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EXPERIMENTAL STUDY OF THE TENSION MECHANICAL PROPERTIES OF PETG AND PLA MATERIALS USED IN 3D PRINTING

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Abstract: *This paper investigates the mechanical behavior of 3D-printed Polyethylene Terephthalate Glycol (PETG) and PLA (Polylactic Acid). The aim of this study is to provide information on how the tension mechanical properties of 3D-printed PETG and 3D-printed PLA are affected by the irregularities in the printing material and from the printing process, using samples with the infill parameter set to 100%. PETG and PLA exhibited elastoplastic behavior during tension tests, characterized by an initial linear elastic region followed by plastic deformation before fracture. Obtained results indicate that samples made with PLA exhibit superior mechanical properties compared to those made with PETG, but also with important variations between samples from the same material.*

Keywords: *tension test; mechanical properties, 3D printing material, stress, strain*

1. INTRODUCTION

During the last decades, the 3D printing technology started to become more available, affordable and more used, and started to replace the traditional manufacturing methods, which was more expensive and time consuming. This is even truer when discussing about prototypes, parts with complex geometry, test components with variable dimensions or features etc. This advantages are useful in many industries as automotive, aerospace, architecture and constructions etc.

Modern 3D printing technology can use different materials in different forms (solid, powder, melt, and liquid) and presents a variety of strength levels.

Fused deposition modelling (FDM™) is one of the most used 3D printing technologies, while is relatively cheap and reliable.

The 3D printing FDM process is using a thermoplastic filament which is melted and extruded through a nozzle. The size of the nozzle determines the thickness of the printed layers, printing time tolerances. The mechanical properties of printed parts are influenced by processing conditions, including temperature, layer thickness and speed [1].

Tensile experiments have been performed to compare FDM materials, contributing in understanding the mechanical behavior and performance of different these printed polymers. The mechanical properties of FDM-printed polymers are affected by layer thickness, orientation angles, and air gaps.

One of the most popular, affordable, and used thermoplastic materials currently available are polylactic acid (PLA) and polyethylene terephthalate glycol (PETG). Other available materials have some limitations: high extrusion temperatures, low mechanical modulus, toxic chemicals, high density etc.

Despite the variety of filaments available, comprehensive information on their properties is often limited and is given for the raw material, while the mechanical characterization of printed samples is insufficient. Further research is needed to develop test standards based on the material’s intended use [1].

Therefore is necessary to conduct tests on samples to determine the material’s mechanical properties. The aim of this presented study is to investigate the variation of material properties with the irregularities found in the printing wire and in the printing process.

2. MATERIAL DESCRIPTION

The Prusament PLA (polylactic acid) by Prusa Polymers (Prague, Czech Republic), is suitable for a multitude of applications, but its main purpose is for small and large 3D extrusion based FDM printing of functional and mechanical parts. It is biodegradable, easy to print and very strong, while having a low thermal expansion coefficient (reduced warping). It supports only wet sanding and is not suitable for outdoor application due to temperature restrictions.

The Prusament PETG (polyethylene terephthalate glycol) by Prusa Polymers (Prague, Czech Republic), is suitable for a multitude of applications, but its main purpose is for 3D extrusion based FDM printing of functional and mechanical parts. Thanks to good layer adhesion it is also suitable for waterproof prints. It supports also both dry and wet sanding. Compared to other similar materials, PETG is more heat resistant, more flexible and less brittle.

The properties of the selected materials are summarized in Table 1.

Table 1. Properties of PETG and PLA

Properties	**PETG**	**PLA**
Melting point [°C]	245 to 260	150 to 160
Injection mould temperature [°C]	200-255	178-248

Density [g/cm^3]	1.27	1.25
Crystallinity	3-11%	<10%
Melt flow [g/min]	0.8	0.6

3. SAMPLES PREPARATION

For this study, the test samples are produced using the Original Prusa i3 MK3S 3D printer. Printing parameters for PETG and PLA filaments were selected as presented in Table 2.

Table 2. Properties of PETG and PLA

Printing properties	**PETG**	**PLA**
Bed temperature [°C]	60	60
Layer thickness [mm]	0.15	0.15
Infill density	100%	100%
Fan speed	100%	100%
Deposition speed [mm/s]	200	200
Deposition temp [°C]	250	245
Extruder temperature [°C]	230-240	215
Print speed for perimeters [mm/s]	50	50
Print speed for infill [mm/s]	56	56

The test sample geometry (see Fig. 1):

- total length L = 84 mm,
- minimum cross-section width w = 10 mm,
- cross-section thickness t = 4 mm (total thickness),
- minimum cross-section area A = 40 mm2.

A density of 100% means that all available volume in one ply (each ply has a constant thickness, therefore a volume) is filled with material.

Orientation 0 means that the fibers (filament laid by the printing head) are aligned with the test sample's longitudinal direction, Fig.1

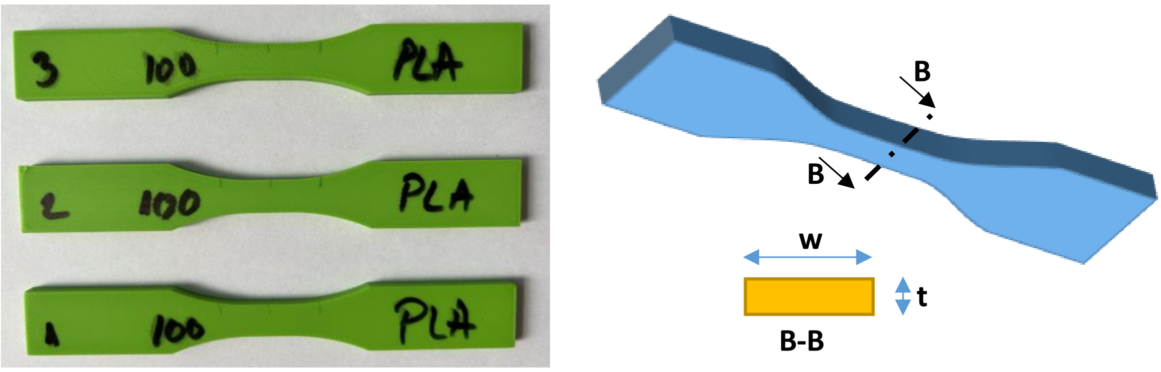

Figure 1: Printed test samples (example for PLA) and geometry

4. TRACTION TEST SETUP

The traction test was performed with an LS100Plus Universal Materials Testing Machine (100 kN maximal applied force), produced by Lloyd Instruments, Great Britain, as presented in Fig. 2.

Other parameters of the test machine: test speed accuracy: <0.2%; maximum travel: 840 mm; load resolution: <0.01% of the used force cell; extension resolution: <0.1 micron; force cell: XLC-100K-A1; analysis software: NEXYGENPlus Data Analysis Software.

The test sample is clamped on both ends. While one end is fixed, the other is pulled away, leading to the elongation of the test sample.

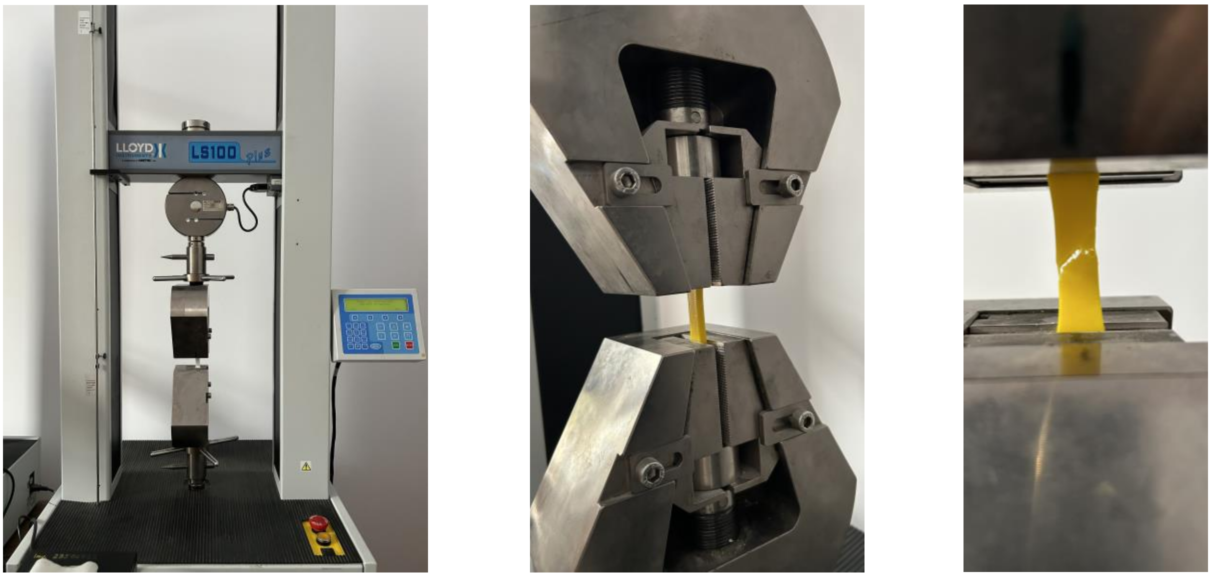

Figure 2: Traction test machine LS100Plus and traction test until failure

The machine direct outputs are: applied force F measured in [N] (incremented from 0 until it reach material failure) and extension Δl measured in [mm], as presented in Fig. 3. Knowing the geometry and the machine outputs, the material strength properties for tension (σ_y yield stress, σ_u ultimate stress, ε strain, E longitudinal elasticity modulus) can be computed.

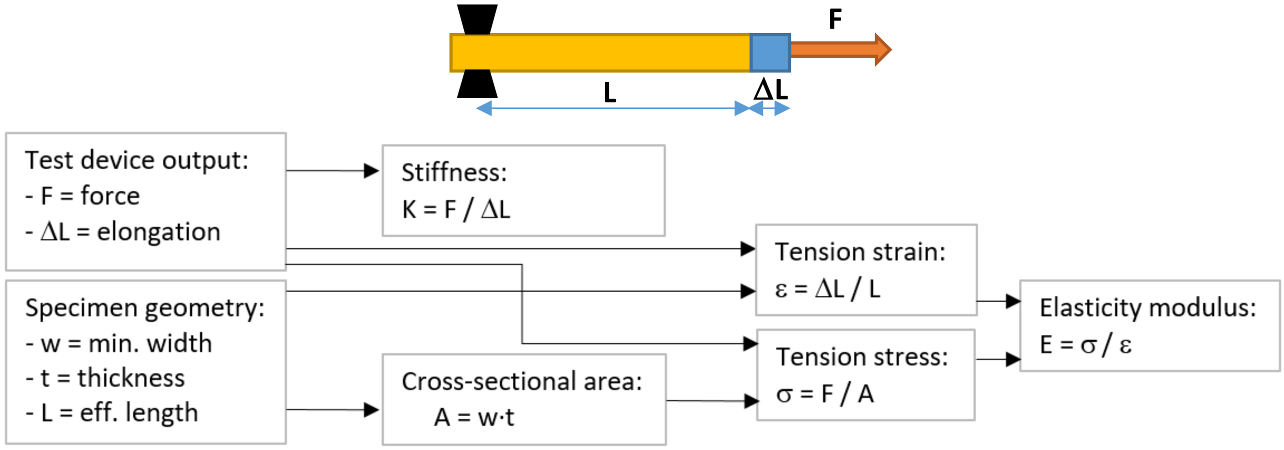

Figure 3: Traction machine outputs and calculated tension strength parameters

5. RESULTS AND DISCUSSIONS

Test samples present a linear elastic region (important for applications) and then transition into a plastic behavior, where remnant deformations occur. The extension then increases until failure, but the material's loading capabilities decrease abruptly.

Some of the tested samples are shown in Fig.4. The typical PETG and PLA material behavior (stress-strain curve) is presented below in Fig. 5.

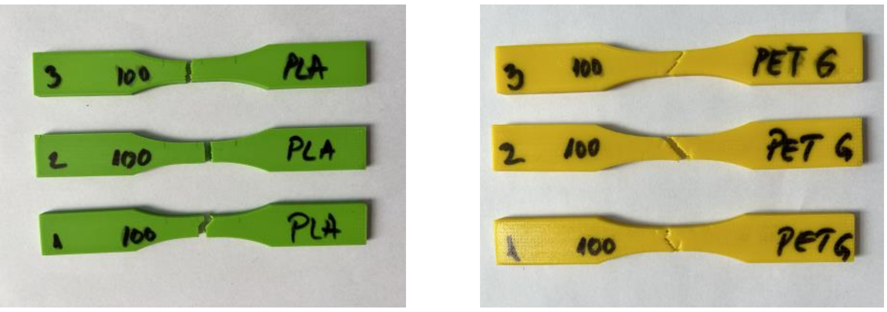

Figure 4: PLA / PETG tested samples after tension failure

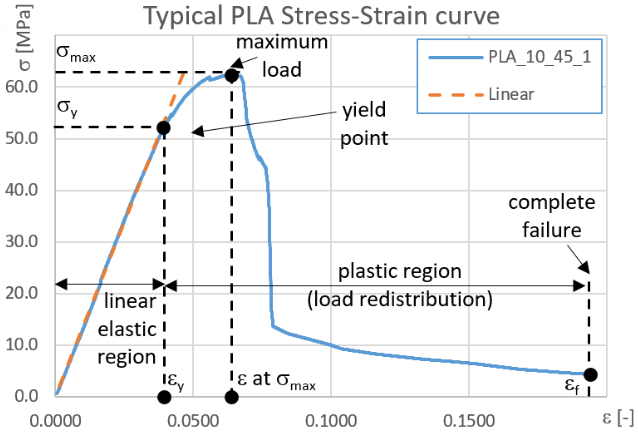

Figure 5: Typical material behavior - stress-strain curve (PLA shown, PETG similar)

As presented in Fig. 5, the maximum loading (σ_{max}) occurs just before failure. The rupture is quick, and the load capability of the part is decreasing rapidly since the sectional area that can carry loads is continuously reducing.

But, even if the part has not failed in the region just before the peak, remnant deformations occur. These deformations will make the part not to function correctly. The material can still be unpredictable, and in this situation, this value cannot be taken into account as an allowable limit because cracks can appear at the level of the structure, passing into the plastic region [2].

Thus, for engineering, a more relevant material parameter is the yield stress σ_y. Up until this point, the stress-strain varies almost linear and will not produce remnant deformations. The traction test results, for each sample type from PETG and PLA, are presented in Fig. 6. The analysis of the average values was followed to ensure the stability of the printed material, without changes occurring in the material. The traction test material parameters for each sample and as average are presented in Table 3 and Table 4.

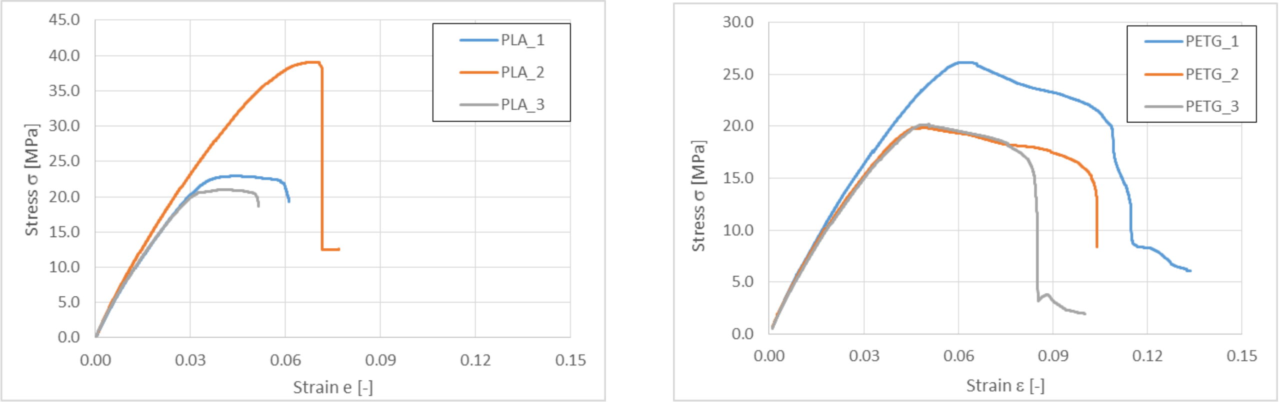

Figure 6: PLA (left) and PETG (right) - Material properties variation due to irregularities

Table 3. Properties of PETG and PLA

Test sample	Values at Yield Point				Values at Maximum Load / Stress			
	σ_i [MPa]	E [MPa]	K [N/m]	ε [%]	σ_i [MPa]	E [MPa]	K [N/m]	ε [%]
PLA_1	**24.1**	**766**	**1276**	**0.0315**	**39.1**	**581**	**968**	**0.0525**
PLA_2	**12.9**	**757**	**1262**	**0.0171**	**20.9**	**529**	**882**	**0.0284**
PLA_3	**14.1**	**740**	**1233**	**0.0191**	**22.9**	**518**	**863**	**0.0318**
Avr	**17.1**	**754**	**1257**	**0.0225**	**27.6**	**543**	**904**	**0.0376**

Table 4. Properties of PETG and PLA

Test sample	Values at Yield Point				Values at Maximum Load / Stress			
	σ_i [MPa]	E [MPa]	K [N/m]	ε [%]	σ_i [MPa]	E [MPa]	K [N/m]	ε [%]
PETG_1	**16.3**	**546**	**910**	**0.0298**	**26.1**	**434**	**724**	**0.0496**
PETG_2	**12.3**	**539**	**898**	**0.0229**	**19.9**	**400**	**667**	**0.0381**
PETG3	**12.5**	**521**	**868**	**0.0239**	**20.2**	**397**	**662**	**0.0398**
Avr	**13.7**	**535**	**892**	**0.0255**	**22.1**	**411**	**684**	**0.0425**

6. CONCLUSIONS

As observed above, the computed material strength properties for tension present a high variation (20%-40%). These are due to a multitude of factors from the entire process, starting with the irregularities in the wire material, the microscopic problems and small local differences in the actual 3D printing process, the differences in temperature between the printed layers and how this is affecting the bonding between the layers etc. All of these factors are adding, and in some instances, the differences in results could be high.

Therefore, in the design phase of the components made from these materials (PLA and PETG), a lower allowable value should be used and in addition a higher safety factor should be considered to cover for the above mentioned factors.

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