Study of the manufacturing process effects of fused filament fabrication and injection molding on tensile properties of composite PLA-wood parts

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Abstract
The present study evaluates the effects of manufacturing parameters on the tensile properties of a commercial composite material based upon polylactic acid (PLA) with wood fibers known as Timberfill. The specimens are built through fused filament fabrication (FFF), and the influence of four printing parameters (layer height, fill density, printing velocity, and orientation) is considered through a $L_{27}$ Taguchi orthogonal array. Tensile tests are applied to obtain the response variable used as output results to perform the ANOVA calculations. Results show that fill density is the most influential parameter on the tensile strength, followed by building orientation and layer height, whereas the printing velocity shows no significant influence. The optimal set of parameters and levels is found, being 75% fill density, $0^\circ$Z-axis orientation, 0.4 mm layer height, and 40 mm/s velocity as the best combination. Applying this combination, a 9.37-MPa maximum strength is the highest value obtained for the material. Additionally, five solid injection molded Timberfill specimens were tested as well and the results compared with the FFF samples. The values of the elastic modulus, elastic limit, and maximum strength of the injected samples were almost twofold of those were obtained for the FFF samples, but the maximum elongation of the injected specimens fell sharply.

Keywords Additive manufacturing · 3D printing · Fused filament fabrication · Composite · PLA · Young’s module · Tensile strength

Nomenclature
AM Additive manufacturing
FFF Fused filament fabrication
DOE Design of experiments
ANOVA Analysis of variance

1 Introduction
Additive manufacturing (AM) has already gained traction in the aerospace and biomedical industries and is now being explored as a viable manufacturing method in the construction sector. Fused filament fabrication (FFF) or 3D printing is one of the most common AM techniques to fabricate complex three-dimensional components to a near-net shape. The mechanical performance of FFF 3D-printed parts depends on several manufacturing process and design parameters. Examples of manufacturing process parameters include machine tolerances, feedstock material, filament diameter, nozzle diameter, nozzle temperature, bed temperature, cooling rate (i.e., fan speed), and printing velocity [1, 2]. On the other hand, there are examples of design parameters such as building orientation, raster angle, layer thickness, and infill percentage [3, 4].

Numerous studies have investigated the effects of aforementioned parameters on the tensile strength and the other mechanical properties of applicable materials. Es-Said, O.S. et al. [5] have examined the effect of layer orientation on the
mechanical properties of rapid prototype ABS P400 samples by performing tensile, three-point bending, and impact tests. The tensile data of the ABS samples with different orientations indicate that the ultimate and yield strengths were the highest in the orientation where layers were deposited along the length of the sample (0° in X-axis), followed by those where the samples are built at 45°, −45°, and 90° in descending order. In [6], influence of five important process parameters such as layer thickness, orientation, raster angle, raster width, and air gap on three responses such as tensile, flexural, and impact strength of test specimen is considered. In this study, the desirability function concept has been used to determine optimal factor levels for improving tensile, flexural, and impact strength independently and all three strengths simultaneously. In another study Fernandez-Vicente, M. et al. [7], the influence of two controllable variables, such as pattern and density of the infill of samples produced using an open-source 3D printer on the tensile mechanical behavior, has been evaluated. The results obtained show that the influence of the different printing patterns causes a variation of less than 5% in maximum tensile strength, although the behavior is similar. The change in infill density determines mainly the tensile strength. The combination of a rectilinear pattern with a 100% infill shows the higher tensile strength, with a value of 36.4 MPa, with a difference of less than 1% from raw ABS material. A study made by John J. Laureto et al. [8] characterized the mechanical property variations of ultimate tensile strength (UTS) and yield strength of FFF-printed components of ASTM D638-14 Type I and Type IV tensile bar specimens, and multiple parameter types were evaluated for PLA material. The results show that the influence of different printing patterns varies the maximum tensile strength less than 5%. The combination of a rectilinear pattern in a 100% infill shows the higher tensile strength, with a value of 36.4 MPa, with a difference of less than 1% from raw ABS material.

Cwikla, G. et al. [9] have concluded the infill pattern, fill density, shell thickness, and printing temperature influence on the selected mechanical properties of the standardized samples, printed with low-cost standard materials (ABS), using a low-cost 3D printer. The results show that, where the objective is to have both a lightweight and durable element, the best set of parameters is the use of a honeycomb pattern with fill density of about 40–50% and a shell thickness of 2–3 layers/lines. If the maximum strength is the priority, shell thickness should be increased. The use of an infill pattern other than the honeycomb can accelerate the printing time at the expense of its strength. Tensile test has also shown that the extrusion multiplier parameter should not be set less than 0.9, because strength of the sample decreases disproportionately to filament savings. Marat-Mendes, R. et al. [10] have studied the influence of FFF processing parameters such as extrusion temperature and raster angle upon mechanical properties and microstructural features of processed PLA parts. In this research, the fill density, layer thickness, and printing velocity were kept constant at 60%, 0.2 mm, and 40 mm/s, respectively. The results indicate that mechanical performance is higher when material is stored under controlled atmosphere before use and when material deposition direction is aligned with applied load. Increasing the extrusion temperature also increases performance, by increasing deformation ability of PLA molecules. In a study focused on the influence of nozzle temperature and infill line orientations for parts made with short carbon fiber (CF)-reinforced PLA by El Magri, A. et al. [11], results have shown the influence of nozzle temperature on the mechanical properties, with an optimum temperature maximizing the tensile properties. Infill orientations also play a significant role in achieving good mechanical properties, with the proper combination of orientation enabling the tailoring of properties along a specific axis.

To reduce the consumption of petroleum-based resources and thereby enhance the eco-friendliness of the material, it could be interesting to replace ABS parts with other materials such as PLA or other composites and renewable materials for the same purposes. To this extend, other researches have compared mechanical characterizations of different materials. The results of study quantifying the basic tensile strength and elastic modulus of printed components using realistic environmental conditions for standard users of a selection of open-source 3D printers from [12] shows that parts printed from tuned, low-cost, open-source RepRap 3D printers can be considered as mechanically functional in tensile applications. For this reason, recently natural fibers have been introduced as the filler adding to common filaments. PLA composition reinforced with natural fibers such as hemp, wood, kenaf, and flax has already been studied [13–16]. Although there are a few studies on PLA-based composites, the majority of the available literatures did not use significant commercial filaments. A summary of the filler, content, and test done by these researches is provided in Table 1.

Additionally, some researchers observed mechanical behavior of parts fabricated with different manufacturing technologies [28–30] and different treatments [31–34] to achieve higher resistances of mechanical properties.

However, it is essential to characterize and understand the performance of FFF-processed Timberfill parts, while many drawbacks could be controlled by carefully choosing the processing parameters [35]. That is why the aim of the current investigation is to examine the effects of various printing parameters on innovative commercial material submitting tensile test to obtain mechanical properties. To avoid manufacturing a big number of specimens, an experimental design of Taguchi L_{27} orthogonal array was applied that refers to how participants are allocated to the different conditions. Then, to evaluate the achieved characteristics of printed Timberfill samples, a comparison was made between injection molded and printed
sample applying the same procedure. This provides a point of comparison to assess the properties achieved by the printed specimens. It is also another forte of this paper, since there are few reported studies in the literature that discuss the differences between the properties of 3D-printed parts and those obtained by other conventional manufacturing technology using the same base material.

### 2 Materials and methods

Timberfill “Rosewood” filament of 1.75 mm diameter developed and manufactured by company Filamentum Ltd. located in the Czech Republic was used to manufacture specimens for this study. Timberfill was developed with a purely aesthetic purpose that of imitating objects with a wood aspect. To achieve this goal, the company developed a composition of biodegradable PLA polymer combined with wood fibers in a 5–10% ratio. Therefore, Timberfill can be proven to be a feasible material for some practical purposes in low-scale manufacturing environments.

Timberfill is a relatively new PLA wood composite material that exhibits similar mechanical features such as ABS or PLA. Models printed with this material have a genuine appearance of wood. It is provided as a commodity material, with the purpose of becoming a commonly used material in FFF machines for various applications.

#### 2.1 Tensile testing and specimens

The tensile specimens in this work were manufactured according to ASTM D-638 standard test method for tension of plastics and composites utilizing dog-bone shape as shown in Fig. 1, with 7 mm thickness. In this study, elastic modulus (Young’s modulus), Elastic limit (Yield stress), Tensile strength, and maximum Elongation to break are calculated to characterize the mechanical behavior of Timberfill pieces submitted to tensile loads.

#### 2.2 Taguchi experimental design

To carry out the study, design of experiment (DOE) has been applied based on Taguchi method which is a robust optimization technique to make experiments to predict responses and optimize the FFF process conditions in accuracy level [36]. The factors and levels shown in Table 1 have been chosen taking into account their high effectiveness on mechanical properties that rely on previous researches [37], printer configurations, and material manufacturer recommendations. Since Timberfill is a composition of PLA polymer with wood fibers, the manufacturer have recommended to use the nozzle...
with minimum 0.5 mm diameter. Finally, it has been decided to select layer height, fill density, printing velocity, and building orientation (Table 2).

To clarify the selected parameters, Fig. 2 shows a definition of different orientations that are used in the slicer software for printing the samples. The cut section of the samples indicates the different orientation with 50% density of grid infill pattern (Fig. 2A), but the support has been applied under the thinner part of the samples in Z-axis orientation. In Fig. 2B, the height of the layers depositing on top of the previous one is shown.

To analyze the influence of the selected factors and levels, an \( L_{27} \) Taguchi orthogonal array has been applied using Minitab 18 software for statistical calculations (Table 3).

It should be mentioned that for each manufacturing parameter set or run included in the array, 5 specimens were manufactured individually and tested, to guarantee the repeatability of the results. Therefore, the rest of the parameters that are not object of study have been kept constant among all specimens (Table 4).

### 2.3 Specimen manufacture

According to the abovementioned test method, the sample was designed by the Catia V5 software with the actual shape and dimensions and has been exported to an STL format, so that it can be read and interpreted by the printing parameterization software. In this project, the Repetier-Host (Slic3r) software has been used which the G-code is obtained to be able to print. All of the specimens were printed using Prusa i3 printer.

### Table 2 Factors and levels used for the DOE

| Parameters       | Level  |
|------------------|--------|
|                  | 1  | 2  | 3  |
| Layer height (mm) | 0.2 | 0.3 | 0.4 |
| Fill density (%)  | 25 | 50 | 75 |
| Velocity (mm/s)   | 30 | 35 | 40 |
| Orientation       | X-axis | 45° X-axis | Z-axis |

### Table 3 L27 Taguchi orthogonal array of DOE

| Runs | Layer height (mm) | Fill density (%) | Velocity (mm/s) | Orientation  |
|------|-------------------|------------------|-----------------|--------------|
| 1    | 0.2               | 25               | 30              | X-axis       |
| 2    | 0.2               | 25               | 35              | 45° X-axis   |
| 3    | 0.2               | 25               | 40              | Z-axis       |
| 4    | 0.2               | 50               | 30              | 45° X-axis   |
| 5    | 0.2               | 50               | 35              | Z-axis       |
| 6    | 0.2               | 50               | 40              | X-axis       |
| 7    | 0.2               | 75               | 30              | Z-axis       |
| 8    | 0.2               | 75               | 35              | X-axis       |
| 9    | 0.2               | 75               | 40              | 45° X-axis   |
| 10   | 0.3               | 25               | 30              | 45° X-axis   |
| 11   | 0.3               | 25               | 35              | Z-axis       |
| 12   | 0.3               | 25               | 40              | X-axis       |
| 13   | 0.3               | 50               | 30              | Z-axis       |
| 14   | 0.3               | 50               | 35              | X-axis       |
| 15   | 0.3               | 50               | 40              | 45° X-axis   |
| 16   | 0.3               | 75               | 30              | X-axis       |
| 17   | 0.3               | 75               | 35              | 45° X-axis   |
| 18   | 0.3               | 75               | 40              | Z-axis       |
| 19   | 0.4               | 25               | 30              | Z-axis       |
| 20   | 0.4               | 25               | 35              | X-axis       |
| 21   | 0.4               | 25               | 40              | 45° X-axis   |
| 22   | 0.4               | 50               | 30              | X-axis       |
| 23   | 0.4               | 50               | 35              | 45° X-axis   |
| 24   | 0.4               | 50               | 40              | Z-axis       |
| 25   | 0.4               | 75               | 30              | 45° X-axis   |
| 26   | 0.4               | 75               | 35              | Z-axis       |
| 27   | 0.4               | 75               | 40              | X-axis       |
Five specimens were also manufactured through the injection process. The same raw material used for the printed specimens was used for this. In this way, the results obtained can be comparable. These specimens were manufactured in the condition which is defined in Table 5.

2.4 Experimental setup

Once all the samples were manufactured, they have been measured to achieve the average area by calculating from the width and thickness of four different sections of samples using digital micrometer.

The universal Microtest EM2/20 machine has been used for these tensile tests equipped with a 25 kN load cell at a 1 mm/min displacement rate, 50 mm extensometer, a Spider and Microtest data acquisition system, two S1 pneumatic jaws, and the Microtest SCM3000-Catman 4.5 control software. In the other side, this setup consist of a set of a high-definition (HD) camera that records the test video at 60 Hz sampling frequency, which is also connected to the spider data logger. The camera has been applied to illuminate the test area and to synchronize the data using a switch-controlled flash (Fig. 3).

Once all the setup is equipped and adjusted, the tests are carried out for all of the 135 FFF specimens and the 5 injected samples.

2.5 Analyzing process

After each test has been completed, two different files are achieved from the data logger: first, a file that includes the force collected from the load cell and displacement of the extensometers, as well as the recorded voltage versus time, and, second, the video recorded by the camera that provided graphical information to compute the strain of the specimen at every stage of the test.

To obtain the defined mechanical properties such as Young’s modulus ($E$), yield strength ($R_{p0.2}$), maximum strength ($\sigma_{\text{max}}$), and maximum deformation ($\varepsilon$), MATLAB R2018b software is used to analyze the data. To perform this analysis, several steps have been followed. First of all, the HD video was processed to obtain each photo frame during the test. In the second step, the photo frames and the recorded data are synchronized by means of a MATLAB script. Next, a rectangular grid pattern is generated in the initial frame of the test sample dotted in red crosses (Fig. 4a). This gridding recognizes the displacement on the section of samples while the deflection occurs (Fig. 4b). During the next step, the marked pixels are tracked and deflection is computed consequently based on the differences between the initial and final position. By finishing this step, two scroll files have been generated which can be used for the deflection script to transfer the values of the points into real deformations. After using the deflection obtained in this step, the process continues to calculate the deformation and create the stress-strain curve.

3 Results and discussion

Table 6 includes the average results of the five repetitions for each manufacturing configuration.

3.1 Analysis of variance

Once the results were obtained, the statistical calculation through analysis of variance (ANOVA) was performed on the dataset included in the Taguchi experimental array, for each parameter that describes the mechanical behavior of the evaluated specimens by the Minitab 18 software. To validate the statistical significance of the parameters included in the model on each of the responses, the $p$ value associated to the ANOVA was compared with a significance level of 5%. In addition, the interactions between the different parameters were analyzed which leads to the conclusion that if there is significant interaction among the pairs of selected values or not, the $p$ values of each pairs should be less than 0.05.

3.1.1 Young’s modulus

In this case, it can be concluded that the most significant parameters, due to their $p$ values, are the fill density and orientation as shown in Fig. 5. This graph evidences that the fill
density results have a direct relation with the Young’s modulus that means higher values of density result in a higher elastic modulus that can be clearly due to the solidity percentage of inside the samples. As it can be seen from the figure, the samples built in Z-axis orientation have shown higher elastic module, and the most significant reason could be depositing layers more than the other building directions. Based on the obtained \( p \) values, layer height also can be taken into account because the value is not so much bigger than 0.05, but printing velocity does not show a significant effect on the Young’s modulus.

Table 6 Results obtained for experimental runs

|   | \( E \) (GPa) | \( S_{0.2} \) (MPa) | \( \sigma_{\text{max}} \) (MPa) | \( \varepsilon_{\text{max}} \) (%) |
|---|--------------|------------------|-----------------|------------------|
| 1 | 0.65 ± 0.06  | 4.50 ± 0.48      | 4.93 ± 0.60     | 1.34 ± 0.25      |
| 2 | 0.60 ± 0.03  | 4.21 ± 0.02      | 4.84 ± 0.22     | 2.03 ± 0.21      |
| 3 | 0.71 ± 0.02  | 4.97 ± 0.24      | 5.16 ± 0.40     | 1.06 ± 0.17      |
| 4 | 0.64 ± 0.00  | 4.98 ± 0.14      | 5.73 ± 0.29     | 2.0 ± 0.50       |
| 5 | 0.80 ± 0.03  | 5.54 ± 0.06      | 5.97 ± 0.16     | 1.42 ± 0.27      |
| 6 | 0.72 ± 0.02  | 4.83 ± 0.17      | 5.39 ± 0.22     | 1.90 ± 0.19      |
| 7 | 1.06 ± 0.07  | 7.07 ± 0.15      | 7.81 ± 0.13     | 2.01 ± 0.10      |
| 8 | 0.93 ± 0.06  | 6.03 ± 0.31      | 6.73 ± 0.31     | 1.77 ± 0.15      |
| 9 | 0.91 ± 0.03  | 6.84 ± 0.41      | 8.17 ± 0.52     | 2.63 ± 0.35      |
|10 | 0.58 ± 0.02  | 4.31 ± 0.26      | 5.05 ± 0.26     | 2.23 ± 0.45      |
|11 | 0.74 ± 0.05  | 5.61 ± 0.7       | 6.17 ± 0.55     | 1.78 ± 0.37      |
|12 | 0.68 ± 0.01  | 4.78 ± 0.13      | 5.26 ± 0.12     | 1.65 ± 0.11      |
|13 | 0.98 ± 0.06  | 7.02 ± 0.24      | 7.37 ± 0.19     | 1.28 ± 0.09      |
|14 | 0.79 ± 0.02  | 5.74 ± 0.18      | 6.36 ± 0.19     | 2.34 ± 0.15      |
|15 | 0.69 ± 0.05  | 5.43 ± 0.48      | 6.43 ± 0.57     | 3.03 ± 0.60      |
|16 | 0.81 ± 0.02  | 5.67 ± 0.11      | 6.34 ± 0.12     | 2.36 ± 0.25      |
|17 | 0.81 ± 0.03  | 6.19 ± 0.20      | 7.63 ± 0.25     | 3.56 ± 0.50      |
|18 | 1.21 ± 0.05  | 8.95 ± 0.30      | 9.37 ± 0.27     | 1.42 ± 0.12      |
|19 | 0.72 ± 0.00  | 5.25 ± 0.10      | 5.67 ± 0.17     | 1.41 ± 0.15      |
|20 | 0.77 ± 0.02  | 5.82 ± 0.23      | 6.35 ± 0.16     | 1.75 ± 0.29      |
|21 | 0.65 ± 0.02  | 4.84 ± 0.19      | 5.58 ± 0.26     | 2.69 ± 0.37      |
|22 | 0.87 ± 0.02  | 6.61 ± 0.14      | 7.22 ± 0.18     | 1.95 ± 0.25      |
|23 | 0.70 ± 0.01  | 5.68 ± 0.19      | 6.55 ± 0.25     | 2.35 ± 0.29      |
|24 | 1.13 ± 0.20  | 7.61 ± 0.48      | 8.15 ± 0.37     | 1.13 ± 0.10      |
|25 | 0.88 ± 0.04  | 6.71 ± 0.18      | 7.94 ± 0.31     | 2.35 ± 0.43      |
|26 | 1.20 ± 0.07  | 8.90 ± 0.32      | 9.15 ± 0.42     | 1.27 ± 0.23      |
|27 | 1.06 ± 0.03  | 7.82 ± 0.09      | 8.55 ± 0.04     | 2.42 ± 0.50      |

In this case, obtained \( p \) values of parameter interactions were more than 0.05; it means that the selected parameters in this study are independent of each other, at least in the analyzed value ranges for Young’s modulus.
3.1.2 Yield strength

It is necessary to analyze the effects of the variation of the different factors on the yield strength, which is indicated in graph of main effects for the averages (Fig. 6). The most significant parameters on the yield strength according to the \( p \) values are fill density, followed by orientation, and layer height. The effectiveness of these parameters has been repeated due to the fact that occurred in case of Young’s modulus. So that to achieve the bigger yield strength, the bigger values of layer height and fill density in \( Z \)-axis orientation should be selected.

Similar to the interaction between parameters on Young’s modulus, the \( p \) value does not show significance on yield strength. It means there is no influential interaction between parameters.

3.1.3 Maximum stress

Regarding the obtained \( p \) values from the factors on maximum stress as shown in Fig. 7, the most significant parameters are fill density, layer height, and orientation in descending order. Printing velocity has not as significant effect on this property. The higher maximum stress is obtained by more fill density and bigger height of the layers. In order to orientation, the higher values are achieved from the printed samples in \( Z \)-axis. These parameters have exhibited the same effectiveness of Young’s modulus and yield strength to the maximum stress as well.

The obtained \( p \) values of interaction are higher than 0.05; therefore, the interaction between parameters should not be taken into account as a significant, like in the previous properties analyzed.

3.1.4 Maximum deformation

In case of maximum deformation, the fill density, layer height, and velocity are not influential parameters, whereas building orientation has shown remarkable effect on the maximum deformation according to the \( p \) values. The higher maximum deformations are obtained from those specimens printed at
in X-axis orientation as shown in Fig. 8. In this case, the correlation between the raster angles to generate the honeycomb shape and the tensile test direction could be mentionable in order to obtained higher maximum deformation of the samples printed in this orientation. Also, the obtained $p$ values of interaction for this response are higher than 0.05; therefore, the interaction between parameters should not be taken into account as a significant.

### Table 7 Summary of significances on responses

| Response                        | Influential parameter                  |
|---------------------------------|----------------------------------------|
| Young’s modulus (E) Elastic properties | Fill density, 75% Orientation, Z-axis |
| Yield strength ($S_{0.2}$)      | Fill density, 75% Orientation, Z-axis  |
| Maximum stress ($\sigma_{\text{max}}$) Plastic properties | Fill density, 75% Layer height, 0.4 |
| Maximum deformation ($\varepsilon$) | Orientation, 45°X-axis               |

### 3.2 Results and discussion

An overview of the results is summarized in Table 7. Based on the $p$ values, the most influential parameters and the levels on the responses are indicated in the relevant cells.

These results evidence that each of the analyzed parameters is related to a different stress-strain functional regime of the FFF Timberfill material. Since the deposited layers’ direction in building Z-axis orientation is aligned to the test axis, it causes the material to endure the stress and the effectiveness of this parameter in elastic regime.

The obtained optimal set of parameters are shown in Table 8. It is worth mentioning that, as the printing velocity...
is not influential in any case, the lowest value has been taken for the sake of productivity.

3.3 Comparison between FFF and injected results

Engineering stress-strain curves achieved from printed and injected samples are shown in Fig. 9. The average of achieved values of Young’s modulus, yield strength, maximum stress, and maximum deformation from the FFF manufactured samples are almost ½ of obtained from the injected samples, while the maximum deformation average of injected samples is lower than FFF samples observably (Table 9), meaning the injection process enhances the overall behavior of the material.

Since the tensile stresses are produced across the whole cross section, the injected specimen demonstrated higher strength to the tension than printed specimens when they are submitted to tensile test. The printed sample meets smaller mean failure which agrees to the solidity percentage of the samples. In contrary, the higher maximum deformation of printed sample can be due to the disengagement of the extruded wires one by one.

| Maximum values | Printed | Injected |
|----------------|---------|----------|
| Timberfill     | 1.21    | 2.81     |
| Yield strength (MPa) | 8.95    | 16.47    |
| Maximum stress (MPa)   | 9.37    | 16.95    |
| Maximum deformation (%) | 3.56    | 0.51     |

Fig. 9 Strain-stress curve of FFF and injected Timberfill

Fig. 10 SEM image of the fractured zone of the samples
3.4 SEM fractography

To clarify the failure mode submitted to tensile test for both injected and printed samples, scanning electron microscopy images of broken zone have been taken (Fig. 10). According to the nature of the material, both different manufactured parts showed brittle behavior to which there are no sign of extending zone due to plasticity. The main reason of this phenomenon could be the poor adhesion of the wood fibers to the matrix that causes an interruption of the molecular chain of the matrix polymer. Also the smooth surface of the wood fibers might experience less friction with the matrix so that lower resistance against the applied load is presented.

Secondly, the existence particles with smaller size less than 10 μm (wood flour) might have decreased the viscosity of the semi-melted material and caused the porosity in the extruded wires which this factor did not happened for the injected samples that can be another reason of the lower resistance of the printed specimens than the injected ones and subsequently than the obtained results for pure PLA.

Thirdly from the material science point of view, the fiber volume ratio or the fraction of fiber reinforcement plays a very important role in determining the overall mechanical properties of the composites as that a higher fiber volume fraction typically results in better mechanical properties of the composite [38]. Therefore, Timberfill is not exempted of this rule neither. Based on the manufacturer statements, the volumetric percentage of the fibers to matrix is in the range of 5–10%, so increasing this percentage can arise the resistance of the material.

4 Conclusions

This study shows the effects of different printing parameters on the mechanical properties of wood-reinforced PLA (Timberfill) material. The selected parameters in this work are as follows: layer height, fill density, printing velocity, and orientation. The mechanical properties that are object of this research are Young’s modulus, yield strength, maximum stress, and maximum deformation. Firstly, it was found that a combination of 75% fill density, Z-axis orientation, and 0.4 mm layer height exhibits the best mechanical properties with their effectiveness in descending order, regardless of the printing velocity. Although:

- The most effective printing parameters are building orientation, fill density, and layer height in the descending order, but there were no significant interaction between them.
- Considering the obtained $p$ value, printing velocity has no critical influence on the responses.
- The achieved Young’s modulus, yield strength, and maximum stress of the injection molded parts were higher than printed ones taking into account the solidity percentages of the samples. Maximum deformation of the printed samples was considerably higher than injected samples.
- Altogether, the achieved values for the responses of this material are not high enough as a thermoplastic composite which the composition percentage of the fibers to matrix could be one reason of its deficiency. Also, creating a good interface between matrix and fibers by performing chemical treatments can be a great career on this field.

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