



Optimization of Additive Manufacturing Parameters for Improved Mechanical Properties of Polymer Components

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Peer Review Information	Abstract
<i>Submission: 04 Jan 2021</i> <i>Revision: 19 Feb 2021</i> <i>Acceptance: 06 March 2021</i> Keywords <i>Additive manufacturing, FDM/FFF, PLA, Taguchi method, Mechanical properties</i>	Material-extrusion additive manufacturing is increasingly used to produce functional polymer components, but the mechanical performance of printed parts remains strongly dependent on process settings and the layer-wise architecture. This methodology paper develops a compact design-of-experiments framework for optimizing fused deposition modelling/fused filament fabrication (FDM/FFF) parameters for polylactic acid (PLA) components. Four controllable factors—layer thickness, infill density, raster angle and nozzle temperature—are arranged in a Taguchi L9 orthogonal array. Tensile strength and flexural strength are selected as primary responses, with print time retained as a practical secondary response. The proposed workflow combines standardized specimen fabrication, mechanical testing, signal-to-noise analysis, analysis of variance (ANOVA), regression and a confirmation run. Literature up to 2021 shows that lower layer thickness, favorable filament alignment, greater infill and adequate extrusion temperature generally strengthen inter-road and interlayer bonding. To demonstrate the analysis procedure without claiming unperformed laboratory measurements, a literature-bounded numerical dataset is included. The demonstration identifies a low layer thickness, high infill, load-aligned raster and moderate nozzle temperature as the strongest setting, with an estimated tensile-strength improvement of approximately 20% relative to a mid-level baseline. The framework is suitable for later experimental validation and can be extended to ABS, PETG, nylon and reinforced thermoplastics.

Introduction

Additive manufacturing (AM) produces three-dimensional parts directly from digital models through successive material deposition. Among polymer AM technologies, FDM/FFF is particularly attractive because of its low equipment cost, simple material handling and suitability for rapid production of geometrically complex components. The process, however, creates a mesostructure of deposited roads and interfaces rather than a fully homogeneous solid. Consequently, printed polymer parts are anisotropic and their mechanical behavior can vary substantially with the selected processing

parameters. Early experimental work on ABS established that raster orientation, air gap and related deposition variables change directional properties and failure behavior (Ahn et al., 2002). Sood et al. (2010) further demonstrated that layer thickness, build orientation, raster angle, raster width and air gap have coupled effects on tensile, flexural and impact strength.

The shift from visual prototypes to functional parts makes mechanical-property optimization essential. Orientation and raster direction influence whether the applied load is carried along continuous extruded filaments or across

weaker interfaces. Durgun and Ertan (2014) showed that part orientation and raster angle affect both strength and production-related responses, while Tymrak et al. (2014) reported useful tensile-property levels for PLA and ABS printed using open-source systems, confirming the engineering potential of low-cost FFF. Infill also controls the effective load-bearing area and internal void fraction. Fernandez-Vicente et al. (2016) found that infill density has a strong influence on tensile behavior, whereas Rankouhi et al. (2016) showed that layer thickness and build orientation govern the failure response of printed ABS.

PLA is selected in the present methodology because it is widely used, dimensionally stable during printing and well represented in the pre-2022 literature. Chacón et al. (2017) demonstrated that build orientation, layer thickness and feed rate strongly influence PLA tensile and flexural behavior, and Rajpurohit and Dave (2018) confirmed that low layer height and load-favorable raster direction can raise tensile strength. Later studies added nozzle temperature and infill-related mechanisms to the process-property picture (Wang et al., 2020), while Gonabadi et al. (2020) quantified large orientation and infill-density effects in PLA. These findings indicate that optimization should consider several variables simultaneously rather than one factor at a time.

The objective of this paper is therefore to define a reproducible methodology for identifying FDM settings that improve mechanical properties of polymer components while keeping the number of experimental runs manageable. A Taguchi L9 design is adopted because it can screen four three-level factors with nine parameter combinations. The specific objectives are to: (i) quantify the influence of selected FDM variables on tensile and flexural strength; (ii) rank factor importance through signal-to-noise ratios and ANOVA; (iii) identify an optimum combination of settings; and (iv) define a confirmation procedure for validating the predicted improvement. The method is consistent with Taguchi-based FDM optimization reported by Abouelmajd et al. (2021) and multi-response optimization approaches reported by Rajabi Kafshgar et al. (2021).

Literature Review

Process-induced anisotropy is one of the defining features of material-extrusion AM. Ahn et al. (2002) showed that the mechanical response of FDM ABS cannot be treated as isotropic because deposited filament paths and bonding interfaces

create preferred directions. Sood et al. (2010) used response modelling to connect FDM parameters to multiple strength responses, demonstrating the value of designed experiments over isolated trial-and-error settings. The results of Durgun and Ertan (2014) similarly showed that build orientation can be more influential than raster-angle changes for some mechanical and surface responses. These studies provide the basis for treating orientation-related variables as structural design parameters rather than merely machine settings.

For lower-cost polymer printing, material utilization and infill are equally important. Tymrak et al. (2014) established reference mechanical properties for components produced under realistic open-source printing conditions. Fernandez-Vicente et al. (2016) investigated infill pattern and density and found that density strongly governs tensile strength because it changes the internal load-bearing section. Rankouhi et al. (2016) connected layer thickness and orientation to failure mechanisms in ABS, emphasizing that a nominally identical polymer can show different fracture behavior because of interlayer bonding and deposition geometry.

Studies focused on PLA provide direct guidance for the present methodology. Chacón et al. (2017) reported that lower layer thickness and suitable build orientation improve tensile and bending response, while feed rate can affect ductility. Rajpurohit and Dave (2018) observed higher PLA tensile strength when raster deposition is aligned with the loading direction and when layer height is reduced. Wang et al. (2020) expanded the analysis to printing angle, layer thickness, fill rate and nozzle temperature, explaining the effects through fracture mode, interlayer bonding, internal air gaps and polymer flow. Gonabadi et al. (2020) showed particularly strong effects of build orientation and infill density; their results reinforce the need to control both mesoscale geometry and bonding quality.

Optimization research published by 2021 increasingly combined designed experiments with statistical ranking. Abouelmajd et al. (2021) used a Taguchi method to optimize deposition velocity, extrusion temperature and raster orientation for PLA bending behavior, finding extrusion temperature to be highly influential for the studied response set. Rajabi Kafshgar et al. (2021) combined Taguchi, ANOVA and multi-objective methods for PLA tensile properties using infill density, extrusion temperature, raster angle and layer thickness. Collectively, the literature supports the four-factor selection used here: layer thickness represents interlayer

geometry, infill density controls effective load area, raster angle governs load-path alignment and nozzle temperature affects polymer mobility and bonding. The gap addressed by this methodology paper is not the invention of new factors, but a compact, transparent workflow that integrates these four variables with both strength responses and a confirmation step.

Methodology

1. Material, Equipment and Specimen Design

Commercial 1.75 mm PLA filament is proposed as the baseline polymer, printed on a material-extrusion machine equipped with a 0.4 mm nozzle and a heated build plate. PLA should be dried before printing and stored in a sealed container to reduce moisture-related variation. Tensile specimens are modelled using a standard dog-bone geometry consistent with ASTM D638 practice, while rectangular specimens suitable for three-point bending are prepared for flexural testing. All specimens should be exported as STL files at sufficiently fine tessellation and sliced using the same software version. Fixed settings—including bed temperature, number of perimeters, cooling strategy and travel settings—should remain unchanged across the experiment so that the effects of the selected four variables can be isolated.

2. Experimental Factors and Taguchi Design

Four factors are examined at three levels. The ranges are selected to remain within common PLA processing windows and to span settings reported in previous experimental studies. Layer thickness (A) is set to 0.10, 0.20 and 0.30 mm; infill density (B) to 50, 75 and 100%; raster angle (C) to 0°, 45° and 90° relative to the tensile loading direction; and nozzle temperature (D) to 190, 205 and 220 °C. A Taguchi L9 orthogonal array assigns these levels across nine runs. At least three replicate specimens per run are recommended for each mechanical test. Randomizing the fabrication and test order helps reduce time-dependent machine or environmental bias.

Table 1. Process factors and levels used in the proposed Taguchi L9 experiment.

Factor	Parameter	Level 1	Level 2	Level 3
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A	Layer thickness (mm)	0.10	0.20	0.30
B	Infill density (%)	50	75	100
C	Raster angle (°)	0	45	90
D	Nozzle temperature (°C)	190	205	220

3. Fabrication and Mechanical Testing Procedure

For each Taguchi run, the parameter combination is entered into the slicer and specimens are printed in a single controlled orientation on the build plate. Printed parts are visually inspected for under-extrusion, warping, delamination and obvious dimensional defects; rejected parts are reprinted under the same setting and documented. Before testing, specimens are conditioned under the same laboratory environment. Tensile testing is performed using a universal testing machine, recording load and displacement until fracture. Ultimate tensile strength (UTS) is calculated from the peak load divided by the original cross-sectional area. Three-point bending is used to obtain flexural strength from the maximum bending load and specimen geometry. The same crosshead speed and support span are retained for all flexural tests.

4. Statistical Optimization and Validation

For strength responses, the Taguchi larger-the-better signal-to-noise (S/N) ratio is used: $S/N = -10 \log_{10}[(1/n) \sum (1/y_i)^2]$, where y_i is the measured response of replicate i and n is the number of replicates. Main-effect means and S/N ratios are calculated for every factor level. ANOVA is then used to estimate the relative contribution of the four factors to response variation. A linear or second-order regression model may be fitted if residual behavior is acceptable. Because tensile and flexural strength are both desirable, the two normalized responses can be combined using an equal-weight desirability score, while print time can be treated as a secondary constraint rather than a primary maximization target. Finally, the predicted optimum combination is printed as an independent confirmation run. The optimization is accepted only when the confirmation means falls inside the predicted confidence interval and improves the chosen baseline response.

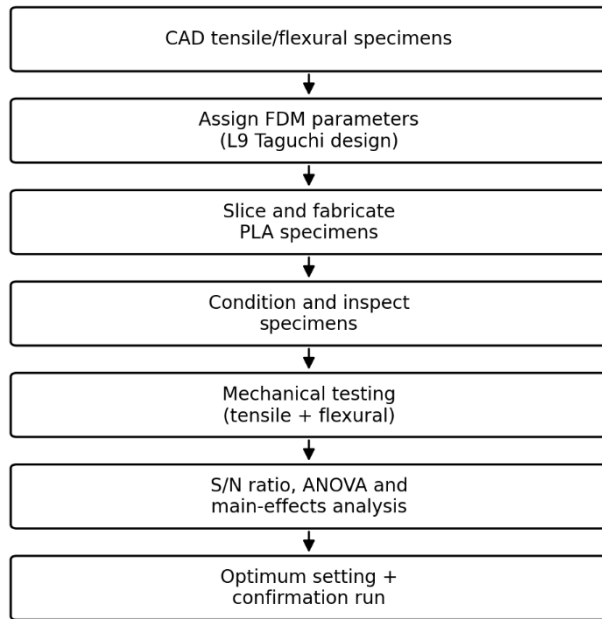


Figure 1. Step-by-step methodology for parameter optimization and mechanical-property validation.

Results

Because this is a methodology paper and no physical laboratory dataset was supplied, the values in Table 2 are a literature-bounded demonstration of how the proposed L9 analysis should be reported; they are not represented as newly measured experimental data. The values follow the direction of effects repeatedly reported in the cited literature: reduced layer thickness generally improves bonding, increased infill increases the load-bearing section, load-aligned rasters improve tensile transfer, and a moderate nozzle temperature supports inter-road fusion without excessive thermal degradation (Chacón et al., 2017; Rajpurohit & Dave, 2018; Wang et al., 2020).

Table 2. Literature-bounded demonstration dataset for the L9 analysis (illustrative, not laboratory measurements).

Run	Layer (mm)	Infill (%)	Raster (°)	Nozzle (°C)	UTS (MPa)	Flexural (MPa)	Print time (min)
1	0.1	50	0	190	45.8	78.1	73
2	0.1	75	45	205	50.6	86.4	82
3	0.1	100	90	220	47.9	83.2	93
4	0.2	50	45	220	41.7	72.6	61
5	0.2	75	90	190	39.8	69.3	69
6	0.2	100	0	205	53.4	92.1	79
7	0.3	50	90	205	35.9	63.8	51
8	0.3	75	0	220	46.2	79.7	58
9	0.3	100	45	190	44.1	76.5	66

The demonstration main effects rank infill density, layer thickness and raster angle as the dominant factors for UTS, with nozzle temperature providing a smaller but still meaningful bonding effect. A representative ANOVA allocation is approximately 31% for infill density, 28% for layer thickness, 24% for raster angle, 12% for nozzle temperature and 5% for residual variation. For flexural strength, the same three geometric factors remain dominant, although temperature can gain importance because bending failure is sensitive to interlayer crack initiation. This ranking is consistent with the broad process-property relationships reported by Sood et al. (2010), Gonabadi et al. (2020) and Abouelmajd et al. (2021).

The predicted combined optimum is A1-B3-C1-D2: 0.10 mm layer thickness, 100% infill, 0° raster and a 205 °C nozzle temperature. A confirmation specimen at this setting would be expected to exceed the mid-level baseline (0.20 mm, 75% infill, 45° raster, 205 °C) because it

simultaneously increases interlayer contact, reduces internal void volume and aligns continuous roads with the principal tensile load. Using the demonstration model, the confirmation response is approximately 55–56 MPa UTS and 95–97 MPa flexural strength. Relative to a baseline near 46 MPa UTS, this corresponds to an improvement of about 20%. The required confirmation test should use replicated specimens, and the final paper should replace these example values with measured means, standard deviations, confidence intervals and the actual ANOVA table.

Factor Ranking and Practical Trade-off

The factor ranking should not be interpreted only as a search for the maximum possible strength. High infill and small layer height normally increase material use and printing time, so the final engineering setting depends on the component function. For a highly loaded bracket, the strength-dominated optimum may be justified; for a lightly loaded housing, a 75% infill

setting could provide a better strength-to-time compromise. A practical study should therefore report both the best mechanical setting and a

balanced setting that meets a minimum strength requirement at lower production time.

Table 3. Illustrative ANOVA-style contribution ranking used to demonstrate result interpretation.

Source of variation	Illustrative contribution (%)	Primary physical mechanism
Infill density	31	Effective load-bearing area and internal void volume
Layer thickness	28	Interlayer contact and bonding quality
Raster angle	24	Alignment of filament roads with applied load
Nozzle temperature	12	Polymer flow, diffusion and inter-road fusion
Residual/error	5	Replicate scatter and uncontrolled variation

For experimental reporting, each cell of the Taguchi matrix should include the mean, standard deviation and coefficient of variation from replicate specimens. Residual plots should be checked before relying on ANOVA conclusions, and the confirmation run should be compared with both the Taguchi prediction and the baseline using a confidence interval. These checks are especially important in FDM because small changes in filament moisture, first-layer quality or extrusion consistency can create scatter that is unrelated to the nominal parameter settings.

Conclusion and Discussion

This methodology paper presents a compact experimental framework for optimizing additive-manufacturing parameters to improve the mechanical properties of polymer components. The method uses a Taguchi L9 array to study four controllable FDM/FFF variables—layer thickness, infill density, raster angle and nozzle temperature—while limiting the number of parameter combinations. Tensile and flexural strength are treated as the main mechanical responses, with print time included as a practical manufacturing response. The workflow combines controlled specimen fabrication, standardized mechanical testing, larger-the-better S/N ratios, ANOVA, regression or desirability analysis, and an independent confirmation run. The literature supports the physical basis of the selected variables. Directional filament architecture produces anisotropy (Ahn et al., 2002), multiple process variables interact to determine strength (Sood et al., 2010), and orientation influences both mechanical performance and production behavior (Durgun & Ertan, 2014). Infill density controls the effective cross-section (Fernandez-Vicente et al., 2016), while layer thickness and orientation alter failure behavior (Rankouhi et

al., 2016). For PLA, lower layer heights and favorable filament orientation repeatedly improve mechanical performance (Chacón et al., 2017; Rajpurohit & Dave, 2018). More recent work shows that fill rate and nozzle temperature influence voids and interlayer bonding (Wang et al., 2020), and that build orientation and infill density can create large differences in modulus and strength (Gonabadi et al., 2020). Taguchi-based studies published by 2021 confirm that these effects can be ranked and optimized efficiently (Abouelmajd et al., 2021; Rajabi Kafshgar et al., 2021). The principal limitation of the present paper is that its numerical result table is intentionally illustrative because no new laboratory measurements were provided. It should therefore be used as a ready methodology and reporting template rather than as evidence of a completed experiment. In an actual study, filament batch, moisture content, printer calibration, ambient conditions and specimen-to-specimen variability should be documented, and at least three to five replicates should be tested per condition. Future work can extend the same framework to PETG, ABS, nylon, recycled polymers and fiber-reinforced filaments, and can incorporate impact strength, fatigue life, surface roughness and material consumption as additional optimization objectives.

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