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THE INFLUENCE OF PROCESSING PARAMETERS ON THE MECHANICAL PROPERTIES OF PLA 3D PRINTED PARTS

In this paper, the effect of two process parameters on the mechanical properties of tensile specimens made by FDM was studied. A commercially available PLA filament (produced by Prusa) was used as raw material, from which several sets of specimens were produced, the varied parameters being the raster angle (RA) relative to the longitudinal axis of the specimen and the overflow (OF). Thus, three printing angles were chosen, 0°, 22.5° and 45°, each set of specimens being made with an OF of 95%, 100% and 105% respectively. The printed layer was chosen with a standard thickness of 0.2 mm. For the analysis of the mechanical properties, the specimen sets were subjected to tensile testing on an Instron 3382 machine and the results obtained were interpreted comparatively. Additionally, the fracture surfaces of the specimens were analysed by stereomicroscope. Two-way repeated measures ANOVA analysis of experimental data indicated that both parameters and their interaction significantly influence the specimen weight but, in the case of mechanical properties (modulus of elasticity, yield strength, tensile strength, yield elongation and tensile elongation) were insignificantly influenced by both process parameters. In this context regardless of raster angle, an overflow of 95% provides the same mechanical properties as an overflow of 105%, but at a minimum weight sample.

Keyword: 3D print process; process parameters; sample weight; mechanical properties

1. Introduction

PLA (Polylactic acid) has become one of the most popular biodegradable materials, being used for a wide range of applications, from packaging to components in the automotive, electronics and prosthetics industries [1]. With the development of 3D printing technologies and especially FDM (Fused Deposition Modeling) technology, the applications of PLA have expanded [2]. The quality of the produced parts can be ensured by a better choice of processing parameters, the best known being layer height, build orientation, filling percentage, infill pattern, raster angle, printing temperature, porosity and printing speed [3-6].

Another important parameter, discussed on forums dedicated to 3D printing users (https://all3dp.com, https://forum.prusa3d.com, https://support.ultimaker.com) but not so studied in the literature [7], is the overflow (often referred to as over-extrusion), which represents the mass of the filament being "pushed" during printing. This parameter has an initial effect on the total mass of material that will form the part and can quite well be an alternative to modifying the structure without altering the fill density.

According to FDM manufacturing principles, layers of material are added in different directions, so AM (Additive Manufacturing) parts may exhibit different mechanical behaviour in different directions. The structural integrity of these materials should therefore be investigated to ensure that parts produced using FDM technology can be used more safely in various engineering applications. Already, in the literature, are some recent studies regarding the influence of the printing direction (usually called Raster Angle or Raster Direction) on various properties of the FDM printed parts.

One of those studies, conducted by Ayatollahi et al. [8] refers to the influence of raster angle on tensile and fracture, strengths of 3D-printed PLA specimens. Dog-bone specimens with four different in-plane raster angles of θ_R = 0/90°, 15/−75°, 30/−60°, and 45/−45° were printed in different layers through the thickness and subjected to tensile tests, with deformation measured using the digital image correlation (DIC) method. On another set of semi-circular bend (SCB) specimens with the same raster orientation, the fracture toughness was measured. It was observed that the 45/−45° specimens had the highest fracture resistance and the largest values of the anisotropic behaviour of the material elongation at break, while the 0/90° showed the

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smallest values of those two properties. Also, it was noticed that, in the elastic region, all the samples had a slight anisotropic behaviour for different raster orientations.

A similar approach was found in a paper by Iyer et al. [9], which studied the mechanical properties of short carbon fibre reinforced acrylonitrile butadiene styrene (SCFR – ABS) printed with seven raster orientations: 0, 15, 30, 45, 60, 75 and 90° and observed that all the mechanical properties were impacted due to the changes in the inter-bead pore orientation.

In another study, Khosravani et al. [10] studied the raster angle influence on the strength of flat dog-bone PLA samples, realised at two different printing speeds (20 and 80 mm/s), with four orientations (0°, 30°, 45°, 60° and 90°), composed by 8 layers and contour. After the quasi-static tensile tests, it resulted that the 0° and 90° specimens have the highest and lowest strength, respectively, and an increase in raster direction has led to a decrease in the elastic modulus and tensile strength of examined specimens.

Another step forward was made by Gonabadi et al. [11], which used the computational models to predict the mechanical properties of the 3D printed parts, developing a numerical homogenization technique to predict the effect of printing process parameters on the elastic response of 3D printed parts with cellular lattice structures. The results demonstrate that by providing an accurate characterisation of the properties to be introduced into the macroscale model, the use of the homogenisation technique is a reliable tool for predicting the elastic response of 3D printed parts. The described approach allows faster iterative design of 3D printed parts, contributing to a reduction in the number of experimental replicates and manufacturing costs.

Thus, as could be observed, there is still a lack of studies in the literature linking the change in mechanical properties of 3D printed parts to the change in working parameters, one of the least studied being over flow (OF).

2. Experiment

2.1. Materials

For this study, 54 samples were used, obtained by 3D printing, from a commercial PLA filament (produced by Prusa), on a printing machine Original Prusa I3 MK3S+ type. The filament characteristics according to the filament producer are listed in TABLE 1, and the mechanical properties of the printed samples are explained with the help of Fig. 1, respectively in TABLE 2.

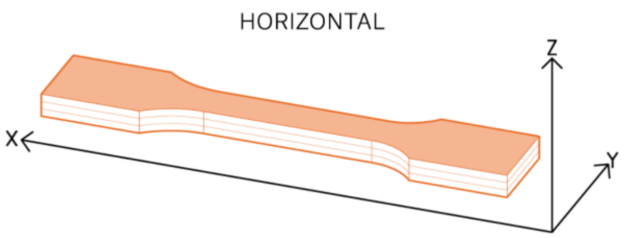


Fig. 1. Print direction used for the properties nominated in TABLE 2.

TABLE 1

Typical material properties of Prusament PLA

Physical Properties	Typical Value	Method
Peak Melt Temperature [°C]	145-160	ISO 11357
Glass Transition Temperature [°C]	55-60	ISO 11357
MFR [g/10 min]*	10.4	ISO 1133
MVR [cm^3/10 min]*	9.4	ISO 1133
Specific Gravity [g/cm^3]	1.24	ISO 1183
Moisture Absorption 24 hours [%]**	0.3	Prusa Polymers
Moisture Absorption 7 days [%]**	0.3	Prusa Polymers
Moisture Absorption 4 weeks [%]**	0.3	Prusa Polymers
Heat deflection temperature (0,45 MPa) [°C]	55	ISO 75
Tensile Yield Strength Filament [MPa]	57.4	ISO 527-1

* 2.16 kg; 210°C
** 28°C, humidity 37%

TABLE 2

Mechanical properties of printed testing specimens*

Property / print direction	Horizontal (see Fig. 1)	Method
Tensile Modulus [GPa]	2.2±0.1	ISO 527-1
Tensile yield Strength [MPa]	50.8±2.4	ISO 527-1
Elongation at yield Point [%]	2.9±0.3	ISO 527-1
Impact Strength Charpy [kC/m^2]	12.7±0.7	ISO 179-1

* Original Prusa i3 MK3 3D printer was used to print testing specimens

2.2. Methods

Slicer Prusa Edition 1.40.0 was used to create G – codes with following print settings: 0,2 mm Quality (layers 0,2 mm); Vertical shells = 2 perimeters, Infill density = 100%, Horizontal shells, solid layers, top 5, bottom 4; Combine infill every 1 layer, 13 layers in the part due to the height of the part (2,6 mm) and the height of the layer (0,2 mm); 215°C extruder temperatures for all layers, 60°C bed temperature for all layers.

Calculated filament parameters were: length of 5710 mm; volume of 13728,44 mm^3 and a mass of 17,02 g.

The considered process parameter was the OverFlow (OF), also called Flow Rate, or simply Flow, which represents the variation of the extruded volume according to the percentage taken into consideration. This is possible by increasing the speed of the step of the motor which feeds the extruder. The second variable taken into consideration was the printing angle relative to the longitudinal axis, referred to as RA (Raster Angle).

Thus, 3 different values of three printing angles were chosen, 0°, 22.5° and 45°, each of them at three different OF degree: 95% (samples A), 100% (samples A'), 105% (samples A"). For a better assessment from the statistical point of view, for each of the nine sets of parameters we made and tested 6 samples, so that each set had, for example, samples A1.1, A1.2 … A1.6.

The thickness of the printed layer is standardized, i.e., 0.2 mm, thus resulting a number of 13 layers for each sample, regardless the OF degree. The test samples were realized according to ISO 572-2 (see Fig. 2) and were subjected to tensile tests on an Instron 3382 machine.

In the image from Fig. 3, is presented the placement of the samples on the surface of the printing bed. In each set of printed parts there are three subsets of samples oriented at a different angle to the OX axis of the printer. In this way we will obtain three different angles for the orientation of the lines deposited by the print head.

So, the three orientations of the samples are given depending on the angle between the vertical axis of symmetry of the samples and the OX axis of the printer. This angle is denoted by "α", and the values of the angle α are the following: $\alpha_1 = 0°$, $\alpha_2 = 22{,}5°$, $\alpha_3 = 45°$.

In accordance with ISO 527-1 standard, for each combination of processing parameters (OF, RA) sets formed from 6 samples were printed. The OF parameter is used to adjust the amount of material extruded through the extrusion head.

The OF is the quantity (volume to be more precise) of filament that passes through the extruder based on the selected printing parameters to make a model. The calculation of the OF is carried out automatically by the 3D printer according to the Steps/mm that the 3D printer manufacturer establishes for the extruder motor, depending on the diameter of the filament and the exit diameter of the nozzle.

Different filaments not only have different densities, but they can have different extrusion properties that can lead to under or over-extrusion issues. Correct calibration of the flow rate for each filament can help improve the accuracy of the prints.

Printing with a too small flow rate, under-extrusion can happen. When the models are missing layers, have thin layers, or have layers with dots and holes in them it appears an under-extrusion problem. For fixing the under-extrusion problem the following methods were used: increasing the flow rate, increasing the temperature, and checking the correct and constant diameter of the filament.

On the other hand, printing with a too-high flow rate, can lead to over-extrusion. Over-extrusion happens when the 3D printer extrudes too much material. Over-extrusion is characterized by oozing, blobs, stringing, and drooping. For fixing the over-extrusion some methods could be used: lower the flow rate or lower the printing temperature, checking the correct

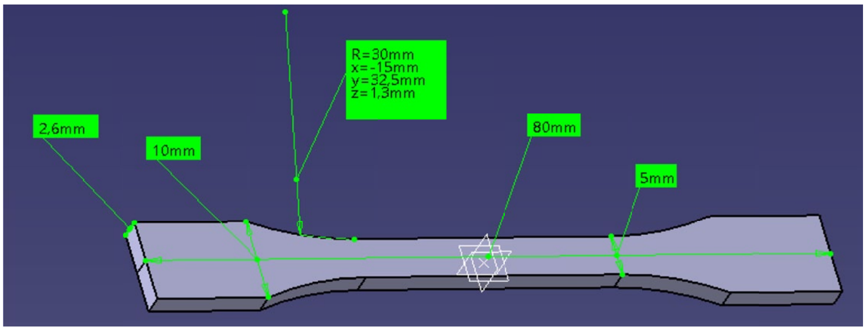


Fig. 2. Tensile test samples geometry, according to ISO 572-2

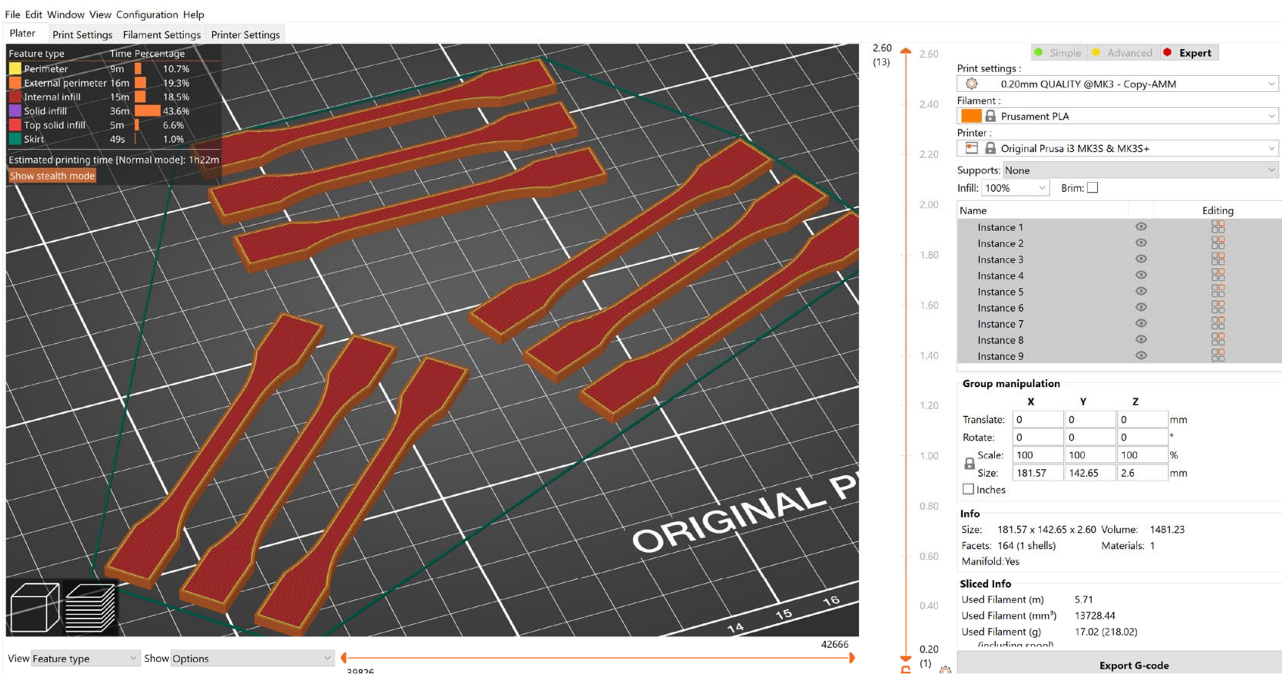


Fig. 3. Virtual 3D printed part aspect according to the Prusa Slicer software

and constant diameter of the filament. This parameter (OF) has a particularly important impact on the adhesion of the layers to each other and thus contributes substantially to the mechanical resistance of the printed parts. It must be mentioned the fact that in the *gcode program the printer defaults to the value OF = 95% for printing parts.

3. Results and discussion

3.1. Structural characterization

The position of the fracture surface of the samples was observed, directly, for each sample after the mechanical tests were performed. Some representative images of the chosen samples from each batch are presented in the Fig. 4. It was observed that a very large part of the samples was broken near one of the extremities, at distances between 25.53 mm from the edge (sample A2"3) and 27.97 mm (sample A 22) and only some of them (9 samples) were broken in the middle part. None of the samples presented delamination between the layers and the fracture surface was linear (perpendicular on the longitudinal axis).

The Figs. 5-7 presented the aspect of the fracture surfaces, for representative samples from all the sample sets. Supplementary, a slice from the digital fracture area was collected, for a better understanding of the layers super-positioning in each of the RA cases.

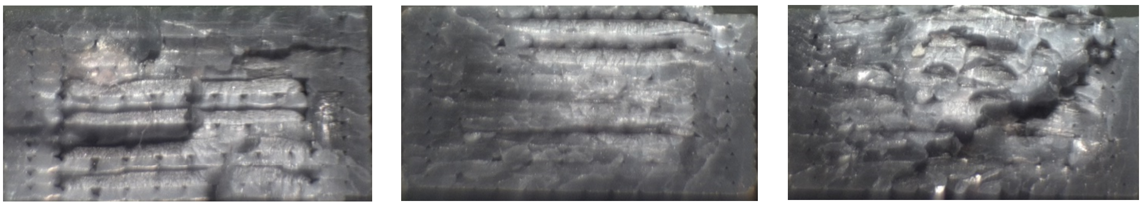
From the images of the breaking surfaces, it can be seen that there are significantly different features between them concerning both OF and RA. For each RA with increasing OF

A1(/1 ÷ 6): OF = 100%, RA = 0° | A2(/1 ÷ 6): OF = 100%, RA = 22.5° | A3(/1 ÷ 6): OF = 100%, RA = 45°

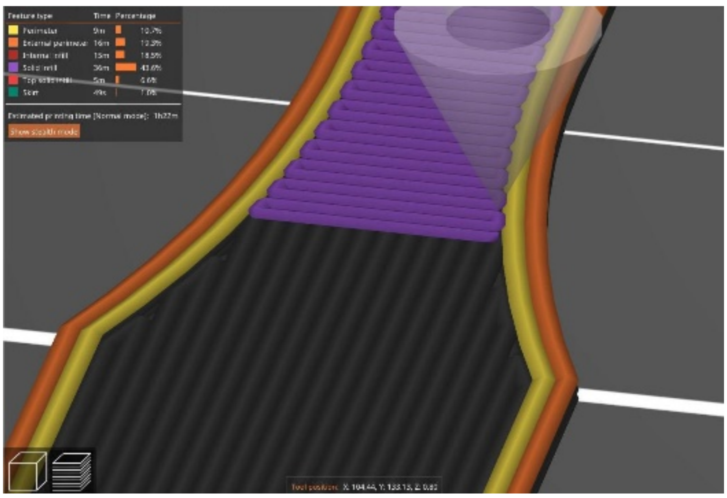
A1'(/1 ÷ 6): OF = 95%, RA = 0° | A2'(/1 ÷ 6): OF = 95%, RA = 22.5° | A3'(/1 ÷ 6): OF = 95%, RA = 45°

A1''(/1 ÷ 6): OF = 105%, RA = 0° | A2''(/1 ÷ 6): OF = 105%, RA = 22.5° | A3''(/1 ÷ 6): OF = 105%, RA = 45°

Fig. 4. The aspects of representative samples from each fractured batch, namely A1, A2 and A3, for each of the three OverFlow values, respectively for each of the three RA

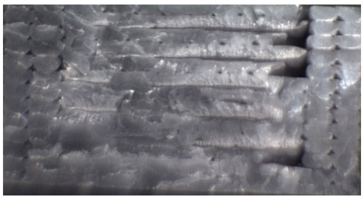


a) OF = 95%; RA = 0.0° b) OF = 100%; RA = 0.0° c) OF = 105%; RA = 0.0°

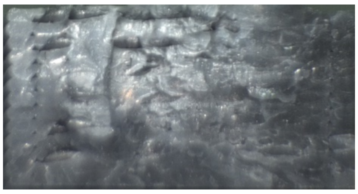


d)

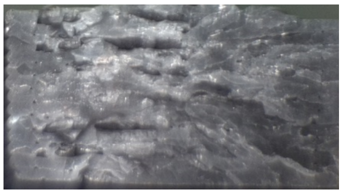
Fig. 5. The aspect of the fracture surfaces of some representative samples from the RA = 0.0°: a) sample A1'3; b) sample A13; c) sample A1"1; d) representation of the 3D printed model in the approximate area of the specimen fracture



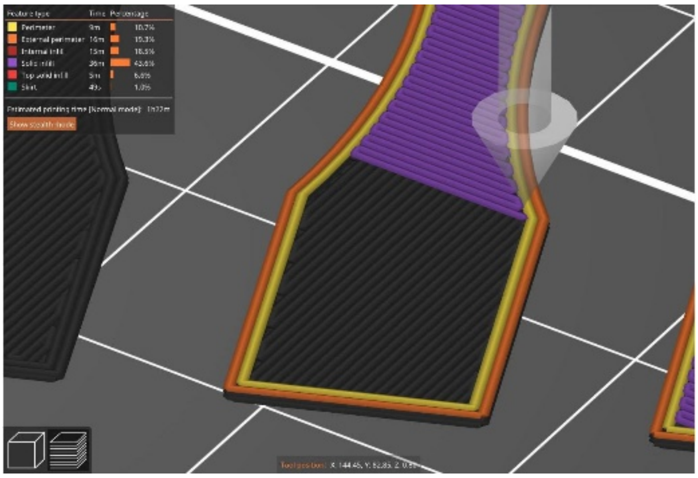
a) OF = 95%; RA = 22.5°



b) OF = 100%; RA = 22.5°

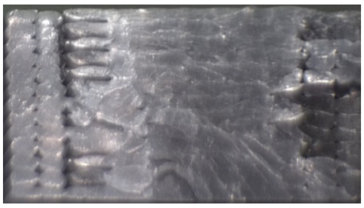


c) OF = 105%; RA = 22.5°

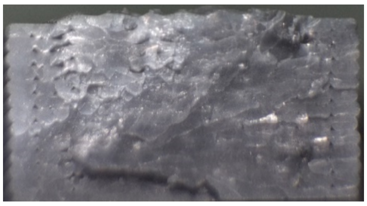


d)

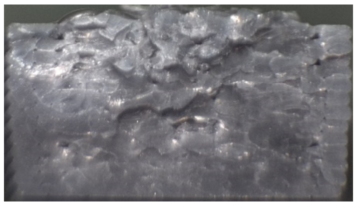
Fig. 6. The aspect of the fracture surfaces of some representative samples from the RA = 22.5°: a) sample A2'1; b) sample A22; c) sample A2"3; d) representation of the 3D printed model in the approximate area of the specimen fracture



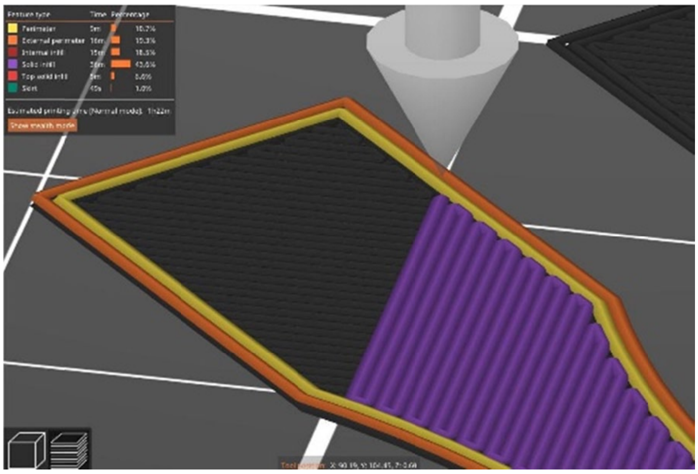
a) OF = 95%; RA = 45.0°



b) OF = 100%; RA = 45.0°



c) OF = 105%; RA = 45.0°



d)

Fig. 7. The aspect of the fracture surfaces of some representative samples from RA = 45°: a) sample A2'1; b) sample A22; c) sample A2"3; d) representation of the 3D printed model in the approximate area of the specimen fracture

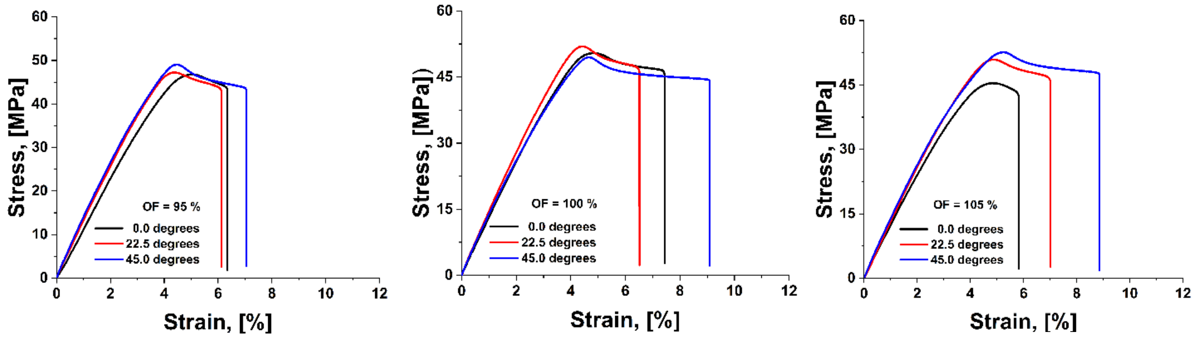
it is observed that the layers deposited, especially, in the central area are less visible. For RA = 0.0° the deposited layers are most visible, increasing RA results in a broken surface where the layers are no longer distinguishable.

3.2. Mechanical properties

The representative Stress-Strain curves for the 9 sets of samples are shown in Figs. 8 and 9.

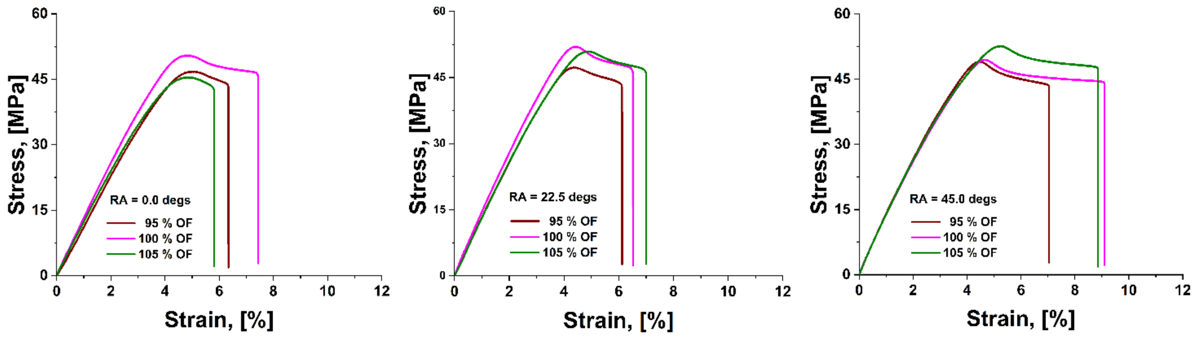
From these curves, in accordance with ISO 527-1 standard ("c" curve) were found the following mechanical properties: i) modulus of elasticity; ii) strain at yield/strength, iii) strain at break, iv) stress at yield/strength; v) stress at break. For these mechanical properties, 2D color-filled contour plots were made as those from Fig. 10.

From plots one can observe the followings: i) higher values of the modulus of elasticity for OF = 95% and RA around



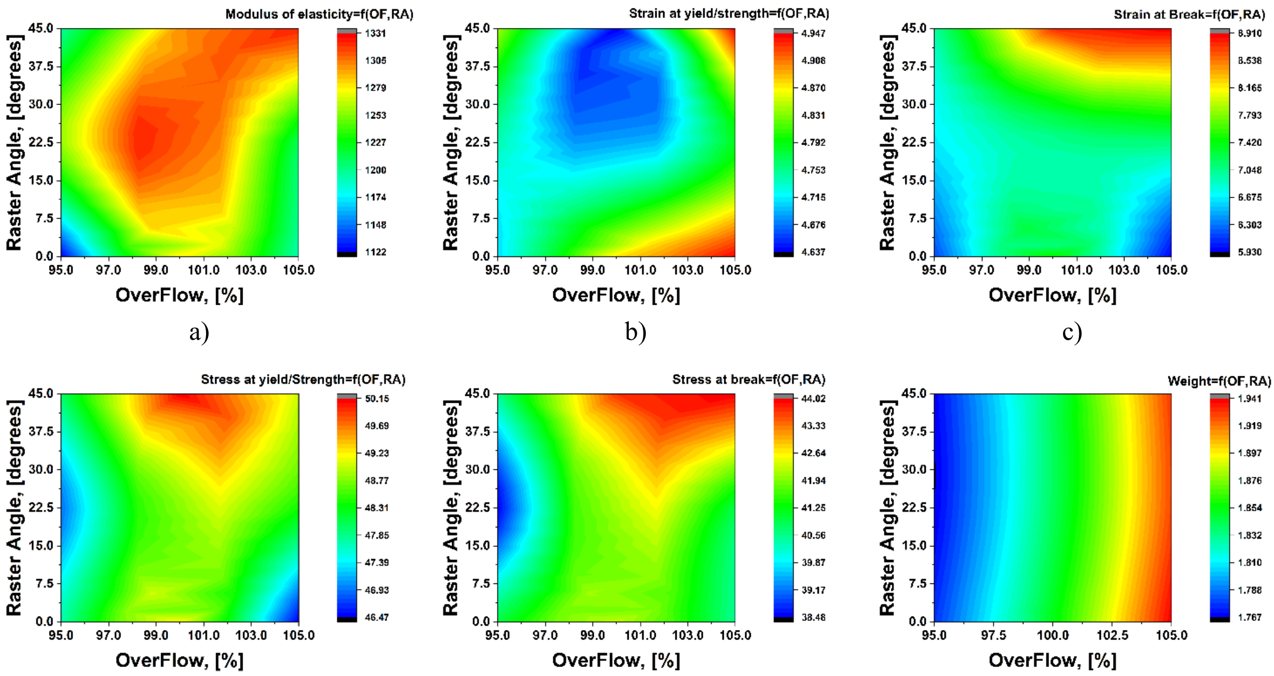
a) b) c)

Fig. 8. The stress – strain diagrams for: a) 95 % OF; b) 100 % OF; c) 105 % OF



a) b) c)

Fig. 9. The stress – strain diagrams for: a) RA = 0.0°; b) RA = 22.5°; c) RA = 45.0°



a) b) c)

d) e) f)

Fig. 10. The z(property) = f(OF, RA) 2D colour-filled plots: a) Modulus of Elasticity; b) Strain at Yield/Strength; c) Strain at Break; d) Stress at Yield/Strength; e) Stress at Break; f) Weight

22.5°, OF = 100% regardless RA values and OF = 105% and RA around 45.0°, ii) lower values of the strain at yield/strength at OF = 100% and RA around 22.5°, iii) higher values of the strain at break at OF = 105% and RA around 45.0°; iv) higher values of the stress at yield/strength, as well as, of the stress at break at OF = 105% and RA around 45.0°.

These observations were validated statistically, by two-way repeated measures ANOVA (Tukey test, Origin Pro software, 0.05 significance level), only for stress at yield/strength at OF = 100%, RA around 45.0° (highest values in comparison with stress at yield/strength values for 95% and 105% OF), and for strain at break at OF = 100% and OF = 105%, RA around 45.0° (highest values). This mechanical behaviour can be put in relation with tensile force direction and RA.

To validate the effectiveness of OF regarding the sample, in Fig. 10f is given 2D plot for sample weight. The two-way repeated measures ANOVA (Tukey test, Origin Pro software, 0.05 significance level) showed that OF has a strong effect on the sample weight, occurring significant difference of sample weight for all OF values.

4. Conclusions

The present study had, as initial assumption, that along with increasing of PLA flow (volume/time) printed, together with weight increase, the remanent porosity will decrease significantly and, hence, an improvement of mechanical properties will be produced. Also, having in view the direction of tensile force in relation to the PLA filament orientation (raster angle), significant changes in the mechanical behavior of the tensile specimens will be produced.

Following the tests carried out in this study, some relevant conclusions were drawn:

- the mass of the samples linearly depends on OF (OverFlow), the raster angle having a smaller effect;
- even though from a statistical point of view the mechanical properties non-significantly depend on both parameters and interaction between them, from tensile testing data used to build the plots from Fig. 11 was observed that for OF = 100%, the all-3D printed samples had the highest YTS and UTS values, and for RA = 22.5° the highest ME. In the case of tensile samples corresponding OF = 105% and RA = 45.0° the elongations had the highest values
- about half of the samples (44%) broke near the boundary of the calibrated area, which requires further studies to explain the incidence of the phenomenon.

Having in view the previously mentioned conclusions, for the next studies the approach strategy will be changed either through changing the sampling method or modifying the specimen shape and printing process.

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