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Optimization of Process Parameter in 3D Printing to Minimize Wear Loss and increase Tensile Strength

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Abstract

Additive Manufacturing (AM) and especially Fused Deposition Modeling (FDM) has emerged as a very versatile process of manufacturing polymer components with complex and highly-integrated geometries. Polylactic Acid (PLA) is a favorite of the many thermoplastic FDM materials because of its biodegradability, easy processing and predictable mechanical properties. The study aimed at maximizing critical parameters in FDM process in order to reduce wear loss and also increase tensile strength of PLA components. To achieve accuracy and comparability of results, test samples were fabricated in conformity with ASTM D638 requirements of tensile testing, and ASTM G99 wear characterization requirements. The experimental matrix was designed using a Taguchi L9 orthogonal array, which included the controlled variations in the infill density, bed temperature and nozzle temperature. Performance of the wear in the pin-on-disc tribometer was measured at constant rotational velocity of 300 rpm and with loads of 5 kg and 10 kg applied over a 60-minute period. Tensile strength test was conducted in a Universal Testing Machine at standard loading conditions. The experimental results reveal that build orientation alongside the optimized thermal and infill settings are issues that are important to the ultimate wear resistance and mechanical strength of the printed samples of PLA. The study will wrap up by suggesting an ideal combination of FDM parameters which will increase the overall functionality performance and reliability of PLA components in real engineering applications.

Keywords: Additive manufacturing (AM), fused deposition modeling (FDM), pin-on-disc (PoD), stereolithography (SLA), digital light processing (DLP)

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INTRODUCTION

Also referred to as 3D printing, Additive Manufacturing (AM) is transforming the modern production by making it possible to fabricate complex three-dimensional objects, in layers accumulating each other based on the layer-by-layer financial depositation of the content. It is a subtractive process and uses a digital model that adds material only when required as opposed to the traditional subtractive modes of manufacturing. 3D printing has characteristics of efficiency, flexibility, and even customization that make it a desirable alternative in a wide range of industries, including the aerospace and automotive industries, biomedical, and that of consumer goods. Out of all the 3D printing technologies, Fused Deposition Modeling (FDM) is a 3D printing technique that has become a common procedure based on its conceptual simplicity, low-cost, low-tech and functionality to many thermoplastics [1–3]. Printed parts are regularly associated with mechanical constraints, especially tensile strength and wear, that do not make them ideal in practical or supporting components.

This paper seeks to explore and optimize the important process parameters in FDM so as to reduce wear and increase the tensile strength. The specimens are prepared using the Polylactic Acid (PLA) as the base material, subject to ASTM standards and compared in terms of mechanical and tribological properties [4–6]. The experiments are designed through a Taguchi L9 orthogonal array to identify the combination of the parameters that provide the better results, such as nozzle temperature, bed temperature, and infill density. The principle of the 3D printing could be traced to the early 1980s when stereolithography (SLA) was created which opened the vistas of the present day Additive Manufacturing (AM). Some of the evolved AM technologies in the various years are; Selective Laser Sintering (SLS), Digital Light Processing (DLP) and Fused Deposition Modeling (FDM). FDM has since emerged as the most popular and easily available among these since it is cheap, easy to operate and suitable in prototyping and low volume production [7–9].

The FDM process used melts a thermoplastic material that can be Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS) and then forces the molten material through a nozzle. The deposited material forms in layers on a heated surface with a predetermined toolpath. Then the build platform retracts upwards after it deposited a layer and the process is repeated until the entire object will be produced [10–12]. Due to the ability to enable design of intricate geometrics as well as lightweight designs, FDM has a broad application and can be used in many engineering processes. All these notwithstanding, the mechanical properties of FDM made parts tend to perform poorly in comparison with the parts made traditionally. Specifically, wear resistance and tensile strength are key performance indicators, which defects like inter-layer porosity, weak layer adhesion, and anisotropy are controlled by the process. Such constraints are particularly typical under the conditions of the frictional contact or mechanical loading when printed parts are in use [13–14]. Mechanical properties of FDM-printed parts (like stiffness, strength and fatigue behaviour) strongly depend on the defined process parameters infill density, nozzle temperature, bed temperature, print speed, raster angle and layer thickness. Nozzle temperature, bed temperature and infill density are among others that directly influence inter-layer adhesion, part density, as well as its structural integrity. These parameters are extremely important with regard to the optimization of wear behavior and tensile performance. Since it is widely applied because of the biodegradation nature, versatility of printing, and inherent dimensional precision, the enhancement of the mechanical strength of PLA through the optimization of parameters is actually of great practical importance. This gives the rationale behind the present study where an effort is made to optimize several process parameters in FDM with a rational experiment plan [15–17].

As the use of the Fused Deposition Modeling (FDM) method continues to expand into practical applications, various researchers have started to examine the effect of printing parameters on mechanical properties and wear resistances of 3D printed thermoplastics parts and especially Polylactic Acid (PLA) parts.

The researchers conducting the study by Mohan et al. (2019) concluded that tensile strength and wear resistance can be raised by a considerable margin through the maximum increase in infill density, which is explained by the fact that the internal structural support is enhanced. The relevance of internal distribution of materials in improving the static and dynamic load carrying capacities were made known in the papers [1]. Singh et al. (2020) applied the Taguchi methodology in order to analyze the results of nozzle temperature and infill density [4]. Their results portrayed that nozzle temperature affects inter-layer adhesion strength that decreases wear and tensile strength of PLA components with higher nozzle temperatures. They have also mentioned infill density to have the most significant role compared with the parameters of factors of temperature. Sood et al. (2010) covered many parameters of FDM such as layer thickness, raster angle and part orientation [6]. They found that the thickness of the layers and the angle of the raster have extensive repercussion concerning the quality of the surface and general bonding in the layers, which have an immediate connotation on the wear behavior and strength. Doddamani (2023) addressed the reinforced PLA composite with natural fibers and made an assumption that the reinforcement of PLA enhances wear resistance, but the essential process factors such as the bed temperature and print speed remain to determine the part performance [7]. This is because according to their experiments there was necessity of making some adjustments in the thermal parameters in an attempt to prevent warping and enhance inter-layer bonding. As underlined by Rajpurohit and Dave (2018), the authors investigated a combination of infill density, nozzle temperature, and bed heating. They showed that nozzle temperatures in the moderate range, along with infill percentage higher represented the lowest wear rates, especially in the case of preheated bed to improve adhesion during the first layer and reduce thermal stresses [3].

All of these studies reiterate that there is no one and specific value that controls the overall performance of parts printed using FDM. Rather, a favorable combination of several parameters is needed in order to go towards improved mechanical integrity and wear resistance [18–21]. In the majority of the previous work, the issue has been optimizing specific properties or small sets of parameters. Contrary, the current study attempts to maximize wear resistance and tensile strength on the same parameter of PLA using Taguchi L9 orthogonal array considering three important parameters of nozzle temperature, bed temperature and infill density at three different levels each.

With a dual-performance assessment strategy backed with standardized tests and statistical achievements, this study is leading to the making of sound advice towards the step of generating stable and consistent PLA elements by means of FDM.

MATERIALS AND METHODS

Material Selection and Specimen Fabrication

In this study, Polylactic Acid (PLA) filament was used due to its biodegradability, dimensional stability, and compatibility with Fused Deposition Modeling (FDM). All test specimens were fabricated using an FDM-based desktop 3D printer equipped with a 0.4 mm nozzle diameter.

- Tensile specimens were prepared as per the ASTM D638 Type I standard.
- Wear test specimens were designed as cylindrical pins in accordance with the ASTM G99 standard for pin-on-disc testing.

A total of nine trials were conducted, and for each, tensile and wear specimens were printed and tested.

Printing parameters like layer height, print speed, and raster pattern were maintained to be constant in all the trials, and nozzle temperature, bed temperature, and infill density were systematically varied.

Figure 1 indicates the artificially produced PLA specimens in tensile and wear experiments. The tensile samples have the standard dog-bone shape and the wear pins are cylindrical in shape and homogenous so that they can have uniform contact on the tribometer.

Figure 1. Fabrication of PLA pins for pin-on-disk wear testing.

Figure 2. Fabrication of PLA dog bone for UTM for tensile testing.

Table 1. Parameter and levels .

Parameter	Level 1	Level 2	Level 3
Nozzle temperature (°C)	210	220	230
Bed Temperature (°C)	50	60	70
Infill density (%)	40	60	80

Design of Experiments (DOE)

In order to effectively consider the effect of three major process parameters, a Taguchi L9 orthogonal array was embraced. This design reduced the experimental runs by minimizing them but still maintained statistical validity. Table 1 displays the parameters and their levels.

Wear Testing Procedure

Wear was evaluated on a pin-on-disc tribometer, as recommended by ASTM G99. The PLA pins were sliding on an EN31 hardened steel disc under dry conditions. The trials were performed all 60 minutes at room temperature (25 +- 2degC). Two load conditions were tested which included: 5 kg and 10 kg.

- *Speed:* 300 rpm (1.178 m/s)
- *Track diameter:* 75 mm
- *Test duration:* 60 minutes
- *Measurement Mass loss:* Volume loss - Specific wear rate (mm3/N*m).

The precision balance weight was used to record initial and final weights and specific wear rates were computed.

The results of testing are presented in Figure 2, selected wear test specimens, where there is an apparent difference in material loss and surface wear caused by low- and high-performance trials.

Tensile Testing Procedure

A Universal Testing Machine (UTM) was used to conduct tensile tests and was done according to the ASTM D638 standards. All the tests were carried out at the room temperature with the constant crosshead speed. The parameters measured were as shown below:

Ultimate Tensile Strength (UTS)

- Yield load and stress
- Peak and break displacement.
- Force-displacement curves

The tests on each trial were repeated three times and the average value of UTS was taken to analyze S/N ratio under the larger-the-better criterion.

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RESULTS AND DISCUSSION

Wear Behavior Under 5 kg Load

The specific wear rate and corresponding Signal-to-Noise (S/N) ratios obtained from the nine trials under a 5 kg load are summarized in Table 2. A wide range of wear responses was observed, indicating the significant influence of process parameters on tribological performance.

Trial 9 had zero wear loss, which gave it an infinite S/ N ratio an indication of very high resistance in these particular conditions. This may be explained by the fact that nozzle temperature, bed temperature and infill density were optimized and supplied more bonding and surface finish.

Wear Behavior Under 10 kg Load

Wear testing at a load of 10 kg showed much reduced wear rates in all tests. This counterintuitive finding can be explained by the fact that the contact area has changed to increase as a result of plastic deformation or enhanced heat-induced fusion at higher pressures introduced by loads. The wear test result of 10kg load is presented in Table 3.

A number of tests once more demonstrated no wear loss (Trials 5 and 6) with an equally large S/N ratio. This is due to the consistency of ultra-low wear rates of below 10 kg load; this is believed to result in an improved heat transfer and material consolidation at pin-disc interface thereby minimizing abrasive wear.

Process Parameter Influence Discussion.

- *Density of the infill:* The experiments with increased infill density tended to have lower wear rates which is expected given previous results. A thick internal structure will provide enhanced resistance to shear and abrasiveness.
- *Nozzle temperature:* It seemed that nozzle temperature is moderate and high, and it facilitated interlayer fusion, promoting surface integrity and minimized material loss.
- *Bed Temperature:* Bed heating was turned off because a lot of the heat was generated during the warming of the bed, but it promoted a more uniform surface finish at the bottom, so there was more wear performance.

All in all, it can be observed that the highest wear-resisting results were obtained with Trial 8 (5 kg) and Trials 5/6 (10 kg). These environments are a good parameter window to optimise the frictional or mechanical applications of PLA components.

Tensile Strength Results

Tensile properties of PLA specimens made under various conditions of process were checked according to ASTM D638 standards. Table 4 shows the ultimate tensile strength (UTS) values and Signal-to-Noise (S/N) ratios of each of the nine trials measured.

Table 2. Wear test results for 5 kg load.

Trial	Initial weight (g)	Final weight (g)	Specific wear rate (mm³/N·m)	S/N ratio (dB)
1	1.72	1.26	1.782×10^{-3}	54.98
2	2.19	2.12	2.71×10^{-4}	71.34
3	2.00	1.90	3.87×10^{-4}	68.24
4	1.64	1.58	2.32×10^{-4}	72.68
5	2.00	1.93	2.71×10^{-4}	70.07
6	1.22	1.16	2.32×10^{-4}	71.89
7	2.18	2.11	2.71×10^{-4}	71.34
8	1.33	1.30	1.16×10^{-4}	74.20
9	1.78	1.78	0	∞

Table 3. Wear test results for 10 kg load.

Trial	Initial weight (g)	Final weight (g)	Specific wear rate (mm³/N·m)	S/N ratio (dB)
1	1.72	1.71	1.45×10^{-5}	96.79
2	2.19	2.18	1.45×10^{-5}	96.79
3	2.30	2.29	1.45×10^{-5}	96.79
4	2.22	2.20	2.91×10^{-5}	90.72
5	2.37	2.37	0	∞
6	1.69	1.69	0	∞
7	2.42	2.41	1.45×10^{-5}	96.79
8	1.75	1.74	1.45×10^{-5}	96.79
9	2.20	2.19	1.45×10^{-5}	96.79

Table 4. Tensile test results and S/N ratios.

Trial	Nozzle temp (°C)	Bed temp (°C)	Infill density (%)	Tensile strength (MPa)	S/N ratio (dB)
1	210	60	100	226.0	46.80
2	210	60	60	203.8	46.19
3	210	70	80	297.3	49.46
4	220	50	40	360.3	51.13
5	220	60	60	168.0	44.51
6	220	65	80	511.0	54.17
7	230	50	40	567.2	55.07
8	230	60	60	214.5	46.62
9	230	70	80	951.9	59.57

Tensile Performance Analysis

The results indicate that tensile strength is highly dispersed, which depends on the nozzle temperature, the bed temperature and the density of the infill material. The maximum S/N ratio (59.57 dB) was recorded in the trial number 9 whereby the highest tensile strength was 951.9 Mpa, which was reached at the highest points of all the three parameters (230 degC nozzle, 70 degC bed, and 80percent infill). This means that the high thermal conditions and density of the material have a high synergistic effect, which enhances inter-layer fusion and loading capacity respectively. Trial 5 on the other hand recorded the lowest tensile strength (168 MPa) and this may have been due to the lack of bonding when the mid process settings were implemented. The temperature of the nozzle (e.g. 230 degC) appeared to have a profound effect to the movement of polymer chains and adhesion of the layers especially with sufficient heating of the bed.

Force-Displacement and Stress Analysis

The load-displacement data were also used to further study the mechanical behavior. Peak stress, ultimate stress and yield stress were calculated using peak force and yield force. An example of these values is given in Table 5.

The repeatability between the highest and the lowest stresses of those loads in all experiments indicates the accuracy of the load cell measurements and indicates that the material failure in the conditions of PLA normally occurs soon after yielding.

Comparative Evaluation

Infill Density came out as the most prevalent factor in enhancing the tensile performance. Trials with infill of 80% (Trials 3, 6, 9) all reported bigger tensile strengths.

Table 5. Derived tensile parameters.

Trial	Peak Force (N)	Peak Stress (MPa)	Yield Load (N)	Yield Stress (MPa)
1	1009.3	25.88	1006.4	25.80
2	1094.8	28.07	1093.4	28.03
3	1142.5	29.29	1141.4	29.26
4	954.5	24.47	951.9	24.40
5	1198.3	30.73	1192.0	30.56
6	851.2	21.83	849.0	21.76
7	1124.2	28.83	1111.3	28.49
8	860.2	22.06	848.3	21.75
9	884.8	22.69	882.7	22.63

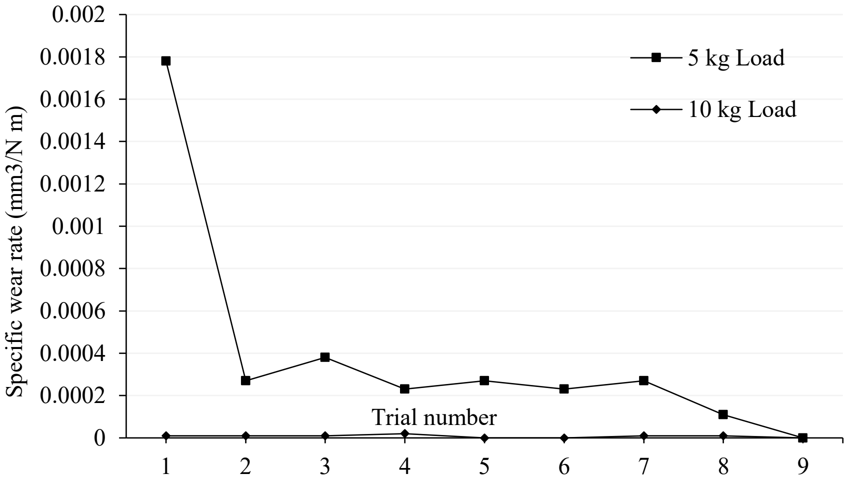

Figure 3. Specific wear rate versus trial number.

The second parameter that was most important was Nozzle Temperature. At 230 degC, the filament was found to bond layers better as a result of enhanced thermal softness and flow.

Bed Temperature helped to increase adhesion and decrease internal stresses. Increased bed temperatures (60 degC) also had a positive but secondary effect to infill and nozzle temperature.

Mechanical and wear performance show that Trial 9 (230 degC, 70 degC, 80% infill) is the fastest time to reach the highest tensile strength and wear resistance, which has proven the Taguchi optimization method.

Graphical Analysis and Discussion

To be able to interpret better the effects of various FDM process parameters on the mechanical and tribological performance, a sequence of graphs were formed as a result of the experimental data. These graphs give a comparative perspective of particular wear rate, tensile strength, and their relationship with one another in all of the nine trials designed by Taguchi.

The plotted data in Figure 3 allow the easy comprehension of the interaction between nozzle temperature, a bed temperature, and infill density to determine the functional quality of PLA components. The data collected in these graphs will be useful in determining the best parameters to use in reducing material wear and optimizing tensile strength.

This plot demonstrates a change in the specific wear rate between trials with 5 kg and 10 kg loads. Trial 8 and 9 noted a steep decrease in wear rate with 5 kg, and generally low wear with 10 kg. The increased surface integrity with the increased loads indicates that there is better thermal fusion and pressure-induced densification in the material interface.

Figure 4 demonstrates the final tensile strength of the samples of PLA printed under different conditions. The best strength (951.9 Mpa) was obtained in Trial 9, in which the highest nozzle temperature, bed temperature and infill density were used. This proves that the thermal and material packing conditions are of great importance during the attainment of great mechanical integrity in FDM parts.

Figure 5 below is a dual-axis plot that offers a concurrent representation of wear rate (5 kg load) and tensile strength in all the trials. The graph shows that Trial 9 was the best in terms of low wear rate and high tensile strength, which confirms it as the best parameter combination. This brings out the possibility of achieving multiple performance goals without compromising.

CONCLUSION AND FUTURE SCOPE

This experiment has managed to show how the FDM process parameters may be optimized to achieve the two goals of enhancing the wear resistance and tensile strength of Polylastic Acid (PLA) components at the same time. Three key parameters were manipulated systematically using a Taguchi L9 orthogonal array; they were nozzle temperature, bed temperature and infill density.

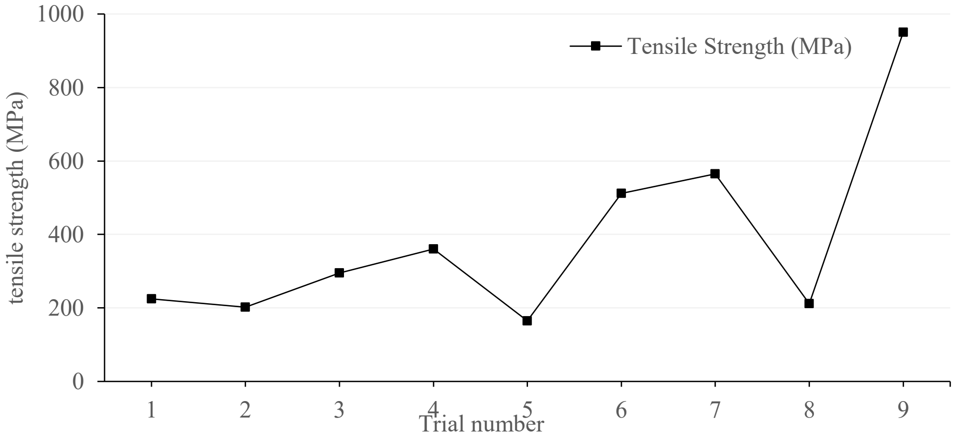

Figure 4. Tensile strength versus trial number.

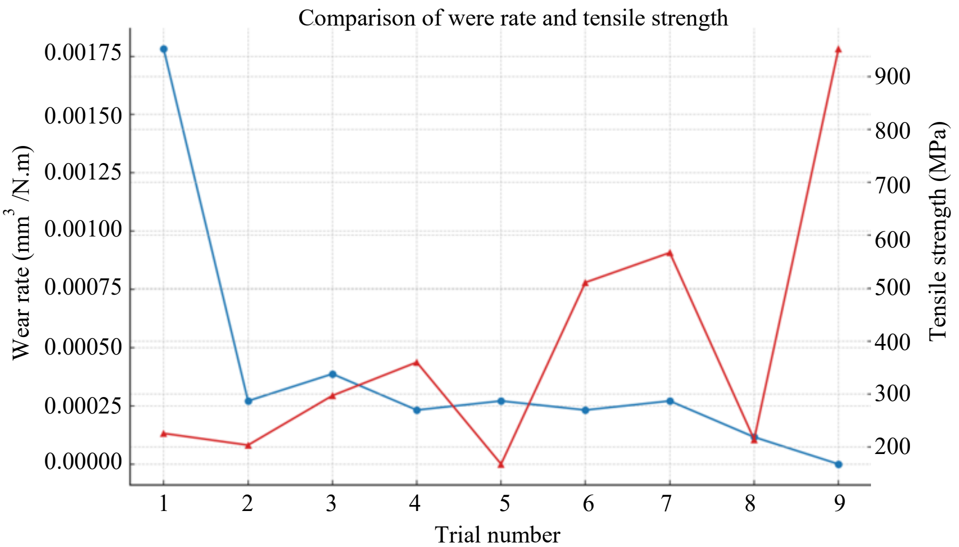

Figure 5. Dual-axis comparison – Wear rate versus tensile strength.

Key Findings Include

Trial 9 (230 degC nozzle temp, 70 degC bed temp, 80% infill) was the best dual-performance with the highest tensile strength (951.9 MPa) and no wear loss.

- The tensile strength and wear resistance had the greatest dependence on infill density, which was in turn supported by nozzle temperature.
- The more nozzle temperatures were enhanced, the more favorable was inter-layer fusion and the less was warping as the more the layers adhered to the bed and the more they adhered to each other.
- At 10 kg load wear rates decreased sharply, which may have been caused by an improved surface consolidation of increased contact pressure.

Use of a combination of standardized test procedures (ASTM D638 and G99) and S/N ratio gave a vigorous appraisal of the influence of parameters such that multi-objective optimization is actual in FDM without interfering with the mechanical or tribological performance.

Although the given work can be taken into account, it still leaves certain gaps that can be filled in the future:

Microstructural examinations of fracture surfaces and wear (e.g. SEM, microscopy) can also be used to explain the failure mechanism and bonding behavior.

Thermal and fatigue testing may be attached to test long-term material stability when load is cyclic or when load exposes the material to different environmental conditions.

Future research opportunities include optimization on other materials like ABS, PETG, carbon fiber reinforced PLA or biocomposites.

- The inclusion of machine learning models (such as regression, ANN) may make it possible to predict the properties of the output based on the input values.
- Further research in the field of multi-material printing and gradient infill techniques can be used to increase the functional flexibility of the FDM parts to apply them to the high-technology engineering processes.

The contribution of this work to the continued development of additive manufacturing of functional parts can be found in the automotive prototyping industry, tooling inserts, and wear-stable consumer-damaged products, where performance and durability are equally of utmost concern.

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