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EFFECT OF CONSTRUCTIVE PARAMETERS ON TENSILE STRENGTH OF 3D-PRINTED PLA-GRAPHITE COMPOSITE

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Abstract: *In recent years, polymers, metals, ceramics and other consumables used in 3D printing are often being replaced with composites. This allows for the enhancement of mechanical and other key properties of manufactured products. The focus of this study is to investigate the effects that the orientation and thickness of the layers of printed specimens fabricated from composite monofilament based on PLA+ with a 5% content of layered graphite have on the ultimate tensile strength of the printed specimens. The specimens, developed in accordance with the ISO 527-2:2012 standard, were printed by fused deposition modelling at different orientation angles (0°, 15°, 30°, 45°, 60°,75°, 90°) and with three layer thicknesses (0,1 mm, 0,2 mm, 0,3 mm) for each angle. Strength was predicted using the Hill-Tsai anisotropic yield criterion. The comparison of results demonstrated a good correlation between analytical calculations and test data. The effect of the angle orientation and print layer thickness on the ultimate tensile strength of fabricated components was examined.*

Key words: *3D printing; PLA-CG+ (Graphite); constructive parameters; ultimate tensile strength; strength criterion.*

1. INTRODUCTION

The rapid adoption of additive technologies (i.e. 3D printing) for the manufacturing of various products has presented new engineering challenges, one of which is the determination of mechanical properties of the printed products. Among the many different 3D printing technologies that exist today, the most common one is Fused Deposition Modelling (FDM), which involves the use of special plastic, metal and ceramic fibers. The components and structures fabricated by 3D printing are currently used in different fields, including biomedicine [1–3, 21], aerospace engineering [1,4], automotive engineering [5], civil engineering [6], the food industry [7] and others.

Albeit the 3D printing technology is highly effective in manufacturing complex or multi-material components, its use is otherwise limited due to the fact that the mechanical properties of 3D-printed components are not yet sufficiently studied. For example, the elasticity and strength characteristics are essential and indispensable for the design of carrying elements and structures. Aiming to widen and accelerate the engineering application of 3D printing technologies, some studies have investigated the mechanical properties of 3D-printed components. Recently, there have been research efforts to examine both the elastic properties [8-15], as well as the bearing capacity [8, 16-21] of such components.

In recent years, 3D printing technologies have been evolving to replace PLA, ABS and other pure thermoplastic materials with composites armed with natural fiber or powder, thus allowing for the enhancement of mechanical and other key properties of manufactured products.

2. MATERIALS AND EXPERIMENT

The focus of this study is to investigate the effects of constructive parameters, i.e. the orientation and thickness of the layers of printed specimens, on the ultimate tensile strength (UTS). The specimens have been fabricated from a 1.75 mm diameter composite monofilament (Figure 1) based on PLA+ with a 5% content of layered graphite, whose orientation can be adjusted within the material flow during printing.

Fig. 1. Composite plastic PLA-CG+ (Graphite)

This plastic is used for the 3D printing of surfaces with a low friction coefficient. With a resistivity of 10^9-ohm cm, the monofilament also has antistatic properties, and its stiffness and heat resistance are greater than that of a regular PLA. Another benefit of PLA-CG+ (Graphite) is the manner of its interaction with radio waves: the monofilament absorbs and screens radio waves and heats up in a microwave oven.

For the purpose of the experiment, Type-1 specimens (Figure 2) were fabricated in accordance with the ISO 527-2:2012 standard. The specimens were printed on an ANYCUBIC I3 Mega S 3D printer at different orientation angles (0º, 15º, 30º, 45º, 60º, 75º, 90º) and with three print layer thicknesses (0,1 mm, 0,2 mm, 0,3 mm) for each angle.

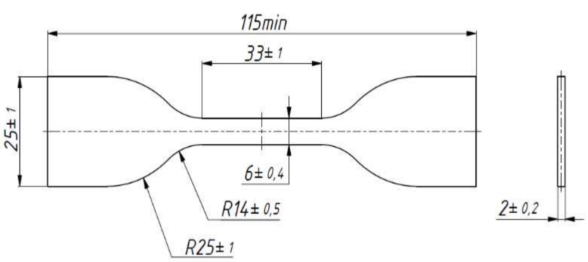

Fig. 2. Drawing of a Type-1 specimen

The manufacturer of the plastic used in this study provides certain recommendations regarding printing modes [22]. In compliance with these recommendations, optimal parameters for achieving high-quality interlayer and bed adhesion were determined experimentally (Table 1).

Table 1

Specimen printing modes

Parameters	Recommended	Applied
Extruder temperature	200-220 °C	210 °C
Printing bed temperature	50-70 °C	60 °C
Cooling	Required	Present
Printing speed	30-80 mm/s	40-60 mm/s
Printer type	closed/open	open

The specimens were tested in a TIRATEST 2151 Universal testing machine (Figure 3) with a displacement measuring accuracy of 0.01 mm, a traverse speed range of 0.5-1000 mm/min, and a load range of 0.01 N-5 kN. During previous testing of this monofilament, the maximum strength value was determined at σ_{max}=51 MPa. The effects of constructive parameters on ultimate tensile strength were researched in compliance with the ISO 527-2:2012 standard, according to the 3x7//21 complete test design (one factor on three levels, and one factor on seven levels, with 21 tests in total) in three parallel experiments. The average UTS values, which were calculated from parallel experiments based on the factors examined in this study (orientation angle and print layer thickness), are shown in Table 2.

Fig. 3. TIRATEST 2151
Universal testing machine

Table 2

Ultimate tensile strength in function of the angle and thickness

Average UTS (MPa)	0,1 mm layer thickness	0,2 mm layer thickness	0,3 mm layer thickness
$T_{0°}$	51,20	52,09	52,01
$T_{15°}$	46,60	47,79	48,80
$T_{30°}$	46,48	47,41	47,73
$T_{45°}$	42,71	46,18	42,14
$T_{60°}$	40,75	42,23	41,63
$T_{75°}$	37,90	40,46	40,54
$T_{90°}$	41,04	42,84	41,47

Photos of the specimens after testing are shown in Figure 4.

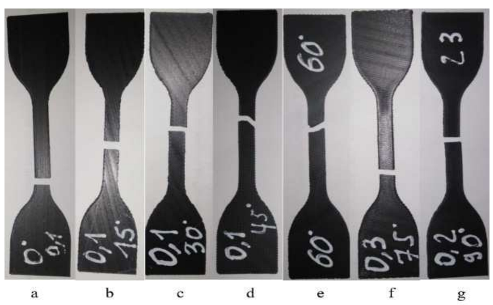

Fig. 4. Photos of the specimens after testing: a) 0^0, b) 15^0, c) 30^0, d) 45^0, e) 60^0, f) 75^0, g) 90^0

3. HILL-TSAI ANISOTROPIC YIELD CRITERION

The two coordinate systems that were used in the current study are shown in Figure 5. The *123* coordinate system represents the principal directions of the composite, whereas the *xyz* coordinate system represents the load direction in the specimen.

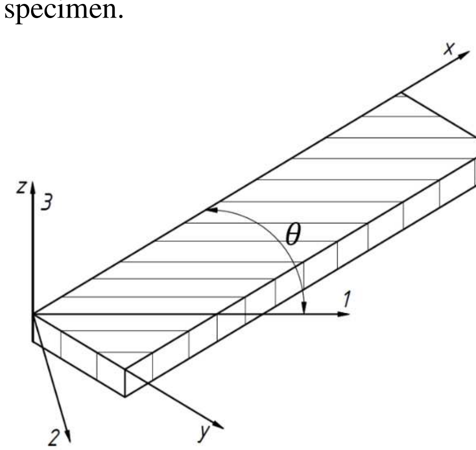

Fig. 5. Angle orientation direction and load direction

As demonstrated in [8], in three-dimensional space the anisotropic yield criterion can be expressed as follows:

$$\left(G+H\right)\sigma_1^2+\left(F+H\right)\sigma_2^2+\left(F+G\right)\sigma_3^2-2H\sigma_1\sigma_2- \\ -2G\sigma_1\sigma_3-2F\sigma_2\sigma_3+2L\tau_{23}^2+2M\tau_{31}^2+2N\tau_{12}^2=1 \quad (1)$$

where F, G, H, L, M, N are anisotropy parameters.

Since the *23* coordinate plane represents the transverse isotropic plane in the material's coordinate system, the material has the same mechanical properties in directions 2 and 3. In following the procedure described in [8], the equation (1) can be reduced to a form which is characteristic for transverse isotropic materials:

$$\frac{\sigma_1^2}{X^2}+\frac{\sigma_2^2}{Y^2}-\frac{\sigma_1\sigma_2}{X^2}+\frac{\tau_{12}^2}{W^2}=1 \quad (2)$$

If σ_x is the only nonzero component in the load direction, then the stress components can be determined in the composite's coordinate system using the following formulas:

$$\begin{cases}\sigma_1=\sigma_\theta\cos^2\theta\\ \sigma_2=\sigma_\theta\sin^2\theta\\ \tau_{12}=-\sigma_\theta\sin\theta\cos\theta\end{cases} \quad (3)$$

By inserting expressions (3) into equation (2), one obtains the expression for σ_x in function of the print angle orientation:

$$\sigma_x=T_\theta=\left[\frac{\cos^4\theta}{X^2}+\left(\frac{1}{W^2}-\frac{1}{X^2}\right)\sin^2\theta\cos^2\theta+\frac{\sin^4\theta}{Y^2}\right]^{-\frac{1}{2}} \quad (4)$$

where X is the UTS of materials in principal direction 1; Y is the UTS of materials in principal direction 2; W is the ultimate shear strength of plane 12; T_θ is the UTS of load direction ($T_{0°}$=X, $T_{90°}$=Y)

From equation (4), the expression for ultimate tensile strength in the shear plane can be derived:

$$W_{HT}=\left[\frac{1}{T_\theta^2\sin^2\theta\cos^2\theta}-\frac{1}{X^2}\cdot\frac{\cos^2\theta}{\sin^2\theta}- \\ -\frac{1}{Y^2}\cdot\frac{\sin^2\theta}{\cos^2\theta}+\frac{1}{X^2}\right]^{-\frac{1}{2}} \quad (5)$$

If test data is available, for UTS at Θ=45° equation (5) can be reduced to the following:

$$W_{HT} = \left[\frac{4}{T_{45^o}^2} - \frac{1}{Y^2} \right]^{-\frac{1}{2}} \quad (6)$$

Based on equations (4) and (6), a theoretical model for predicting the ultimate tensile strength in function of angle Θ was developed in [8]:

$$T_\theta = \left[\frac{\cos^4\theta}{X^2} + \left(\frac{1}{W_{HT}^2} - \frac{1}{X^2} \right) \sin^2\theta \cos^2\theta + \frac{\sin^4\theta}{Y^2} \right]^{-\frac{1}{2}} \quad (7)$$

Figures 6-8 show the comparison of analytical calculations made using equation (7) and the test data.

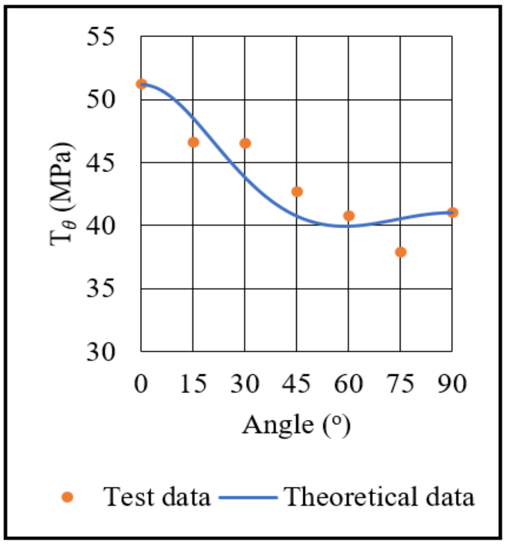

Fig. 6. UTS comparison between theoretical data and test data for materials with 0,1 mm layer thickness

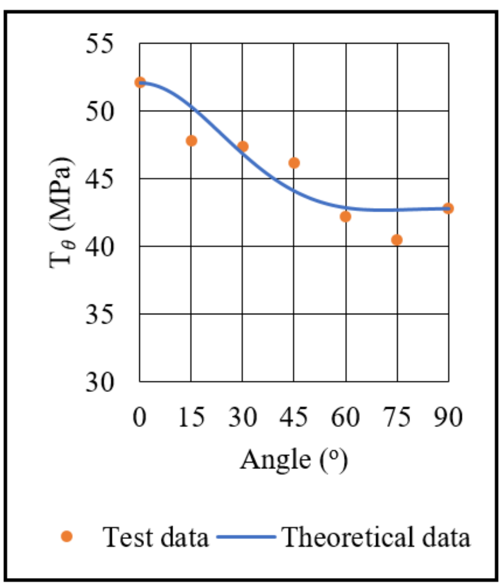

Fig. 7. UTS comparison between theoretical data and test data for materials with 0,2 mm layer thickness

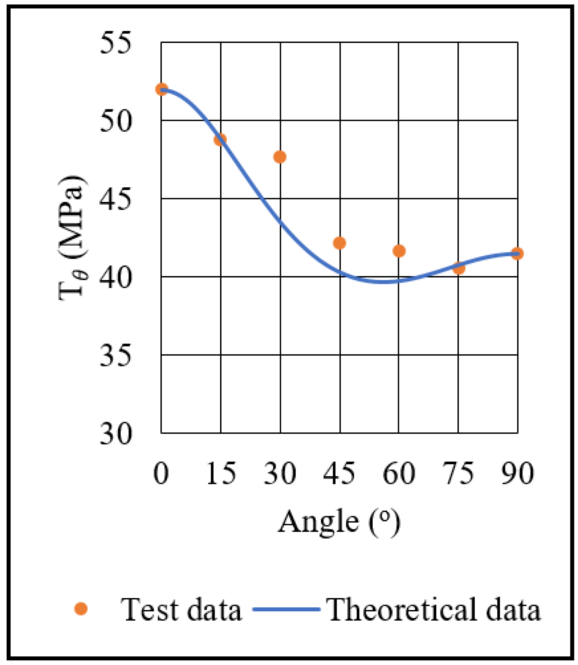

Fig. 8. UTS comparison between theoretical data and test data for materials with 0,3 mm layer thickness

4. CONCLUSION

1. New test results were obtained related to the effects of constructive parameters (i.e. the orientation angle and the print layer thickness) on the ultimate tensile strength of products fabricated by 3D printing from a composite monofilament based on PLA+ with a 5% content of layered graphite.

2. The comparison between the ultimate tensile strength of the monofilament and the specimens fabricated from it has indicated an up to 25% decrease in ultimate tensile strength for the specimens, depending on the orientation angle and the print layer thickness.

3. The test results have shown that the constructive parameters selected for this study, i.e. the orientation angle and the print layer thickness, have an effect on the ultimate tensile strength of components fabricated from composite plastic.

4. The test and calculation results have indicated a decrease in ultimate tensile strength with the increase of the print orientation angle (up to 25%)

5. A comparison between ultimate tensile strength values obtained analytically and

experimentally have shown a good correlation with each other, with a maximum error not exceeding 9%. It can therefore be concluded that the anisotropic yield criterion-based analytical approach that was employed in this study may be used for predicting the ultimate tensile strength of composites fabricated by FDM 3D printing with various angle orientations.

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Efectul parametrilor constructivi asupra rezistenței la tracțiune a compozitului PLA-grafit imprimat 3D

Rezumat*: În ultimii ani, polimerii, metalele, ceramica și alte consumabile utilizate în imprimarea 3D sunt adesea înlocuite cu compozite. Acest lucru permite îmbunătățirea proprietăților mecanice și a altor proprietăți cheie ale produselor fabricate. Accentul acestui studiu este de a investiga efectele pe care orientarea și grosimea straturilor specimenelor imprimate fabricate din monofilament compozit pe bază de PLA+ cu un conținut de 5% grafit stratificat le au asupra rezistenței maxime la tracțiune a specimenelor imprimate. Epruvetele, dezvoltate în conformitate cu standardul ISO 527-2:2012, au fost tipărite prin modelare prin depunere topită la diferite unghiuri de orientare (0°, 15°, 30°, 45°, 60°,75°, 90°) și cu trei grosimi de straturi (0,1 mm, 0,2 mm, 0,3 mm) pentru fiecare unghi. Rezistența a fost estimată folosind criteriul de cedare anizotropă Hill-Tsai. Compararea rezultatelor a demonstrat o corelație bună între calculele analitice și datele de testare. A fost examinat efectul orientării unghiului și al grosimii stratului de imprimare asupra rezistenței finale la tracțiune a componentelor fabricate.*

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