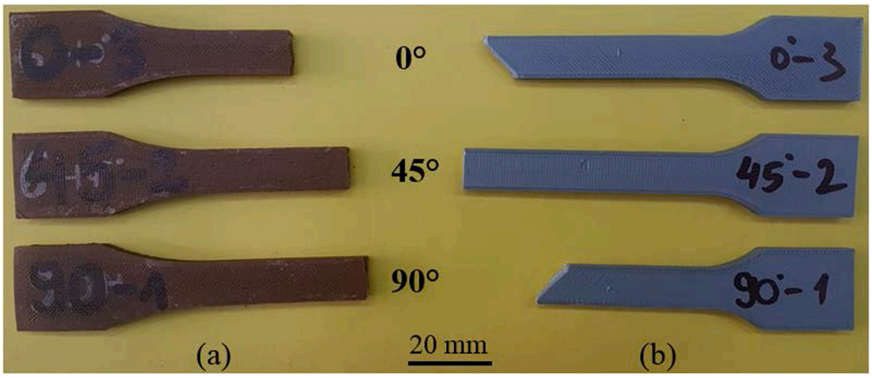

Fig. 4. Fractured DB specimens after tensile tests for vertical (a) and horizontal (b) growing directions.

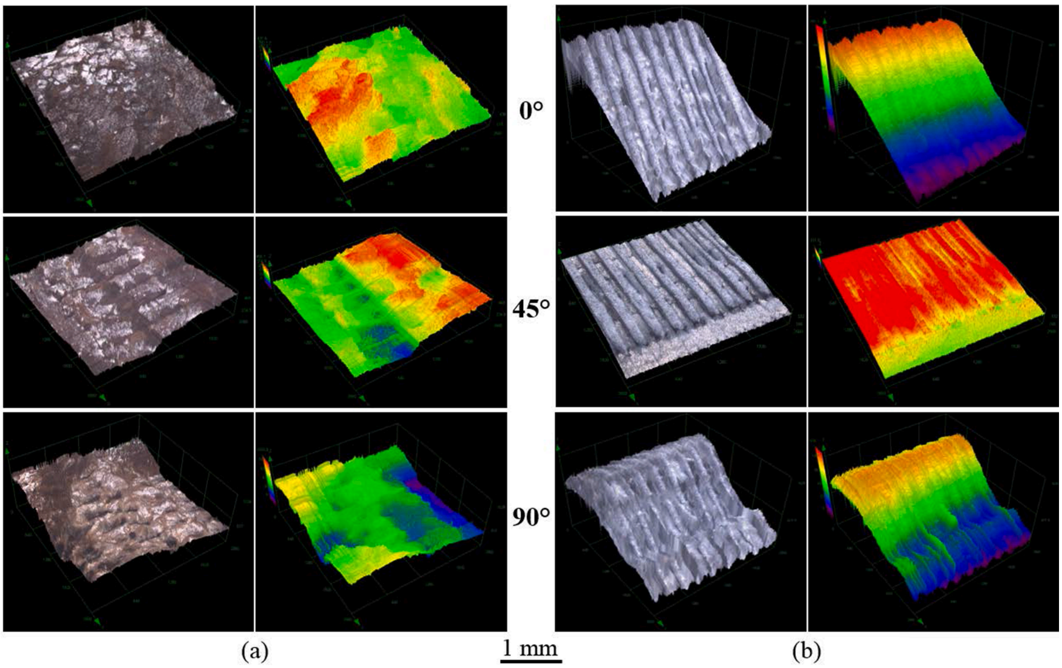

Fig. 6. Fracture planes of DB specimens for vertical (through the thickness) (a) and horizontal (through the width) (b) growing direction.

The fracture planes of the DB specimens are directly related to the orientation of the printed layers with respect to the loading direction. The 3D printed specimens were investigated after tensile tests using Confocal Laser Scanning Microscopy (CLSM). The specimens were oriented up in order to be evaluated using 3D measuring laser microscope (2020 last edition, Cannon, Japan) for 3D characterization of the fracture surfaces. The scanning was performed at 50X magnification and the investigated areas were about three dimensional around 50 millimeters. A detailed optical 3D pro les of the fracture zones are shown in Fig. 5. The images are taken from the fracture area of the DB specimens and perpendicular to the loading direction. Identical examples geometries, characterized by a thickness equal to 4 and 10 mm, layer thickness of 0.15 mm (considered printer) and 0.40 mm (3D Platform printer), respectively, were manufactured by using the two above-mentioned printers. For this study, specimens made of black color lament grown horizontally have been prepared. A comparison of the mechanical properties in term of the Young modulus is shown in Fig. 4, while the tensile strength is shown in Fig. 5. It can be observed that the Young modulus increases with the specimen thickness; further, for both thicknesses higher values of approximately 7.6% were obtained for the specimens printed on 3D platform. Higher tensile strength values (+10.4% for specimens with 4 mm thickness and + 5.2% for specimens with 10 mm thickness) were obtained for considered printer. The tensile strength values on thicker specimens resulted to be higher of about 12% for considered printer, while an increase of 17.4% was observed for 3D Platform printer. The Young modulus and tensile strength results are shown in Fig. 5, where some results from the literature are also reported. It can be observed that the maximum Young modulus was obtained for red specimens 3379.8 MPa, while the minimum one, equal to 2855.0 MPa, was obtained for the orange specimens. The highest values of tensile strength, resulted to be above 50 MPa, were observed for purple and red specimens.

4.0 CONCLUSIONS

We have investigated the in hence of some manufacturing parameters on the tensile and fracture properties of PLA specimens obtained via FDM technique. Higher stiffness was obtained for vertical growing direction, higher ultimate tensile strength was obtained for horizontal direction, respectively. Tensile tests results highlighted the in hence of specimen orientation, layer thickness and lament color on Young modulus and tensile strength. propagation occurs along the symmetric induced stress yield in the specimens. In this case, the crack growth resistance is lower and it can be observed that the fracture happens at lower load and a lower elongation at failure is observed. Using the same argument as the mode I results, in the specimens where the angle between the maximum tangential stress and the raster angles is smaller, the crack resistance is expected to be lower. The presence of the outer walls of the specimen is very important when it comes improving the mechanical properties. Regardless of the loading mode, in order the crack to growth inside the bulk material, it must break and propagate through these walls. When the notch is created by milling, the outer walls do not exist in the notch region, meaning that this barrier is removed, making for the crack easier to start propagating under a lower load level. This has resulted in lower fracture toughness values for the milled specimens. One important point for the milled notches is the higher standard deviation for the fracture toughness observed in these specimens. The presence of the uniform outer wall is an element making the specimens be in almost same outer condition. By removing that wall, any factor can be amplified, and possibly large defects within the bulk material and changes of temperature during the milling can be responsible for a huge scattering of the measured quantities. By looking at the fracture surface a clear trend of the bar failure can be observed; it can be appreciated that the bars were the load bearing members in the specimens. In this scenario, having larger bars for the same volume of the specimens, can improve the load bearing of the element. The fracture and crack propagation take place as a step-wise process. If in each step a thicker bar has to be broken for the crack to propagate, it would require a higher applied load, which consequently results in a higher fracture toughness. The other possible explanation can be the crystallization taking place during and after the printing. Depending on the printing speed, layer height and some other parameters, the heat history can be different in FDM parts. If the average induced heat (residual heat) in the larger parts has been higher, that could result in higher mechanical properties and better bonding of the layers.

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