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THE ROLE OF OVERFLOW ON THE MECHANICAL PROPERTIES OF 3D PRINTED PLA

3D printing is a technology used on an ever-increasing scale, which makes it easier to obtain parts with complex geometry. The printing process is very complex because, in addition to the variables introduced by the various materials that are used, there is a multitude of process parameters: printing direction, layer thickness, infill level, filament feed rate, printing temperature, printing bed temperature, etc. Each process parameter influences the mechanical properties of the 3D-printed structure, which is why it is necessary to define the range of possible values where the effect is maximum. In this paper it was studied the effect of process parameters variation on the roughness and mechanical properties of the 3D-printed samples. Using a commercially PLA filament (produced by Prussia), we made six sets of 3D-printed samples, using six different overflow (OF) values: 90%, 95%, 100%, 105%, 110%, 115%. The test samples (realized according to ISO 572-2) were subjected to tensile tests on an Instron 3382 machine, and the results were interpreted comparatively. It has been observed that there are variations of the mechanical properties, dependent on the chosen values of the overflow and, in addition, this process parameter has an important role for the achieving the desired structure.

Keyword: 3D printing process; overflow value; mechanical properties

1. Introduction

The evolution of Additive Manufacturing (AM) technologies in recent decades has opened up multiple possibilities for the development of lighter and stronger parts or assemblies with complex geometry, both on an industrial scale and for small or one-off series production [1]. This method can be used to make parts from a variety of base materials: metal alloys, ceramics and even concrete, the most commonly used type of material being polymers (PLA, ABS, PET) [2,3]. Several technologies have been developed, the most popular being [4]: lithography, FDM, power bed fusion, direct energy deposition, 3D printing or laminated object manufacturing. All these have become possible due to the explosive development of digital technologies, which have replaced analogue technologies in almost all fields [5].

AM technology, regardless of the 3D printing process applied, has a major drawback [6]: the long time required to realize the finished product, which justifies its applicability in the case of small series or one-off parts, or large series with very complex geometry that would require a large sequence of operations and therefore much higher costs.

Although at first glance the technological flow for the production of additive manufactured products seems simple, it consists of a succession of stages that must be rigorously established, some of which are decisive for the success of printing a product [7]: creation of the 3D model, slicing, model generation, selection of printing material, defining of process parameters, 3D printing and post-processing of the printed parts (mechanical finishing or application of heat or chemical treatments).

A lot of research is currently being carried out to address the challenges related to the selection of process parameters for each step in the 3D printing process, as they have a decisive influence on the mechanical and aesthetic properties of the printed products [8]. A critical point, after the choice of the material, is the establishment of the process parameters: bed temperature, feed rate, overflow, pattern and infill [4,9,10].

Several studies are available in the literature dedicated to the influence of infill pattern and infill density influence on the mechanical characteristics of 3D printed parts. Thus, Gunasekaran et al. [4] studied how the different percentages of infill density (25%, 50%, 75% and 100%) influenced the mechanical properties of the PLA specimens. It was thus observed that a degree of 100% resulted in the best values in the hardness tests (97 HRC versus 73, 79 and 85 HRC), tensile strength (53 MPa versus 39, 43 and 47 MPa), impact strength (70 J/m^2 versus 61, 65 and 67 J/m^2) and flexural strength (53 MPa versus 42, 46 and 49 MPa). Dharmalingam et al. [10] also considered that infill density is a very important parameter and studied how

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its variation affects the impact strength of biodegradable PLA. The samples were produced with infill rates of 50%, 75% and 100% with on-edge orientation. It was observed that the samples with 100% infill density had the best values in the impact and hardness tests, which means that the bonds created between the layers were sufficiently tight and a complete fusion was ensured. Other studies from Mishra et al. [11] have been carried out to evaluate the impact resistance of samples with different infill patterns, the research being focused on the combinations: line, zig-zag and concentric with different infill densities (50%, 75%, 80%, 85%, 90%, 95%, and 100%). After applying the impact tests, the best values were recorded for the samples with line pattern and 85% infill density, which can be explained by the fact that small gaps remained between the infill layers and the crack propagation is slowed down.

Garriga et al. [12] studied the influence of infill parameters on the mechanical characteristics of samples produced from polyetherimide (PEI ULTEMTM 9085) with a 45° raster pattern and air gaps of 0 (solid samples), 0.25, 0.50 and 0.75 mm. In the mechanical tests (tensile, flexural, and shear loading tests) it was observed that the values recorded decreased with the size of the gap, compared to the values obtained in the testing on the solid samples. It was thus concluded that, although the use of a smaller quantity of material for the production of a part would lead to considerable savings in time and material, the working parameters must be correlated with the applicability of the parts thus produced. Another study is that by Kui Wang et al. [13], who investigated how infill parameters affect the mechanical properties, elasto-plastic deformation and fracture behaviour of lightweight cellular structures produced by 3D printing of polyamide-based composites (Onyx®) reinforced with short carbon fibres. Samples were made with two different patterns: triangular and hexagonal and infill densities of 29% vol, 39% vol and 49% vol. It was observed that the hexagonal structure has higher tensile modulus and tensile strength but lower elongation at break compared to the triangular one, at a given infill density.

Other studies have focused on infill patterns, because the way 3D printed layers interact with each other can influence both the structural cohesion and the behaviour of the printed part in different directions. Bandar Aloyaydi et al. [14] studied the influence of infill pattern on the mechanical characteristics of PLA samples, and four printing directions were chosen: triangle, grid, quarter-cubic and tri-hexagon. The samples were subjected to LVI (Low-Velocity Impact) and compression tests, and it was observed that for those with a triangular pattern the maximum penetration force of 1190.5 N and a penetration energy of 7.50 J were recorded, mainly due to the fact that this type of pattern is characterized by the highest number of contact points per unit area.

Several infill pattern configurations have been studied by Benoit Pernet et al. [15], which has 3D printed from PLA 14 cylindrical specimens (Grid, Lines, Cubic, Triangle, Tetrahedral, Concentric, Concentric 3D, Zigzag, Gyroid, Octet, Cross, Cross 3D, Tri-hexagonal and Quarter Cubic) with infill densities of 20%, 40%, 60%, 80% and 100%. The influence of infill patterns on the maximum supported compression load and on the strength-to-weight ratio was analysed and it was observed that grid, cross and triangle had the best behaviour at infill densities between 80 and 100%.

Naik et al. [16] took the studies further and made multi-infill PLA specimens with overlapping triangular, honeycomb and rectilinear patterns printed at 25%, 50%, 75% and 100% infill density and investigated the influence of these parameters on tensile strength. It was also concluded from this study that the printing orientation has a decisive influence on the tensile strength, and the best behaviour was recorded for the samples with on-edge orientation.

Another multi-infill pattern system is the one tested by Ambati et al. [17], who printed several PLA samples with different infill pattern and infill density combinations: Grid – 60%, 75%, 90%, Triangle – 60%, 75%, 90%, Gyroid – 60%, 75%, 90%. Tensile strength measurements of printed specimens showed that the highest values were recorded for the grid pattern with 90% infill (32,6 MPa) and the lowest for the triangle pattern with 60% infill (23,4 MPa).

From the data gathered from the literature, it can be concluded that there are several parameters that decisively influence the mechanical characteristics of 3D printed structures, among which the following can be listed [17]:

1. infill pattern – which represents the deposition pattern of the layers,
2. infill density – which represents the percentage of the structure volume that is filled with material, the rest being air (voids),
3. raster angle – the angle of orientation of the wires deposited during the 3D printing process,
4. layer thickness – which is dependent on nozzle thickness,
5. the melting temperature of the material undergoing the 3D printing process.

Another important parameter, discussed on the forums dedicated to the 3D print users (https://forum.prusa3d.com, https://support.ultimaker.com, https://all3dp.com) but very little studied [8], is the *overflow* (usually named over-extrusion), which represents the volume of filament "pushed" during the printing process. This parameter has an initial influence on the total volume of material that will form the part and implicitly, could be an alternative for adjusting the structure without changing the infill density.

Starting from this premise, we carried out the study presented in this paper, in which we varied the overflow parameter and studied how the resulting structure behaved in terms of tensile strength. The "Overflow" parameter (OF) can be set in percentages. It relates to the default program set flow rate of 100%, which the printer uses. By modifying this parameter, we were be able to change the flow of material extruded through the nozzle. Using a commercially PLA filament, we made six sets of 3D-printed samples, with different OF values: 90%, 95%, 100%, 105%, 110%, 115%. The samples were subjected to tensile tests and the results were interpreted comparatively. It has been observed that there are variations of the mechanical properties, dependent on the chosen values of the overflow and, in addition, this process parameter has an important role for the achieving the desired structure.

2. Experiment

2.1. Materials

For this study, 6 sets, each formed from 3 samples, were realized by 3D printing, using a commercially PLA filament and a printing machine Original Prusa I3 MK3S+ type (produced by Prusa Research a.s, Czech Republic, 2020). The filament characteristics according to the filament producer (Prusament PLA, manufactured by Prusa Polymers, Czech Republic) are listed in TABLE 1. The mechanical properties of the printed samples are explained with the help of Fig. 1, which shows the printing direction used for the tested samples, respectively in TABLE 2, which contains data from the manufacturer.

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

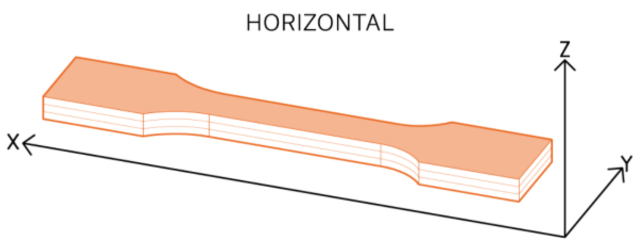


Fig. 1. Print direction used for the properties nominated in Table 2

2.2. Methods

The open-source software Slicer Prusa Edition 1.40.0 (released by Prusa Research a.s, Czech Republic) was used to create G – codes (see Fig. 2) with following print settings: 0,2 mm FAST (layers 0,2 mm); solid layers: Top = 0; Bottom = 0; 100% infill density, infill pattern – aligned rectilinear (fill angle = 0°), 13 perimeters, 200 mm/s infill print speed, 215°C extruder temperature for all layers, 60°C bed temperature for all layers. Resulted that the filament necessary length calculated by the software is of 1,86 m, the calculated volume of the sample is 4461,91 mm^3 and the filament mass is 5,53 g.

Fig. 2 presents the virtual 3D printed part aspect retrieved from the Prusa Slicer software, just before the printing operation. As it can be seen, the aspect of the top layer consists of parallel lines of extruded PLA. There are 13 perimeters on the grip part and 6 perimeters on the active sample area. All the layers have exactly the same configuration stacked on each other at 0.2 mm, which is the height of each layer.

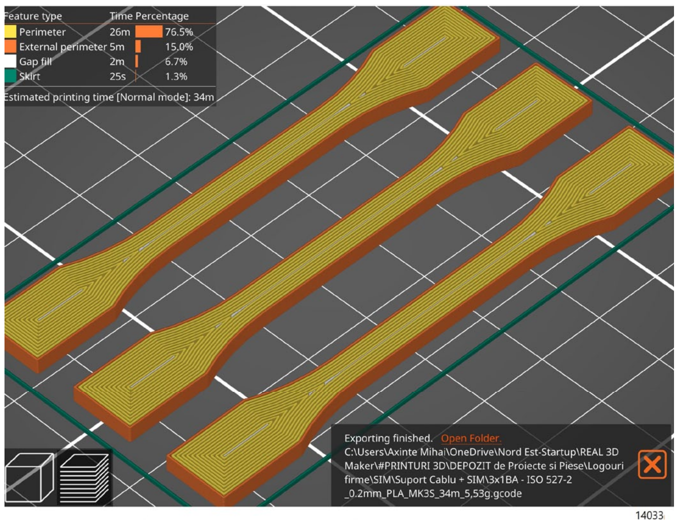


Fig. 2. Virtual 3D printed part aspect according to the Prusa Slicer software

The considered process parameter was the OverFlow (OF), which represents the variation of the extruded volume according to the percentage taken into consideration. This variation is possible by increasing the speed of the step of the motor which feeds the extruder. Thus, 6 different values were used: 90% (samples B1), 95% (samples B2), 100% (samples B3), 105% (samples B4), 110% (samples B5), 115% (samples B6). For a better assessment from the statistical point of view, for each of the six sets of parameters we made and tested 3 samples, so that each set had, for example, samples B1.1, B1.2 and B1.3.

The thickness of the printed layer is standardized, i.e., 0.2 mm, thus resulting a number of 13 layers on Oy direction for each sample, in the thicker area of the sample, regardless the OF degree. The test samples were realized according to ISO 572-2 (see Fig. 3) and were subjected to tensile tests on an Instron 3382 machine.

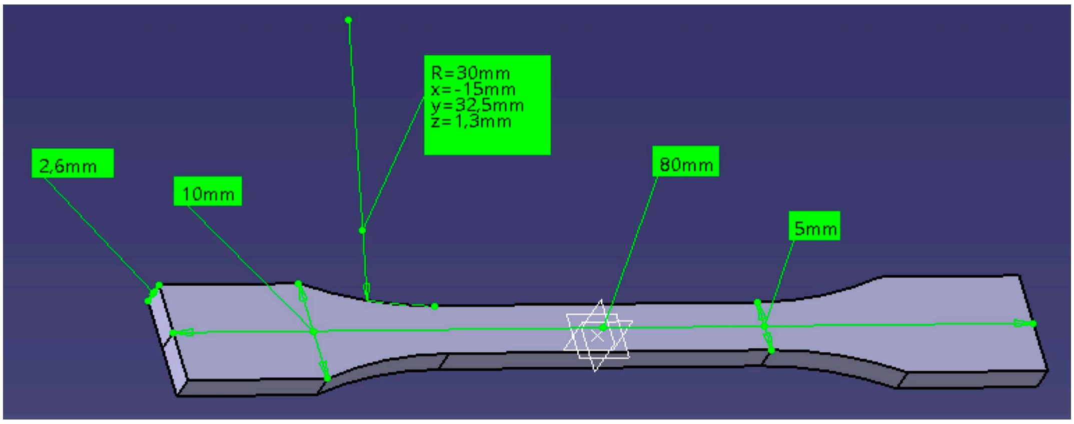


Fig. 3. Tensile test samples geometry, according to ISO 572-2

The surfaces topography and the fracture aspect were analysed using a digital microscope and the results are presented in the Figs. 4 and 5.

3. Results and discussion

3.1. Structural characterization

After the mechanical tests were performed, the aspect of the samples was observed, directly, for each sample. The photos of some representative samples from each batch are presented in Fig. 4 and Fig. 5.

In the images b) and c) from Figs. 4 and 5 can be observed that the exterior appearance is strongly influenced by the OF parameter. Important sample variations aspect due to OF parameter, from B1 to B6(90% to 115%) can easily be highlighted.

In b) images, the print bed contact side, can be observed that from B1 to B6 the distance between the lines of material is smaller and smaller. The best appearance is observed at B3(100%) and B4(105%). The most distant lines are observed at B1(90%). On the other side, at B5(110%) and B6(115%), can be observed some overlapping through the lines.

Same observations can be made in c) images, on the upper side of the part. The best appearance is observed at B2(95%). Some thin spaces between the lines are observed at B1(90%).

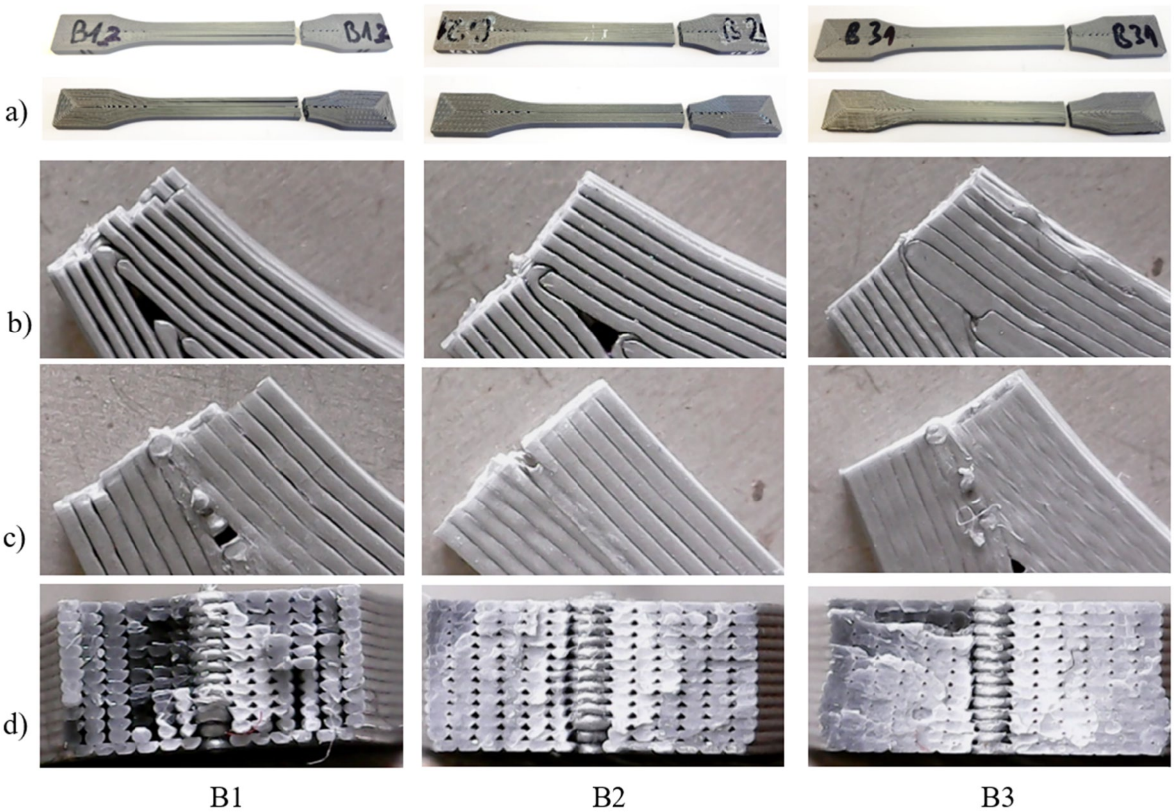


Fig. 4. The aspects of representative samples from each batch, namely B1, B2, and B3: a) general aspect of the sample, on both sides (top and base); b) base side aspect on the fractured zone; c) top side aspect on the fractured zone; d) fracture aspect

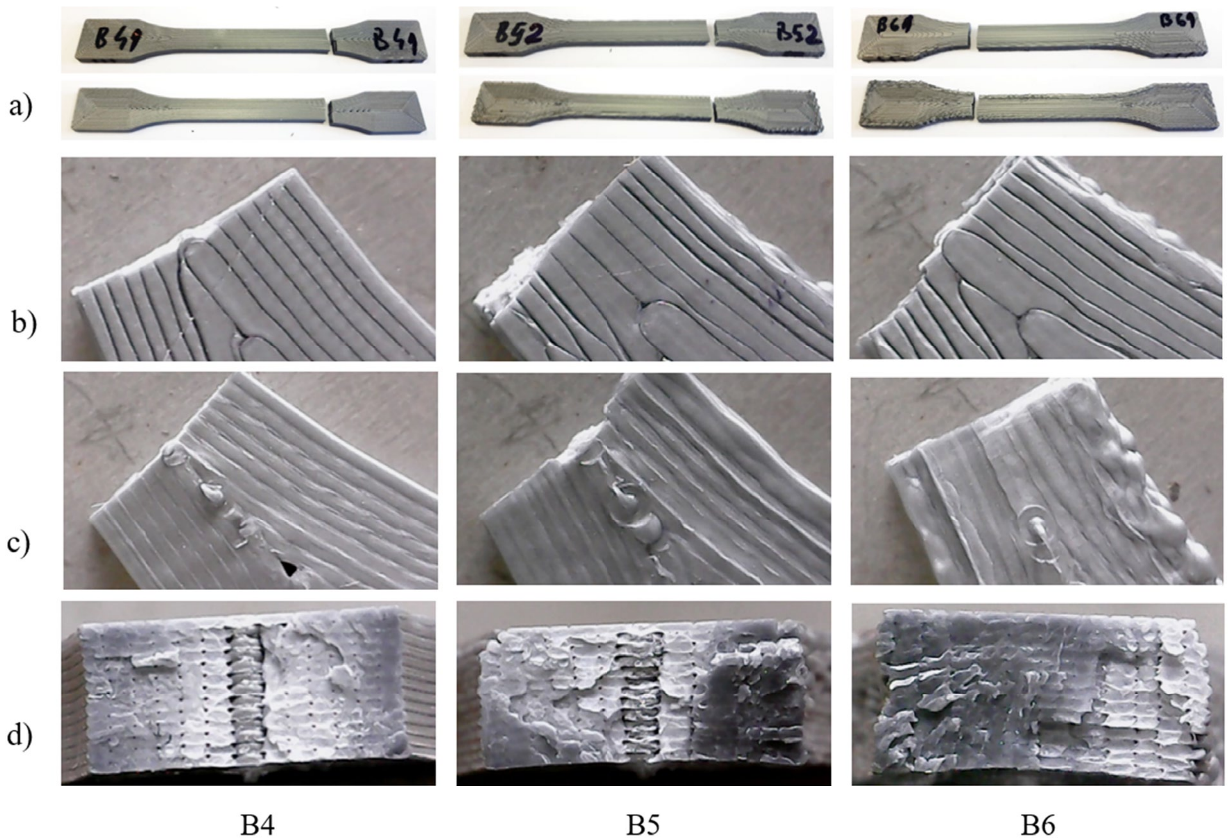


Fig. 5. The aspects of representative samples from each batch, namely B4, B5, and B6: a) general aspect of the sample, on both sides (top and base); b) base side aspect on the fractured zone; c) top side aspect on the fractured zone; d) fracture aspect

On the other side, at B5(110%) and B6(115%), can be observed severe overlapping through the lines. The surface in B6, is severely distorted, due to material overflowing on the edges.

In d) images are highlighted the aspect of inner structure, after tensile test breaking. The samples are not homogenous and do not have isotropic properties. The interior configuration corresponds to the orthotropic materials. The pulling direction has the same angle as printed lines. As can be seen inside the structure some holes between the printing lines are observed – *triangular shape voids*. These holes are spaces left between adjacent lines of the printed material, located at the virtual intersection of the lines that connect the centre cross-section of four adjacent extruded material lines, two on the current layer and two on the below layer.

From a geometrical point of view, all the samples are obtained with the standard dimensions as shown in Fig. 3. However, in Figs. 4 and 5(b, c), the differences caused by the OF variation can be seen: at 90% and 95% OF, the demarcation lines between the beads are visible, especially on the lower face (the one on the printing bed) of the samples, while at 110% and 115% OF, the excess material generated by the increase in the flow of material deposited by printing is visible. This excess material is pushed to the outside of the sample and appears as areas of clumping on the upper face and on the entire side profile of the samples. Figs. 4 and 5(d) show the changes in cross-section generated by the OF variation: at OF of 90% and 95% the triangular shape voids are very visible, as well as the interfaces between beads and layers, which attests a weaker interaction (bond) between the elements constituting the sample. Moreover, in these two types of samples, delaminations between beds and layers were also observed, which are important factors for the value of the breaking strength of the samples. In the case of 100% OF and 105% OF it is observed that the triangular voids have much smaller dimensions (about 50% smaller than in the case of 90% OF), and the interfaces between the layers, respectively between the beads, are less defined. In the case of 110% and 115% OF, the voids are small, punctiform, and the interfaces have the same appearance as in the 100% and 105% OF samples, having overall a more compact appearance. This increase in compactness is also supported by the breakage appearance, which in the case of samples with OF greater than 100% is more similar to the breakage appearance of compact materials (with crack initiation zones, fine, coarse and cleavage breakage zones).

3.2. Weight variation

After 3D printing each sample of all sets were weighted and compared. The results of the weight measurement and specific weight are graphically shown in Fig. 6. The dependence between OF and weight is almost linear. The weight values increase with the OF according with the percentage. The specific weight of the printed sample increases along with the OF increasing. This increase in specific weight can be explained by the internal configuration of the sample. The holes inside the structure are smaller and smaller inside the sample due to OF increased values, thus meaning that the density of the obtained structure is higher.

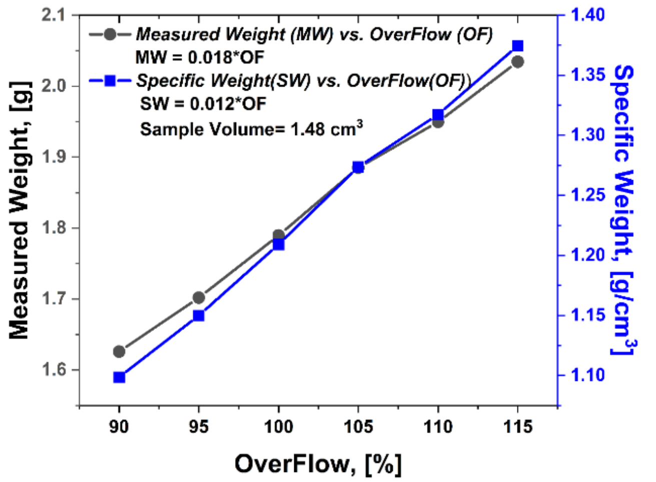
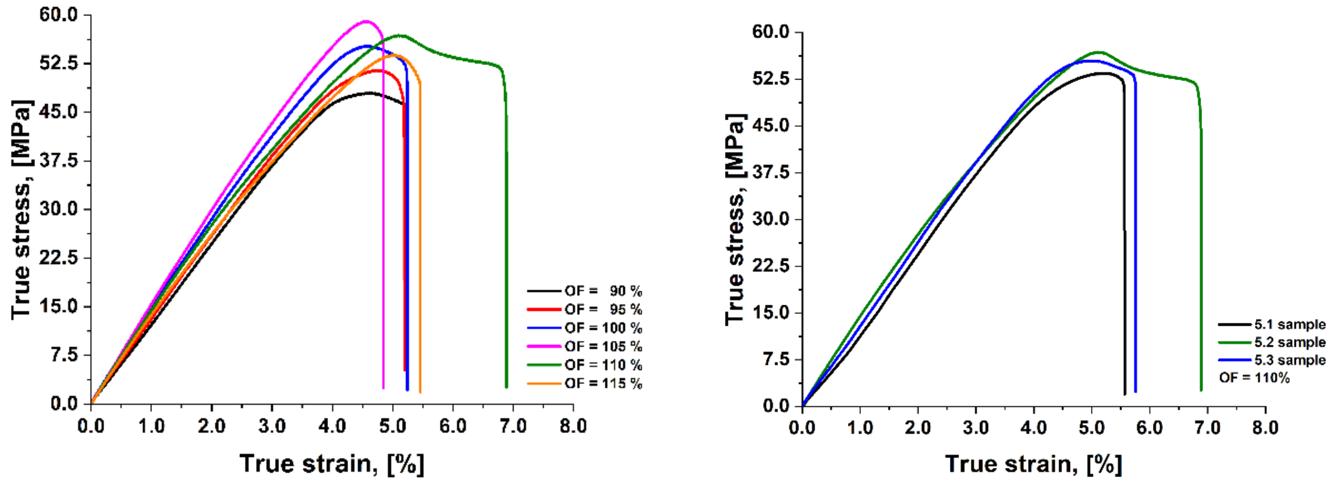


Fig. 6. Weight vs. OverFlow

3.3. Mechanical properties

The representative True strain – True stress curves for the second set of 6 samples (B1.2, B2.2, B3.2, B4.2, B5.2, B6.2) are shown in the Fig. 7. It can be seen that all samples behaved similarly, with maximum true stress values between 45 and 60 MPa, at true strain of about 5-5.5%. All curves show an initial elastic zone, up to about 45 MPa, followed by a non-linear zone until maximum stress is reached. After reaching the maximum peak, a decrease in stress was observed for each of the samples, together with an increase in strain, until the failure occurred.

It is observed that the maximum stress value is recorded for the 105% OF sample, followed in descending order by the 110%, 100%, 115%, 95% and 90% OF samples. An exception observed in the case of set 2 is that recorded at the breakage of sample 5.2, which records a double curve variation and a value of about 7% of true strain. However, this variation is not characteristic of this set of samples but is an exception, as can be seen in Fig. 7b, which shows the plots generated at breakage of the three samples in the 110% OF set.



a) b)

Fig. 7. True strain-True stress curves for: a) the 6 samples of the second test set; b) all the 110% OF tested samples

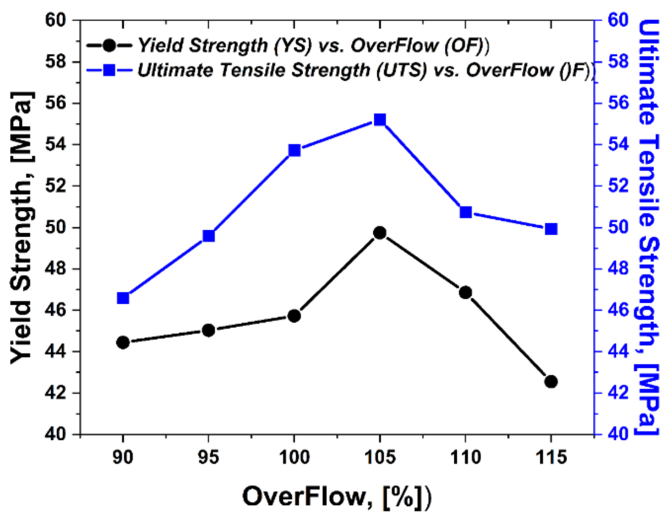


Fig. 8. Mechanical properties vs. Overflow

From plots it observes that, for example, the „*Ultimate Tensile Strength*" have increasing values with increase of overflow up to 105% after that the values of these quantities decreased. The dependence of the mechanical properties in relation with OF are graphically shown in Fig. 8.

3.4. Roughness evolution

In Fig. 9 are shown the dependence of some roughness parameters in relation with Overflow.

The dependence between the roughness and OF is not linear. From the graph can be seen that the lowest value for roughness is obtained at 100% and 105% OF parameters values. Differences can be obtained for top surface, and bed contact surfaces. The top surfaces roughness maximum is lower than 4. The bottom surface

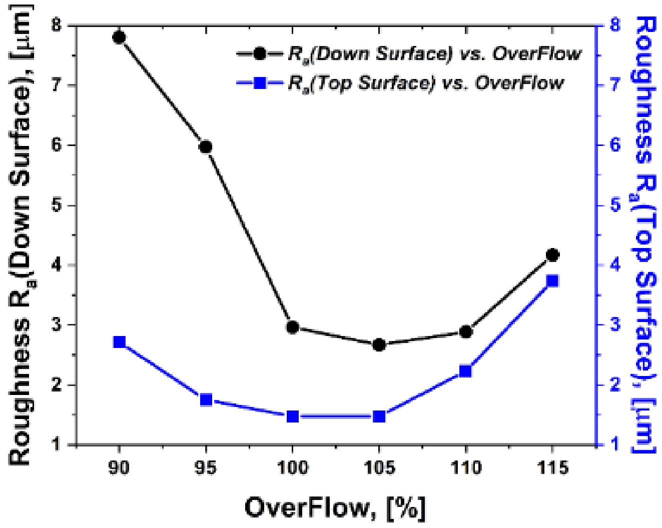


Fig. 9. The Roughness vs. OverFlow

roughness maximum is almost 8 for 90% OF parameter. These aspects must be taken into consideration when using the OF parameter variation.

3.5. Discussions

The mechanical properties of 3D printed parts are directly influenced by the deposition mode of the printed material. The material fill rate decisively influences the mechanical properties because it increases the actual cross section that is subjected to stress. The value of the real cross-section can be controlled in two ways:

- the internal structure of the part, controlled by the "Infill" parameter,
- the flow of material pushed through the nozzle, controlled by the "Overflow" parameter.

In this paper we refer to the influence of the second way of controlling the real section. The "Overflow" parameter, unlike the "Infill" parameter is only found in the 3d printer menu, and can only be set after the printing process has started.

The "Overflow" parameter can be set in percentages, and is related to the 100% flow rate set by default by the program that the printer uses. By changing this parameter, the flow rate of extruded material through the nozzle can be changed.

If this parameter is increased, the excess material will fill the interstitial voids that naturally occur in the internal structure of 3D printed parts. These triangular voids are observed in the section of parts that have been printed with 100% infill and influence the mechanical properties of the part, by appearing interruptions in the structural continuity and by decreasing the real section.

In this paper, the OF function was used with the aim of filling the gaps that appear between the deposited areas. These are mainly located at the intersection or at the base of two parallel deposition lines: the interface between layers and the interface between beads. Filling is achieved by forcing an additional amount of material to occupy these voids, without interfering with the nozzle path or travel speed.

In this paper we used 6 values for the OF parameter, from 90% to 115%, every 5 percent, to make a comparative study between the mechanical properties obtained around the 100% values. With this approach we wanted to find out if there is a possibility to improve the mechanical properties by changing this parameter and if there are disadvantages associated with changing this parameter.

4. Conclusions

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

- the mass and specific density of the samples increase linear, in direct proportion to OF (OverFlow);
- the roughness, regardless of the surface on which it was measured (down or top surface) decreases with the increase of OF up to a percentage of 105% OF, after which it follows a decreasing trend;
- the absolute values of the yield strength and the ultimate tensile strength increase up to 105% OF, then diminish;
- the specific strengths are not characterized by a major variation, being approximately constant up to a value of 105% OF, after which they record a descending tendency;
- the OF parameter, because it is only found in the printer menu, is more difficult to control. It is useful for controlling some mechanical parameters and it would be useful to be able to access it from the printer software.

As general conclusion, a slightly higher OF parameter is beneficial, but a OF value higher than 105% is not efficient either from a mechanical point of view or in terms of the roughness of 3D printed parts.

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