Parameter design of PLA/Wood Fused Filament Fabrication using Taguchi optimization methodology

John D. Kechagias (✉ jhnkchgs@gmail.com)

University of Thessaly: Panepistemio Thessalias <https://orcid.org/0000-0002-5768-4285>

Stephanos Zaoutsos

University of Thessaly

Dimitrios Chaidas

University of Thessaly

Nectarios Vidakis

Hellenic Mediterranean University

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Abstract

This study investigates the effects of four variables during fused filament fabrication of organic biocompatible composite material, PLA with coconut flour, at the ultimate tensile strength and elasticity module of the printed parts. The parameter optimization uses Taguchi L18 design and regression models. The examined deposition variables are the layer thickness, the nozzle temperature, the raster deposition angle, and filament printing speed. The effects of the above variables on the strength of the parts are essential to enhance the mechanical response of the printed parts. The experimental outcomes are investigated using the ANOM and ANOVA analysis and modeled utilizing linear regression models. In addition, an independent experiment was repeated three times at optimum parameters' levels to evaluate the methodology, giving predictions errors less than 3%.

Article Highlights

- Organic PLA wood material for eco-friendly additive manufacturing
- Robust design with applying the L18 Taguchi orthogonal array
- Mechanical response optimized considerably after Taguchi methodology
- Three evaluation experiments at optimum conditions with errors less than 3%

1. Introduction

Additive manufacturing (AM) is a sub-group of manufacturing processes that uses metallic, plastic, ceramic, and composite materials in solid-state (powders, filaments, sheets, bars, etc.) or fluids (liquid or droplets) that are deposited using plenty of different deposition mechanisms and techniques[1]. Fused filament fabrication (FFF), also known as Fused Deposition Modeling (FDM) or 3D printing (3DP), is the most popular among AM processes due to the simple deposition mechanism and the variety of available materials that exist in the market. Nowadays, more innovative materials and colours are extensively used in an eco-friendly way in applications, including the furniture industry, design, and fashion, among others [2].

The strength of the FFF parts is one of the main concerns of the end-users when the material deposition parameters are selected before the printing process starts [3]. The strength characteristics of FFF parts have been continuously explored for over two decades [4]. Part orientation inside the build space and the deposition parameters affect the interlaminar strength between the deposited material [5] and consequently the strength and the surface quality of the FFF parts [6]. The raster deposition angle (DA) also affects the tensile stress of polylactic acid (PLA) FFF parts [7]. It is observed that the PLA parts in X build orientation (zero DA) exhibit higher tensile stress than those in Y and 45° deposition directions. The solid print mode is used for all the experiments, which means that the FFF variables such as the nozzle temperature (NT), printing speed (PS), and layer thickness (LT) were kept constant. The LT and the orientation of the specimens on the X-Y platform also affect the tensile strength of the ABS-FFF parts [8].

Many other studies have been examined the effects of the LT, part build orientation, raster angle, raster width, and air gap on the strength characteristics of the FFF test specimen [9–11]. It is concluded that the strength of the FFF parts varies according to the quality of the interlayer bond formation. The thermal properties of the polymeric materials and the deposition rates need optimization to achieve a robust bond interface and better strength [12]. All the investigations conclude that different printing parameters are appropriate for each other material for optimizing the quality of FFF parts, such as strength and shape accuracy.

Concerning the organic biocompatible composites, PLA mixed with wood flours materials (PLA/W); research effort has been applied for investigating the strength properties according to material synthesis [13–16] and the FFF parameters [17–19]. dependable adhesion between PLA and wood flours is reported in Faludi et al [14]. In Chansoda et al. [13], the utilization of parawood powder derived from the furniture industry is tested as an infilled material in the PLA matrix. Zandi et al. [18] investigate the fatigue behavior of a PLA/W (Timberfill, 8% wood fibers) processed through FFF process parameters, i.e., the layer height, the nozzle diameter, the infill density, and the printing velocity. They used the Taguchi L27 orthogonal array and found that the layer height was the most critical parameter. In Kain et al. [20], two wood fiber contents (15 and 25 %; Wood fibers, ARBOCEL C100) mixed with PLA (Ingeo™ 3251D) are tested in different raster DA during FFF (0-90; step 15 degrees). It is proved that the 25% wood content gives better strength than 15% and that the infill DA affects the strength of the FFF parts. The strength performance of PLA/W parts, changing the NT between 210 and 250°C also investigated [21]. The increase of the NT from 210 to 230°C improves the strength slightly. Above 230 °C, the strength is influenced by the wood particle's degradation and is not suggested. Ayilmis et. [19] alinvestigated the impact of LT on the water absorption and strength of FFF-PLA/W specimens. By increasing the LT, the water absorption and the cross-section porosity increase, and the durability decrease. More, it was found that the density of the printed PLA/W part increased as the PS decreased and that the UTS and flexural properties of the FFF-PLA/W specimens were not altered significantly by the deposition rates [17].

The above researchers investigated the influence of the FFF parameters on the strength of different PLA wood flour contents. In conclusion, to the author's knowledge, it was not reported any research in literature where the influence of the LT, NT, raster DA, and PS on 3D printed PLA/W is studied. Moreover, the proposed experimental area of the selected parameters is investigated for the first time.

Therefore, this work is an experimental investigation of how these four FFF parameters, the LT, NT, raster DA, and PS, influence the tensile strength and the elasticity module of the PLA mixed with coconut wood flour FFF parts. The results were analyzed and presented using statistical tools such as main effect plots (MEP), analysis of variances (ANOVA), interaction charts, and linear regression models. So, the optimum parameters proposed to optimize the strength of the organic biocompatible composite FFF-PLA/W material.

2. Materials And Methods

2.1. Preparation of experiment

According to ASTM D638 standards (see Fig. 1a), a dogbone was designed having a thickness of 4mm and translated in STL format at the SolidWorks CAD program. Then, the Craftbot Plus 3D printer (Fig. 1b) fabricated the specimens. Its platform is made of aluminum, thus giving the capability for printing specimens using different types of material. The maximum volume of the vat was 250 X 200 X 200 mm, and the printing speed was up to 200 mm/s. The commercially available material NEEMA3D™ WOODPLUS consisted of 30% wood fibers of coconut and additives, and 70% pure PLA polymer was utilized. The filament diameter was 1.75mm. The specific gravity was 1.2g/cc (ASTM D1505), the melting point between 140-150°, and the nozzle's diameter was 0.4mm. The minimum produced tensile strength and modulus is 70 MPa 1900 MPa, respectively (ASTM D882).

The static tensile testing is performed on a strain-controlled Instron 3382 Universal Testing Machine with a load capacity of 100 kN, as per ISO, equipped with an especially gripping fixture as shown in Fig. 2. All specimens were manipulated at a crosshead speed rate of 1mm/min. At the same time, force and displacement data for each test coupon were recorded through a data acquisition system and stored through BlueHill software for further treatment.

2.2. Design of experiment

In the current study, the Taguchi L18 ($2^1 \times 3^7$) experimental approach was employed [22–24]. This methodology adopts balanced experiments according to Taguchi's proposed Orthogonal Arrays (OA). Although the number of the executed experiments is a fraction of the full combinatorial design, the results are proved to find the best parameter levels and construct predictive mathematical models [25, 26]. Finally, three validation experiments against the best conditions are applied to verify the experimental design and evaluate the experiment's spread at the optimum conditions.

The first step in the above approach is selecting the variable parameters that affect the aspired attributes: the UTS and the elasticity module (E). This task is critical and has two main concerns: (i) to select the appropriate variable parameters and levels and (ii) all the experiments of the decided orthogonal array (OA) to be achievable (should do all experiments contained in the OA).

After the literature review in the introduction section and a 'trial-and-error' procedure, the selected variables and the constant parameters are tabulated in Table 1. According to the literature review, layer height and nozzle temperature (LT and NT) influence the dimensional accuracy, surface roughness, and mechanical response of the FFF parts [3]. In addition, raster deposition angle (DA) is also an essential parameter [27]. It affects the strength of the FFF parts, as this parameter defines the direction of the strands of the woven pattern. Finally, the printing speed determines the time between layers and affects the interlaminar quality between layers [12]. All other FFF process parameters were kept constant in this study to minimize the noise error.

Table 1
Parameters with levels.

Parameters	Units	Levels			
		1	2	3	
Variable parameters					
Layer Thickness (LT)	(mm)	0.1	0.3	-	
Nozzle Temperature (NT)	(°C)	180	200	220	
Deposition Angle (DA)	(degrees)	0	45	90	
Printing Speed (PS)	mm/s	30	40	50	
Constant parameters					
Travel speed	mm/s	40			
Infill density	%	100			
Bed temperature	°C	60			
Room temperature	°C	20			
Room humidity	%	50			
Outline/perimeter shells/top layers/bottom layers	Number	1/1/1			

The Taguchi orthogonal array, known as L18, is adopted for the above variable parameters and levels. This OA consists of eighteen arrays and eight columns [28, 29]. The eighteen arrays show the number of the experiments, 18 experiments, and the columns show the possible variables [23]. We have used only 4 out of 8 columns, i.e., four parameters (LT, NT, DA, and PS). According to the Taguchi approach, the empty columns contribute to calculating the error. So, it is not necessary to repeat each combination of the 18 experiments. Table 2 lists the variable parameters (LT, NT, DA and PS), the measured attributes (UTS and E), and the eighteen (18) fractional combinatorial experimental design according to the Taguchi L18 ($2^1 \times 3^7$) OA. The eighteen printed dogbones and strength experiments were done very carefully to eliminate noise errors.

Table 2
Parameter combinations and experimental measurements.

Variable parameters, $L_{18} (1^2 \times 7^3)$					Attributes measured					
	1	2	3	4	5	6	7	8		
No exp.	LT (mm)	NT (°C)	DA (o)	PS (mm/s)	Empty Columns				UTS (Mpa)	E (MPa)
1	0.1	180	0	30	-	-	-	-	17.420	692.62
2	0.1	180	45	40	-	-	-	-	7.043	410.59
3	0.1	180	90	50	-	-	-	-	5.480	347.95
4	0.1	200	0	30	-	-	-	-	15.410	627.77
5	0.1	200	45	40	-	-	-	-	10.240	448.88
6	0.1	200	90	50	-	-	-	-	7.745	375.92
7	0.1	220	0	40	-	-	-	-	16.920	651.88
8	0.1	220	45	50	-	-	-	-	12.580	478.50
9	0.1	220	90	30	-	-	-	-	10.010	445.97
10	0.3	180	0	50	-	-	-	-	16.920	678.84
11	0.3	180	45	30	-	-	-	-	12.145	425.52
12	0.3	180	90	40	-	-	-	-	8.970	374.89
13	0.3	200	0	40	-	-	-	-	15.420	624.65
14	0.3	200	45	50	-	-	-	-	12.080	468.83
15	0.3	200	90	30	-	-	-	-	10.010	402.12
16	0.3	220	0	50	-	-	-	-	15.210	611.23
17	0.3	220	45	30	-	-	-	-	12.007	483.17
18	0.3	220	90	40	-	-	-	-	10.150	431.88
Average									11.987	498.96
Min									5.480	347.95
Max									17.420	692.62
Spread									11.94	344.67

3. Results And Discussion

All the results from the experiments conducted in this work are presented in Table 2. The UTS is the higher tension that a material can sustain while being stressed before breaking. At the same time, the elasticity module (E) is the linear proportion between the stress and the strain in the elastic deformation zone of the stress-strain curve. Thus, both the UTS and E are used for characterizing the material's withstand properties. The results basic statistics of the process performance are presented in Table 2 (mean, min, max, spread). It is evident that the spread values of the mechanical response are considerable, 100% and 69% for the UTS and E. Thus, process optimization is vital for sustainable FFF printings [30].

3.1 Effects of the variable parameters on UTS and E

The diagrams that show the effects of the variable parameters on an attribute are known as ANOM diagrams (analysis of means) or main effect plots (MEP). Such diagrams explain the influence of each variable graphically in consideration of the attribute measure and are utilized for finding the optimum levels of the variables. For example, by employing these plots, the effects of the four process parameters (LT, NT, DA, and PS) on both the UTS and E can be extracted (see: Fig. 3).

The MEP plots showed that the dominant parameter in the utilized experimental space for the UTS and E measures is the DA. The three other variables are significant at a lower level. Due to both the UTS and E being characterized as 'the maximum the best' attributes, the optimized values for all the variables are zero DA, 30 mm/s PS, 220°C, and 0.3 mm LT.

A way for identifying how one parameter interacts with another is by utilizing the interaction plots [29, 31, 32]. Fig. 4a and 4b show how LT, NT, DA and PS interact concerning the UTS and E accordingly. These two plots show a strong interaction between the dominant parameter DA and the others (PS, NT, and LT).

After the MEP and interaction plots, the ANOVA analysis is the qualitative tool to investigate the importance of each variable parameter on the quality attributes (here, the UTS and E). Analysis of variances (ANOVA) decomposes the errors of each variable on the total error when a mathematical model is fitted on the results. The 'MEP' plots results showed that the DA is the dominant parameter. Therefore, it is decided to use linear regression models for the 'UTS' and 'E' analysis of variances (see: Tables 3 and 4, respectively).

Table 3. ANOVA analysis: UTS versus DA; PS; NT; LT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
DA	2	176.746	88.373	35.68	0.000	80.1%
PS	2	6.592	3.296	1.33	0.307	3.0%
NT	2	6.857	3.428	1.38	0.295	3.1%
LT	1	5.627	5.627	2.27	0.163	2.6%
Error	10	24.766	2.477			11.2%
Total	17	220.587				100.0%
R ²						88.77%
R ² adj						80.91%
R ² pred						63.62%

Table 4. ANOVA analysis: E versus DA; PS; NT; LT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%
DA	2	208926	104463	88.24	0.000	92.6%
PS	2	1769	884	0.75	0.498	0.8%
NT	2	2991	1495	1.26	0.324	1.3%
LT	1	25	25	0.02	0.888	0.0%
Error	10	11838	1184			5.2%
Total	17	225548				100.0%
R ²						94.75%
R ² adj						91.08%
R ² pred						82.99%

The ANOVA showed that the DA variable affects 80.1% and 92.6% on UTS and E, respectively. The three other variables (PS, NT, and LT) are insignificant for both the UTS and E, respectively. The F values are below two, and the P values are higher than 0.05.

The outcomes occurring from Figs 3 and 4 as well as of Tables 3 and 4 conclude in the following:

The raster DA parameter dominates both the UTS and E values, 80.1% and 92.6%, accordingly. The F values are higher than four (4) and P values smaller than 0.05, which means this conclusion is

statistically significant. The best value for the raster DA is zero degrees, and the worst the 90°. The interactions of raster DA with the other parameters are slightly synergistic (Fig. 4). The mechanical response (UTS and E) increases by decreasing the raster deposition angle. It means physically that the zero degrees aligned filament show the highest UTS and E values.

The other three parameters (NT, PS, and LT) are of lower importance for the utilized experimental space. The F values are smaller than 2, and P values are higher than 0.05 ($F < 2$ and $P > 0.05$). It is noted that the F value for the LT concerning the UTS attribute is between 2 and 4 ($2 < F_{LT} < 4$), which statistically means that it is more significant than the NT and PS. These statistical values show that the PS, NT, and LT affect the optimal thermal bonding condition in an anti-synergistic way (see interaction charts, Fig. 4).

Considering previous experimental work and knowing that the interlaminar bonding conditions are affected initially by the PS and NT, and secondly, by the LT [33], the following MEP plots (Fig. 5) are drawn using the subsets of 0.1 mm and 0.3 mm of the LT parameter of Table 2. It is concluded that the NT is a significant parameter for 0.1 mm LT and not significant for 0.3 mm LT, denoting that the interlaminar conditions are different in the case of 0.3 and 0.1 LT.

The NT has different trend lines for 0.1 and 0.3 LT. In the case of 0.1 LT, when the NT increases, the UTS and E increase (Figs 5a and 5b). On the other hand, for 0.3 LT, the NT is insignificant for both UTS and E (Figs 5c and 5d).

Finally, concerning the PS parameter, Figs 5a-d show a significant influence for both UTS and E attributes for each of the two LT (0.1 and 0.3 correspondingly). An increase in the values of the PS parameter results in the decrease of the values of the UTS and E for 0.1 LT, followed by a respective increase for 0.3 LT. In the total experimental space (Fig. 3), the trend line of the PS is similar to that of the 0.1 LT (Figs 5a and 5b). The ANOVA analysis shows that the PS is an insignificant parameter ($F < 2$ and $P > 0.05$; Tables 3 and 4).

3.2 Modeling and validation

Considering the ANOM analysis (Table 3 and 4) and the MEP plots (Figs 3 and 5) as well as the interactions charts (Fig. 4), linear regression models were developed for both the UTS and E for the 0.1 mm and 0.3 mm LT respectively (eq. 1-4).

$$UTS_{LT=0.1mm} = 2.84 - 0.0889 * DA - 0.0839 * PS + 0.0797 * NT \pm e \quad (1)$$

$$E_{LT=0.1mm} = 549 - 2.570 * DA - 3.62 * PS + 1.04 * NT \pm e \quad (2)$$

$$UTS_{LT=0.3mm} = 15.89 - 0.06615 * DA + 0.0186 * PS - 0.0056 * NT \pm e \quad (3)$$

$$E_{LT=0.3mm} = 444 - 2.379 * DA + 2.12 * PS + 0.392 * NT \pm e \quad (4)$$

Finally, three evaluation experiments are executed to validate the developed regression models (Table 5). The specimens for the validation experiments were built with the optimized parameters according to the MEP in Fig. 3 (zero DA, 0.3 mm LT, 30 mm/s PS and 220 °C NT). All three experiments give accurate predictions with an accuracy lower than $\pm 5\%$, which means that the models accurately predict both the UTS and the E attributes.

Table 5. Validation tests.

Exp. No	DA (o)	LT (mm)	PS (mm/s)	NT (°C)	Eq 3. UTS (MPa)	Eq 4. E (MPa)	Actual UTS (MPa)	Actual E (MPa)	Error UTS (%)	Error E (%)
1	0	0.3	30	220	15.23	593.8	14.93	591.12	2.0%	0.5%
2	0	0.3	30	220	15.23	593.8	14.79	579.4	3.0%	2.5%
3	0	0.3	30	220	15.23	593.8	15.28	578.83	-0.3%	2.6%
Average					15.23	593.8	15.00	583.12	1.5%	1.8%

4. Conclusions

In this experimental research, four variable parameters (LT, NT, DA, and PS) are examined as far as their effect on the UTS, and the elasticity module (E) of FFF specimens with PLA wood flour (70-30%) as filament material is concerned.

The observed UTS and E values were between 5.48 - 17.42 MPa and 347 - 692 MPa, accordingly for solid PLA/Coconut (70%PLA/ 30%C) parts. In Afrose et al. [7], FFF of solid specimens of pure PLA remarked values between 31 - 39 MPa and 1246 – 1538 MPa for the UTS and E, respectively. The above indicates that UTS and E of the composite PLA/C are considerably smaller than that of pure PLA. In Afrose et al. [7], zero DA also optimizes the UTS for pure PLA, which is following the observations of the current research for the PLA/C composite material. Additionally, it is notable that the specifications of the used PLA/C material in filament form have UTS and E minimum values of about 70 and 1900 MPa, respectively, denoting that the PLA/C FFF parts have the 25% and 36% UTS and E of the filament specifications correspondingly.

The experimental results were analyzed using the main effect plots (MEP), interaction diagrams, and ANOVA analysis and conclude the following:

- The DA parameter dominates on both the UTS and E values, while when this parameter increases, both UTS and E attribute decrease. The DA influences the UTS and E at about 80% and 90%, accordingly. Physically the zero-oriented filament shows higher UTS and E values like in fiber composites. This conclusion follows the literature [7].

- The optimal thermal bonding condition is affected by the PS, NT, and LT in an anti-synergistic way (see interaction charts, Fig. 4) but trivially.
- The PS parameter affects the UTS and E slightly. When decreases, improve both the UTS and E for the 0.1 LT and decrease the UTS and E for the 0.3 LT.
- The NT parameter affects both the UTS and E for the 0.3 LT insignificantly. Concerning the 0.1 LT, when the NT increases, both the UTS and E increase slightly.
- The LT is a significant parameter but is highly dependent on the interlaminar bonding condition (PS and NT) and should be studied individually.
- Finally, the developed linear regression models proved adequate, having an accuracy better than 5% by three independent validation experiments.

As future work, the authors propose a multi-parameter multi-objective optimization of the PLA/wood parts, including more wood flour types and wt. %.

Declarations

Authors declaration: The submitted work is original and has not have been published elsewhere in any form or language

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Figures

Figure 1

Dogbone: (a) 2D views and (b) 3DP of the specimens.

Figure 2

(a) A view of a PLA/Coconut organic composite specimen mounted in the tensile grips of the INSTRON 3382 Universal Testing Machine, (b) Representative Stress-Strain curves for three specimens with LT

0.3mm, NT 180o, and different DAs (0, 45, 90 degrees) and PSs (50, 30 and 40 mm/sec) and (c, d) A series of the dog bone specimens.

Figure 3

Main effects plot for (a) UTS and (b) E.

Figure 4

Interaction plots between DA, PS, NT, and LT according to the: (a) UTS and (b) E.

Figure 5

MEP plots: (a) DA, NT and PS vs UTS for 0.1 LT, (b) DA, NT and PS vs E for 0.1 LT, (c) DA, NT and PS vs UTS for 0.3 LT and (d) DA, NT and PS vs E for 0.3 LT.