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The Impact of Process Parameters on Mechanical Properties of Parts Fabricated in PLA with an Open-source 3-D Printer

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1. INTRODUCTION

Rapid Prototyping (RP), Additive Manufacturing (AM) and 3D Printing (3DP) are three synonyms used to describe a range of processes which makes it possible to fabricate parts, by various materials, through an additive process, layer upon layer, starting directly from a CAD model. The first term which was coined in the mid-80s to identify these processes was *Rapid prototyping* [1,2]; *Additive Manufacturing* is the term that scientific and technical communities prefer to use as the official standard term, according to ASTM F42 and ISO TC261 committees [3,4]; *3D printing* is by far the most popular term which is being used today. As a matter of fact, Google shows about 23 million hits for 3D printing, compared to 19,5 million for Additive Manufacturing and 5,93 million for Rapid Prototyping [5].
From the first patent registered on March 11th 1986 [6] up to the present day, many things have changed. In fact, many economists define the adoption and use of 3D printing today as the "third industrial revolution", following mechanization in the 19th century and assembly-line mass production in the 20th century [7-9].
In particular, the turning point was marked by the expiration in 2009 of the Fused Deposition Modeling (FDM) patent, a technique developed by S. Scott Crump (June, 9th 1992), and the widespread open-source movement which created significant cost reductions for these new 3D printers.
Nowadays, there are many low cost 3D printers available on the market (<2000 €). They fall into three categories: not-assembled "DIY" (Do It Yourself) open-source, fully assembled open-source, and commercial systems with proprietary software.
One of the best-known open-source 3D printer project was developed in 2005 by Dr. Adrian Bowyer, of the University of Bath (UK) and is known as the Rep-Rap (Replicating Rapid prototyper) Project [10].
These self-replicating 3D printers can replicate a significant number of their own components and produce objects using the fused-filament fabrication (FFF) typically in PLA (Polylactic acid) or ABS (Acrylonitrile butadiene styrene) polymers. These systems consist of a combination of printed components, stepper motors for 3D motion and extrusion, and a hot-end for melting and depositing sequential layers of material, which are controlled by an open-source microcontroller, such as the Arduino [11]. Different official 3D printing machines have been released in the course of the Rep-Rap Project and nowadays there are hundreds of variations.
Rep-Rap 3D printers demonstrated their use in a wide range of applications for conventional prototyping and engineering [12], customizing scientific equipment [13] and appropriate technology-related product manufacturing for sustainable development [14]. However, no detailed information is currently available about the mechanical properties of parts printed by low-cost 3D printers.
Several studies were performed to investigate the modification of process parameters in order to improve the mechanical properties of parts created by using the original Stratasys FDM technology [15]. In [16] a study on the tensile strength of polycarbonate parts made by Stratasys FDM with varying process parameters such as air gap, raster width and raster angle was made. The main result was the experimental identification of the tensile strength

for parts made from FDM and its comparison with the tensile strength of the moulded and extruded PC parts. In [17] the experimental testing of ABS materials carried out by different research teams to determine the strength of FDM is reported and discussed giving a complete view of the effects produced by the different geometrical parameters. In [18] the attention is focused on the determination of the tensile strength, yield strength and modulus of elasticity for different values of build orientations of polycarbonate materials, which is, together with ABS, widely used for this kind of application. In [19] the identification of optimum values for the main geometrical parameters was related to the manufacturing time in order to achieve minimum maintenance costs. Research results suggest that orientation has a more significant influence than the raster angle on the surface roughness and the mechanical behaviour of the resulting fused deposition part. However, by examining literature, it can be noted that the investigation of mechanical properties of parts processed by open-source low-cost 3D printers is not currently receiving much attention. In particular, this applies to the material used in this study, the polylactic acid (PLA) which, unlike ABS, has not been extensively used in this kind of experiments [20].

In [21] the characteristics of mechanical properties of PLA components made using different desktop open-source RepRap 3D printers are presented. The results indicated that 3D printed components by the above 3D printers can be compared for what concerns the tensile strength and the elastic modulus to parts printed by commercial 3-D printing systems. However, it should be pointed out that a study should examine the process parameters settings in relation to the mechanical properties.

Fig. 1 - Rep-Rap Prusa I3

The present study, which was carried out at the Fraunhofer Joint Lab IDEAS-CREAMI (Interactive Design and Simulation - Center of Reverse Engineering and Additive Manufacturing Innovation) of the University of Naples Federico II, by using an open-source Rep-Rap 3-D printer, *Prusa Iteration 3* (Fig. 1), reports on the impact of three process parameters - layer thickness, infill orientation and the number of shell perimeters - on the mechanical properties of parts fabricated in PLA. The purpose is to improve our knowledge about optimal settings and assist users in the correct selection of process parameters.

2. MATERIALS AND METHODS

The open-source RepRap Prusa I3 3D printer (Fig. 1) with 0.35 mm nozzle diameter was used to fabricate the tensile test specimen (Fig. 2b) in 2.85 mm PLA material. Typical values of main mechanical properties are reported in Table 1.

Table 1 – PLA mechanical properties

The 3D printer was assembled in two days at JL IDEAS-CREAMI and calibrated with an accuracy of ±10 µm using the Mitutoyo 2046-08 (Mitutoyo, Japan), magnetic base dial indicator.
The Marlin firmware open-source software and the Simplify 3D slicing software were used to generate G-code files and to command and control the 3D printer for the fabrication of the desired parts.
The tensile testing was performed by a JJ Instruments - T5002 test machine type with crosshead speed of 2.4 mm/min (which is the minimum speed allowed by the test machine)

and a load cell of 1100 N. Three specimens per experimental run i.e. a total of 60 parts were fabricated.

Fig. 2 a) - Specimen positioned and ready to be tested – b) Test specimen dimensions [mm]

Each specimen was placed in the grips of the electromechanical testing machine (Fig. 2a) at a specified grip separation and loaded along the longitudinal axis until failure. Each manual grip clamps the end of the specimen allowing the application of the testing load through frictional contacts with the surfaces of the specimen.
The relative angular position between the loading line and the infill is highlighted in Fig. 3.

Fig. 3 - Boundary conditions and relative angle between infill and loading line

In order to determine the failure of the specimen at the minimum cross section, the geometry of the specimen conforming to the ASTM:D638 has been modified. For such a purpose, a parabolic profile for the fillet was used in combination with a curvature radius equal to 1000 mm for the opposite faces of the central portion. This modification allows the reduction of the stress concentration due to the curvature variation and ensures the failure of the specimen at the minimum cross section.

2.1 Experimental plan

The experimental characterization of FDM parts made of ABS was performed considering the tensile load. Due to the surface roughness and the manufacturing process the tensile behaviour is likely to be more critical in comparison with the compressive behaviour. Moreover, the key factor in the design process of each component is the identification of the ultimate tensile strength (UTS) by which the admissible stress is derived when a material shows a brittle behavior, as in the case which is being discussed here. For such a reason, UTS values will be identified and discussed in the following sections.
On the basis of literature review about consolidated FDM (Fused Deposition Modelling) processes [21-26] and through a focus group with open-source 3D printers experts, the main control factors considered for the tensile strength of Rep Rap processed parts are defined as follows:

- *layer thickness* [mm], the thickness of each slice of the building part. It is well-known [1, 2] that the lower the layer thickness the better the accuracy of the part. This is strictly related to the diameter of the nozzle used.
- *Infill orientation* [degree], the pattern angles for each layer and it can take values ranging from 0° to ±180°.
- *Number of shell perimeters,* is the number of shells to use for the exterior skin of the part. This one ranges from a minimum of 1 to a maximum equal to the number of filaments extruded, having a diameter equal to the diameter of the nozzle, which can be included within the perimeter of the layer.

The detailed factors were set constant, as shown in Table 2:
- *Flow rate* [%], the flow of the material that is extruded from the hot-end and is expressed as a percentage of the number of the motor revolutions of the extruder, to extrude 1 mm filament.
- *X-Y and Z deposition speed* [mm/min], the hot-end speed. The lower the deposition speed, the better the accuracy of the part and the longer the fabrication time.

- *Fill Density* [%], the quantity of material inside the part. The greater the percentage of fill the better the mechanical properties of the part but the longer the printing time and the amount of material to be used.
- *Bed Temperature* [°C], the temperature of the printing bed. This parameter depends on the material and its correct setting increases as the adhesion on the bed prevents warping phenomena.
- *Printing Temperature* [°C], the extrusion temperature of the material.
- *Outline Overlap* [%] it is a parameter which removes gaps between solid infill and outline shells.

Table 2 - Constant factors

In order to build an empirical model for tensile strength, a sequential approach to experimentation, based on *central composite design* (CCD), was adopted aiming at characterizing and optimizing the process [27-29].
A CCD is an experimental design which is often used in the Response Surface Methodology (RSM) to build a second order (quadratic) model for the response variable, without the need of a complete three-level factorial experimental plan [27]. It contains an embedded factorial or fractional factorial design with center points which are augmented with a group of 'star points' that allows an estimation of the curvature [27]. The values of axial or star points should be selected in consideration of the rotatability of a CCD.
The CCD can fit second order polynomial. In order to reduce the experiment run, the half factorial 2^k design (*k* factors each at two levels) is considered. Maximum and minimum value of each factor are coded into +1 and -1 respectively. The center point is coded into 0 and ±α level (star points) of each factor are also included. In the present work, in order to get a reasonable estimate of the experimental error, six center points are considered. Moreover, each center point was determined as the mean value over three repetitions [22].
The type of CCD used for the study is a rotatable design which uses the factor setting as the star points and creates a full factorial design within those limits. The value of α is set as $\alpha = [2^k]^{\frac{1}{4}}$. It depends on the number of factors and is chosen to maintain the rotatability property. In our case k=3 factors which gives α=1.682.
The Ultimate Tensile Stress (UTS) and the nominal strain at break (ε_f) were considered as objective functions. UTS parameters were computed as the maximum value of the stress reached during the test, whilst the ε_f is the strain attained at the UTS value.
All control factors and condition sets for the experimental treatments are listed in Tab. 3.

Table 3 - Control Factors and their levels

3. RESULTS

The experimental results obtained from the CCD runs related to the 60 samples are shown in Table 4.

Table 4 – Experimental data obtained from the CCD runs

Experimental data, obtained from CCD design runs, were analyzed through the MINITAB software using the following full quadratic response surface model:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i X_i + \sum_{i<j} \sum \beta_{ij} X_i X_j + \varepsilon$$

where y is the response, X_i is the factor, k is total number of factors.
The ANalysis Of VAriance (ANOVA) of the response surface regression of UTS versus layer thickness, infill orientation and the number of shell perimeters is shown in Table 5.

Table 5 – Response surface regression of UTS versus layer thickness, infill orientation and number of shell perimeters

Table 6 shows the ANOVA results of the response surface regression of ε_f versus layer thickness, infill orientation and number of shell perimeters.

Table 6 – Response surface regression of ε_f versus layer thickness, infill orientation and, number of shell perimeters

The single p-values given in the ANOVA tables (Tabs. 5 and 6) support the influence on the response variable UTS of X_1 (layer thickness), X_2 (infill orientation) and X_3 (the number of shell perimeters) and the advantage of a second order term for X_3. The proposed model is therefore:

$$y_{UTS} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{33} {X_3}^2 + \beta_{23} X_2 X_3 + \varepsilon$$

Fig. 4 shows the predicted optimal combination of parameters for UTS maximization.

Fig. 4 Predicted optimal combination to maximize UTS

Fig. 5 shows the predicted optimal combination of parameters for Elastic modulus maximization.

Fig. 5 Predicted optimal combination to maximize E

In Fig. 6 the contour plots of the predicted optimal combination to maximize UTS (left) and Elastic modulus (right) are shown.

Fig. 6 Contour plots of the predicted optimal combination to maximize UTS (left) and E (right)

As shown in Figure 4 and 6 (left), the combination of parameters that maximize the UTS value, by means of the response surfaces, is: layer thickness 0.2, infill orientation 0° degrees and shell parameters 3. The predicted value, of max UTS, was 55.6 MPa.
As shown in Figure 5 and 6 (right), the combination of parameters which maximize the Elastic modulus value, by means of the response surfaces, is: layer thickness 0.2, infill orientation 0° degrees and shell parameters 3. The predicted value, of max Elastic modulus, was 3736 MPa.

4. DISCUSSION

In the present paper the UTS was evaluated together with the nominal strain at break and the Elastic Modulus of FD printed specimens according to the variation of three process parameters.
It is well known that parts printed by a Rep-Rap process show an anisotropy behaviour and are very sensitive to the processing parameters affecting the meso-structure and the fibre-to-fibre bond strength [23]. The printing process consists of deposition of semi-melted filaments in a directional way, which implies that the mechanical behaviour of FD components can be investigated using the same approach adopted for composite materials. Rodriguez [23, 24] and Li [30] proposed analytical formulations to establish the constitutive models and determine the elastic constants of FD components. The common approach is that to evaluate the elastic constants using the mixture rule and introduce corrective factors by which the fibre-to-fibre bonding strength can be taken into account. However, in most applications the filament deposition in each layer is not along a single direction. In particular, the specimens produced for the present work have different numbers of filaments deposed along the perimeter, which are aligned along the longitudinal direction. The remaining part of the cross section is filled by filaments deposed along a variable angle with respect to the longitudinal direction. The deposition sequence makes the identification of a single direction in each layer impossible, in this way limiting the applicability of the analytical approach previously mentioned.
The number of perimeters is essentially a different view of the infill orientation. The effects on the strength are related to the fact that they are always oriented along the longitudinal direction of the specimen and thus contribute to withstand the axial load. Taking into account these general considerations, the results of tests carried out on the 60 specimens are being discussed in this paragraph.
First of all, it is suggested to modify the geometry of the specimen in order to overcome anomalous failures occurred in the fillet during some preliminary tests. This problem is common in literature [21, 25, 30] and it seems to be related to the approximation of the continuous curvature with the stepped geometry produced by the filaments bonded in sequence. The proposed modifications, which allow for testing all the 60 specimens always having the failure at the minimum cross section (Fig. 7), consist of a modification of the fillet geometry using a parabolic profile which is tangent to the middle part of the specimen.

Fig. 7 Failure of all 60 specimens always in correspondence of the minimum cross section

The comparison of the overall results, in terms of mean values, shows variation between different specimen sets which fall in the range 42.28 ÷ 53.59 MPa for the UTS, 2799.43 ÷ 3497.63 MPa for E (Elastic modulus) and 0.01511 ÷ 0.01932 for the ε_f.. These results confirm those reported in literature for the PLA [21] case. Moreover, it could be shown that the general trend can also be compared with that observed for similar printed parts [23, 24]. In Tabs. 7÷9, the mean values and the standard deviation of all the results are reported as a function of the three process parameters, each with five levels.

Table 7 – Mean effects of infill orientation

Table 8 – Mean effects of Layer thickness

Table 9 – Mean effects of the number of shells

In Tabs 7 ÷ 9 a larger standard deviation for the Elastic modulus and UTS values at some parameters values was observed. Moreover, the high variability of both mechanical properties occurred at the same values of the parameters. This occurrence can be explained, in accordance with [21, 22, 23], by considering that the fabrication process accuracy of about 0.125 mm, in combination with a positive air gap between fibres, affects the bonding among fibres in each layer. During the deposition process, the semi-melted filament is deposed and a discontinuous bonding occurs. The nature of such phenomenon is random and is due to this variability, different values of the stiffness and failure stress in each test are observed. The effects of such variability which are reported in the present paper are in accordance with the results discussed in a previous experimental work [21].

Fig. 8 Contour plot of the UTS in function of the three process parameters

The statistical analysis, for UTS, shows that all linear terms are significant while only the number of shell perimeters square terms is significant. Interactions between infill orientation and number of shell perimeters are significant. In this case R-sq(adj) is 68%. The combined effects of process parameters on UTS values are reported in the graphs in Fig. 8.

In particular, the strength increases as the infill orientation decreases with a rate which is as greater as the layer thickness increases. Similar results were observed considering the combined effects of the infill orientation and the number of perimeters. Increasing the number of perimeters, which are oriented along the longitudinal direction, the number of fibres, which withstand the tension load increase until the infill orientation is set to 0° and the number of perimeters is ineffective, since all fibres are lying along the longitudinal direction. Moreover, the strength increases as the layer thickness and the number of perimeters increase. As reported by [22], this effect can be explained considering that by increasing the layer thickness, a lower number of layers are needed for a given total thickness and distortion effects are minimized with an increase in strength. By reducing the number of perimeters, the tensile load is taken by the bonding surfaces between fibres and the effects of air gap become significant. The reduction becomes more and more significant as the infill orientation approaches 90°.

Fig. 9 a) - UTS and Elastic modulus vs Infill orientation – b) Normalized UTS vs infill orientation

In Fig 9 a the UTS and the Elastic modulus values are reported as a function of the infill orientation. The trends are in accordance with those theoretically and experimentally derived in [23, 24, 26, 30]. Moreover, in order to better validate these findings, the results of the presented research were compared to those reported in literature. In particular, Rodriguez [23, 24] produced many experimental data by testing specimens made of ABS P400. The data produced and those reported in literature were normalized for comparison purposes (see Fig. 9b). In Fig. 9b it can be noted that experimental values lay on the same curve. It can be then stated that the trend followed by the elastic modulus in function of the infill orientation does not depend on the material. Moreover, a linear fitting can be defined considering the mean values of both the elastic modulus and UTS values, grouped by infill orientation (see Fig. 10).

Fig. 10 Elastic modulus vs UTS values and linear regression line

The combined effects of layer thickness and the number of perimeters on the values achieved by the elastic modulus are reported in Fig. 11. The maximum value of the elastic modulus is reached at the minimum value of the layer thickness and four perimeters. On the other hand, the maximum value is reached at the minimum value of the infill orientation and the maximum value of shell perimeters. In other words, the maximum value of the Elastic modulus is reached when all fibres are oriented along the loading line. In this condition, the specimen shows the highest stiffness since each fibre takes the load and the effects of the fibre-to-fibre bonding is minimized. Moreover, the minimum value is reached at the minimum value of the layer thickness and at the maximum and minimum value, in the range investigated in the present work, of the number of perimeters. As for UTS values, lower values of the layer thickness promote a stronger bond between adjacent fibres in each layer and among layers, improving the strength. However, the competitive effects of the layer thickness and the infill orientation reduce the stiffness. This result is in accordance with the previous considerations since low values of the layer thickness or the infill orientation result in a reduced specimens deformability and, as a consequence, in an increase in stiffness [21].

Fig. 11 Contour plot of the Elastic modulus in function of the three process parameters

In Fig. 12, a microscopic view of the fracture surfaces of three tested specimens highlights the occurrence of the phenomena previously described. There are shear planes at a discontinuous bonding between fibres (Fig. 12a). Ductile failure occurs on different planes parallel to the fracture surfaces being offset from each-other. In (Fig. 12b) fibres are pulled until yielding with necking and material separation on plane which is normal to the loading direction. Infill orientation close to 90° reduces strength and stiffness because part of the tensile load is taken by the bonding surfaces among fibres, which are weaker and more prone to fail (Fig. 12c).

Fig. 12 SEM images reporting details of the fracture surfaces

According to [24], the UTS value first decreases and then increases as the layer thickness increases due to thermal diffusion properties. At the first increase in layer thickness, the effect of the thermal diffusion is to make the fibre-to-fibre bonding stronger by reducing the deformability of each layer. For a given value of the total thickness, an increase in the layer thickness results in a reduction of the number of layers, in a decrease of the deformability and consequently of the strength. However, a further increase in layer thickness allows semi-melted material to flow between the increased space among fibres and results in an increase in strength.
Fig. 13 shows the increase in strength with the number of perimeters. Moreover, the number of filaments aligned along the loading direction increases as the number of perimeters increase. The nonlinear trend of the UTS values with the number of perimeter can be explained considering that the specimens were built using a positive gap, which increases the possibility of discontinuous bonding surfaces between adjacent fibres. Therefore, stress concentration at the local bonding promotes the premature failure of the specimen.

Fig.13 - a UTS vs Number of perimeters – b UTS vs layer thickness

There is a lack in literature regarding the effects of process parameters on the strain. The statistical analysis, for ε_f, show that only a number of shell perimeters linear terms is significant, whereas only layer thickness square terms is significant. The interaction between infill orientation and the number of shell perimeters is significant. In this case R-sq(adj) is 54%. In Fig. 14 the strain at failure in function of the layer thickness and the number of perimeters are reported. An interesting effect is related to the layer thickness, since the strain value is maximum at 0.15 mm and decreases as it approaches 0.2 mm. The minimum value is reached at 0.1 mm.

Fig. 14 - a Strain at failure vs Number of perimeters – b strain at failure vs layer thickness

In order to further analyse interactions between UTS and ε_f, Fig. 15 shows the scatter plot between UTS values and the nominal strain, when results are grouped using the number of shell perimeters.

Fig. 15 Stress strain mean values estimated at the number of shell perimeters

The effects of the number of perimeters and the infill orientation on the strain at failure, the UTS and the elastic modulus values should also be discussed considering the graphs reported in Fig. 15, in combination with the two behaviours reported in the σ-ε curves (Fig. 16). These two parameters also affect the material behaviour passing from an essential brittle fracture when the filaments are all oriented along the longitudinal direction of the specimen, to a ductile behaviour as the number of perimeters is reduced and the infill orientation approaches 90° degrees.

Fig. 16 σ-ε curves

Different failures were also observed depending on different materials behaviour. The ductile fracture (Fig. 17a) corresponds to an inclined plane of fracture whilst for the brittle fracture (Fig. 17b) the separation of the two parts of the specimen occurs on the same plane of the minimum cross section.

Fig. 17 Details of the two types of failures – a ductile failure – b brittle failure

As previously stated, the strength is also affected by the ratio ρ between the portion of the cross section filled with respect to the voids [30]. Fig. 18 shows pictures of the cross sections of specimens having different ρ values. Note that the different layers are not all in contact with each-other. During the loading phase, the interaction among the different perimeters is not uniform over the thickness of specimens as well as those between perimeters and the infill material. The effect is a stress concentration at some layers that affect the specimen strength.

Fig. 18 - Images of the cross sections of specimens (20x) – a infill orientation 0° - b infill orientation 72 °

This consideration can justify some discrepancies in the experimental results presented in this paper up to a certain degree only. In addition, there may be possible parameters (e.g., micro and macro-geometrical variability, humidity and temperature) which are not being investigated in this study, but could have affected the results.

In order to validate the statistical model adopted, two replications of the confirmation experiment were carried out by setting parameters on their optimal set for UTS (layer thickness 0.2, infill orientation 0° degrees and shell parameters 3). The mean UTS value obtained from the confirmation experiment (52.3 MPa) is only 6% lower than the predicted value by the mean response surface (55.6 MPa).
The Elastic modulus value predicted by means of response surfaces, which is characterized by the following values: layer thickness 0.2, infill orientation 0° degrees and shell parameters 3, is equal to 3736 MPa. The mean Elastic modulus value obtained from tests was 3326,77 MPa, which is 10,9% lower than the predicted value.
Considering the high results variability, which was previously discussed, related to several parameters some of which are not examined in the present paper, the predicted value is in good accordance with the experimental one.

5. CONCLUSIONS

In this paper a Rep-Rap Prusa I3 open-source 3D printer was studied. By using the Simplify 3D slicing software, it was possible to vary the common process parameters and understand the impact on the mechanical properties of specimens in PLA.
The second order response surface model was used to derive the required relationship among process parameters and the tensile strength.
The analysis of the experimental results made it possible to understand the impact of control factors on the mechanical properties of specimens produced using the Rep - Rap method. With regard to UTS values, it is possible to observe a decrease in strength as the infill orientation approaches 90° degrees and an increase as the perimeters increase. An initial increase is evident as the layer thickness approaches 0.18 mm. Beyond this value, a reduction in strength values occurs. An interesting effect is related to the layer thickness, since the strain value reaches its maximum at 0.15 mm and decreases as it approaches 0.2 mm. Considering the combined effects, further correlations were observed between UTS and ε_f, when results were grouped with the infill orientation and the number of perimeters. The reliability of the statistical model was validated by comparing the predicted maximum UTS value with that established experimentally for a given parameter set.
The lack of data in literature and the high variability in experimental results, as well as the effects of other factors, such as micro and macro-geometrical variability, humidity and temperature suggest that further investigations are needed in order to improve the knowledge about the mechanical behaviour of printed components using PLA.
The experimental results can be translated into practical suggestions for the settings of process parameters with a view to improve the performance of 3D printers in relation to mechanical properties.
The methodology utilised in this study can be applied for future analyses on other low cost 3D printers.

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