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Characterization of a Polylactic acid (PLA) produced by Fused Deposition Modeling (FDM) technology

Domenico Corapi^{a*}, Giulia Morettini^a, Giulia Pascoletti^a, Chiara Zitelli^a

^aUniversity of Perugia - Department of Engineering, Via G. Duranti, 93, Perugia 06125, Italy

Abstract

PLA is an organic polymer that lends itself to multiple applications. It is commonly used in fused deposition modeling technology (FDM), which operates by depositing successive layers of material. The material extrusion, in the form of a wire, follows an imposed pattern, which influences the static and dynamic behavior of the final component. In the literature there are many works concerning the mechanical characterization of the PLA but, due to the natural orthotropy of the FDM process and, above all, to the ascertained influence of the particular technical system with which the operations are performed, it is necessary to characterize the extruded material through different metrological techniques. In order to allow the use of this technology for structural elements production, in the present work, quasi-static tests have been carried out to characterize the material and the process considering the three spatial growth directions (x, y and z). In particular, uniaxial tensile tests were performed for the determination of mechanical strength, modulus of elasticity and percentage elongation.

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Keywords: 3D Printing; Tensile strength; Rapid prototyping; acrylonitrile; butadiene styrenepolylactic acid; FDM

1. Introduction

Additive Manufacturing (AM) is a technology that, starting from a CAD model, creates objects through addition of materials, in opposition to subtractive technologies, where a cutting tool is used to obtain the final result.

* Corresponding author. Tel.: +39 328 262 5320.

E-mail address: domcorapi@gmail.com

Since its first appearance in the manufacturing scenario as stereolithography (Hull, (2015), (1986); Hull et al., (1993)), the 3D printing techniques have been improved and nowadays are one of the most important subjects in many engineering fields.

The increasing interest in this technology is due to the main advantage that it offers in terms of design flexibility. Indeed, the material's asportation technologies have intrinsic limitations related to the impossibility for the cutting tool to reach every point of a part whit a complex shape.

The principle of the slice-by-slice, which is the basis of AM, makes it possible to obtain, at the end of the production process, a fully functional assembly, building one part connected to another through the aid of support structures; moreover, the additive manufacturing technique allows using multiple materials for the creation of the same part.

All these properties have encouraged the development of the technique for its application in many industrial fields: biomedicine and biomechanics (Ji and Guvendiren, (2017); Knowlton et al., (2016); Murr, (2016)), aerospace (Kobryn et al., (2006); Murr, (2016)), automotive (Talagani et al., (2015)), civil engineering (Labonnote et al., (2016)), food (Lipton et al., (2015)). The main technologies for the production with plastic materials are stereolithography (SLA) (Jacobs et al., (1992)), fused deposition modeling (FDM) (Masood, (1996)) and selective laser sintering (SLS) (Mukesh, (1995)). The McKinsey Global Institute, considers a growth of the 3D printing global market at the level of 230-550 billion USD in 2025 (Gebler et al., (2014)), so a particular attention to this technology must be paid. FDM technology (Stratasys Inc), consists of a layer by layer manufacturing process, so it determines orthotropic mechanical properties along the building axis (z). The raw material is a filament of a specific diameter, that is extruded through a calibrated hot nozzle and deposited following a given pattern. After the layer cooling and solidification phases, the movable printing platform moves in the z direction and a new layer is extruded; this sequence of operations is repeated until the whole part or assembly has been completed. The main thermoplastic materials used are PLA, ABS, PET, Nylon, HIPS, ASA, Polycarbonate, Polypropylene, PVA, metal/wood/carbon fiber filled plastics. One of the major shortcomings of the AM in general and of the FDM technology in particular, is the use of 3D printed components for industrial applications. Indeed, the definition of the mechanical properties of the final product is not trivial, because of their strong dependence on the printer model and machine printing parameters.

In the present study a first step for the mechanical characterization of 3D printed parts is exposed. The work is focused on the analysis of the static mechanical properties of PLA (polylactide polyester) due to its interesting properties in terms of nontoxicity, biodegradability, ease of extrusion also at low temperature and negligible shrinkage effect after cooling. Three perpendicular growing directions have been investigated in order to analyze the effects of this parameter on the static tensile behavior of the material.

2. Materials and Methods

A commercial PLA filament provided by Henan Suwei Electronic Technology Co., LTD, Zhengzhou City, Henan Province, China, has been extruded with a Creatbot F430 FDM machine, for the production of specimens with a dumbbell geometry according to ASTM D638-14 type I for static tensile tests. In Table 1, the main material's parameters suggested by the filament provider are described.

Table 1. Suggested parameters for PLA.

Average filament diameter	Nozzle temperature	Hot bed	Platform adhesion type	Fully enclose or not
1.75 mm	190 °C – 210 °C	None / 45 °C	None / raft	Can open

Some studies (Kotlinski, (2014); Lanzotti, (2015)) have dealt with the analysis of FDM printed PLA mechanical properties (Table 2).

Table 2. Typical mechanical properties for PLA parts manufactured by FDM.

Properties	PLA
Tensile strength (MPa)	15.5 – 72.2
Tensile modulus (GPa)	2020 - 3550
Elongation at break (%)	0.5 – 9.2
Flexural strength (MPa)	52 – 115.1
Flexural modulus (GPa)	2392 - 4930

CAD files of the specimen's geometry, have been created with DesignSpark Mechanical v4.0 and then exported as an STL format file. In figure 1, dimensions of tensile specimen are shown.

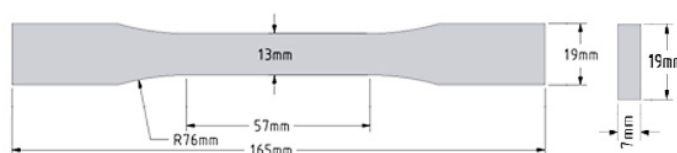


Fig. 1. Tensile test specimen's geometry and dimensions.

6 specimens for each direction (horizontal, on side, vertical, figure 2) have been printed for a total of 18 samples for the static tensile test.

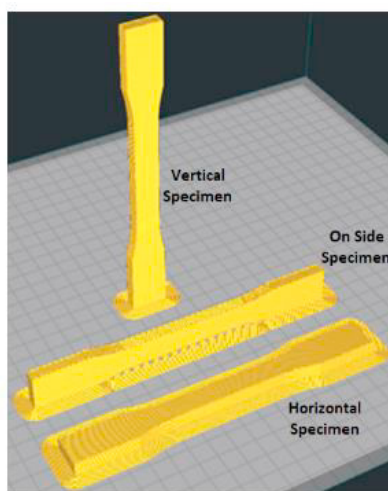


Fig. 2. Three orientations of specimens on the printing plate.

Specimens have been manufactured using a Creatbot F430 dual extrusion 3D printer (Henan Suwei Electronic Technology Co., LTD, Zhengzhou City, Henan Province, China), with an extruder of 0.4 mm diameter installed. Ultimaker Cura printing control software (free open source, version 4.0.0-BETA) has been used for the pre-processing of CAD models, in order to properly prepare the geometry for the manufacturing process and for the generation of the G-code file. PLA mechanical performances are affected by moisture; thus, all samples have been manufactured immediately after that the original vacuum bag, where the filament was placed, has been opened. After that, final products have been stored in a dry box, and sacrificial bases (brims) have been removed before final testing. In table 3, technological parameters applied for the manufacturing process are summarized.

3. Tensile tests

The results of the tensile tests describe most of the fundamental mechanical proprieties of the tested material and define the essential engineering behavior, useful for the designer activity. For these reasons uniaxial tensile test is the most commonly used for obtaining mechanical characteristics of plastic materials. The reference standard for the determination of static properties measured via tensile test is the ASTM D638 (American Society For Testing and Materials, (2014)). In the present paragraph, the ASTM has been used to determine the ultimate tensile strength, Young's modulus and the maximum elongation of the set of 18 specimens, whose geometry and manufacturing methods are fully described in the previous section. This investigation has the final aim of establishing the relationship between the printing orientation directions of the specimen to the static properties.

Table 3. Set of used technological parameters

Filament diameter	1.75 mm
Layer thickness	0.2 mm
Extrusion temperature	210 °C
Nozzle diameter	0.4 mm
Build orientation	Horizontal, On side, Vertical
Hatching	100%
Infill orientation	±45°
Speed	60 mm/s
Cooling fan speed	100%
Brim	Activated
Number of shells	2
Top solid layers	2
Bottom solid layers	2
Bed temperature	45°C

4. Results and discussion

To perform the tensile tests, an Instron 3382 testing machine was used, with load frame actuated through the Instron control software. A 100 kN load cell was installed for loads control, while strains have been measured using an Instron W-6280 extensometer, as shown in figure 3a. This type of machine has two crossheads, one is adjusted for the length of the specimen and the other is driven to apply tension to the test specimen. The complete set of 6 specimens for each direction was tested at chosen speed of 2 mm/min, as suggested by standard ASTM D638. Results in term of ultimate tensile strength with respect to strain for the three different set are show in figure 3b.

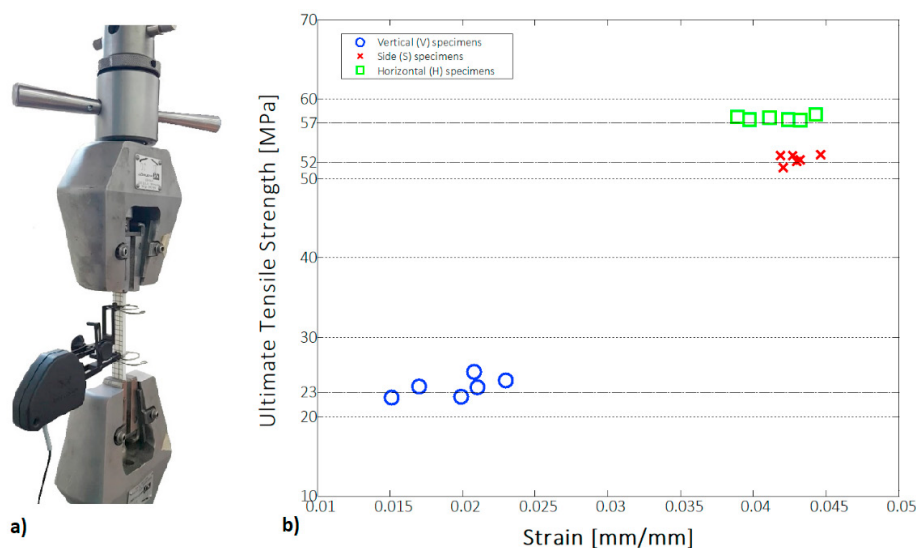


Fig. 3. (a) Configuration of the tensile machine; (b) Strain-UTS results.

Other mechanical parameters derived from postprocessing of collected testing data are reported in table 4. In particular, in addition to the mean values of the ultimate tensile strength and the strain of the presented data sets, it is also reported the mean value of the modulus of elasticity and of percent elongation at maximum stress for each test case. Moreover, statistical standard deviation for each corresponding parameter are reported to better analyse the dispersion of the data.

Table 4. Mechanical Characteristics resulting from tensile test.

	Ultimate Tensile Strength [MPa]		Strain [mm/mm]		Percent elongation at maximum stress [%]		Modulus of Elasticity [MPa]	
	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Vertical (V)	23.75	1.24	0.0195	0.003	1.95	0.28	2363	75
On Side (S)	52.40	0.57	0.0429	0.001	4.29	0.10	2415	78
Horizontal (H)	57.58	0.29	0.0416	0.002	4.16	0.28	2571	74

Data from testing showed some variation between the three different sets; this is principally due to the fact that the building direction of the specimen on different planes changes the amount of extruded filament aligned with loading and this significantly affects tensile strength (Tymrak et al., (2014)). In particular, specimens printed in horizontal direction exhibit the greatest ultimate tensile strength (57.58 MPa) and a mean value of the elastic modulus equals to 2571 MPa, in accordance with the range declared by the supplier of the PLA filament. The mean UTS value of the on side specimens do not deviate much from the maximum value registered for the horizontal specimens, while the mean UTS value of the specimens vertically printed diverges significantly from it, showing an UTS that is 41.25% less than the horizontal ones. Nevertheless, also in this unfavourable case, the elasticity modulus falls within the supplier's range. The strain and the percentage elongation show how the behaviour of the vertical specimen is more brittle if compared with that of the horizontal or on side specimens. All the results are comparable with others existing in literature (Graupner et al., (2009); Kobryn et al., (2006)).

5. Fracture location analysis

In figure 4, fracture visual analysis has been summarized, showing fracture distance from the same specimen's end for each growing direction set.

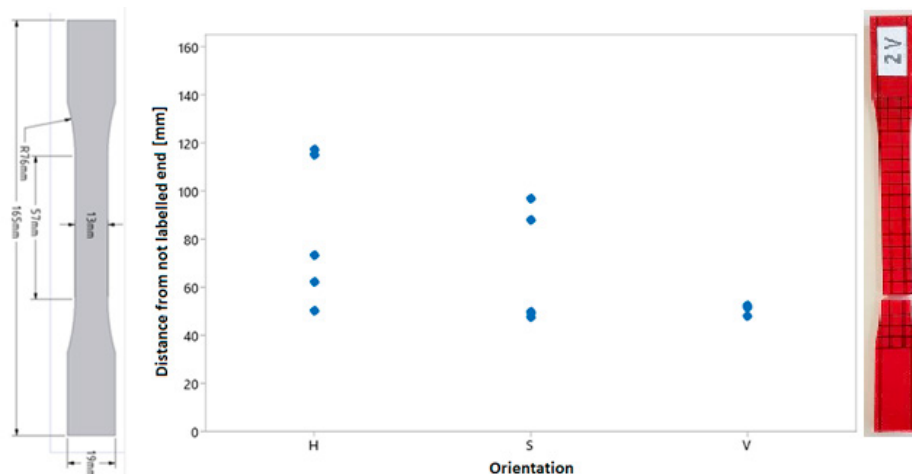


Fig. 4. Fracture positions for growing direction set.

Through this qualitative analysis of the location of the fracture point, a different behavior between vertical specimens and the other two sets (on side and horizontal) is evident. In vertical samples, the fracture distance from the same specimen's end is consistent. It is supposed that the width reduction from the grip zone to the calibrated central part, generates a tension concentration zone. Indeed, even if the CAD file is defined locally by a curve, the manufactured part shows the typical layers-shaped geometry that corresponds, in vertical samples, to the layer growing direction (z axis). In the other two set of specimens the fracture point is more randomly positioned along the specimens.

6. Comments and future research

A first step of the mechanical characterization of 3D printed PLA test specimens on a Creatbot F430 machine, has been performed. PLA extruded material has been characterized through quasi-static uniaxial tensile tests, considering the three spatial growing directions (x, y and z) and determining ultimate tensile strength, modulus of elasticity and maximum percentage elongation. Data analysis has pointed out that the highest UTS and elastic modulus are associated to the horizontal specimens. Moreover, the fracture point location analysis, has shown a different behaviour between vertical specimens and the other two sets (on side and horizontal), which are characterised by a more random fracture point location. With this work, basic mechanical proprieties of the PLA materials and their correlation with the building orientation have been quantified. These preliminary results provide a starting point for a material property database and guideline for the designers, as well as a development tool for printing parameters technologists. The next steps will be to obtain, through random fatigue tests and Dynamic Mechanical Tests (DMA), the dynamic behaviour of printed specimens, in order to expand the material database and improve the technological parameter set, useful for 3D components structural applications.

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