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Parametric Study of Three Body Abrasive of FDM 3D Printed PLA and Glass Fiber Reinforced PLA Using Taguchi Design

[1]Sankalp P Yelave , [2]Dr. M.K.Patil,
[1] Student, [2]Professor,
[1]Production Engineering and System Technology,
[1]Angadi Institute of Technology and Management, Belagavi, India

I. ABSTRACT

The present work examines the three-body abrasive wear characteristics of neat PLA and glass fiber reinforced PLA (PLA+GF) specimens manufactured through Fused Deposition Modelling (FDM), with process optimization carried out via the Taguchi method. Three critical printing variables — layer height, printing temperature, and printing speed were varied across an L9 orthogonal array, and their collective influence on wear loss was studied. Wear tests were conducted on a three-body abrasive wear machine using silicon carbide as the abrasive medium. S/N ratio plots and ANOVA were used to rank the relative importance of each printing variable and to determine the conditions that yield minimum wear loss. The findings show that layer height exerts the most pronounced effect on the wear behavior of both material types, while the combination of optimized parameters leads to a meaningful reduction in material loss. The presence of glass fiber reinforcement in the PLA matrix was found to further strengthen the wear performance of FDM-fabricated parts.

Keywords: FDM, PLA, PLA+GF, Wear Behavior, Taguchi Method, ANOVA, Additive Manufacturing.

II. INTRODUCTION

- **Additive Manufacturing**

Additive Manufacturing (AM), popularly known as three-dimensional (3D) printing, is a class of advanced manufacturing technologies where parts are built up layer by layer directly from digital computer-aided design data. Unlike conventional manufacturing routes such as machining, casting, or forming — which depend on material removal or mold-based shaping AM deposits material only in locations required by the target geometry. This layer-wise approach makes it feasible to realize highly intricate shapes, internal channels, lightweight lattice architectures, and individualized designs that would be difficult or economically impractical to produce through traditional means.

The origins of AM date back to the late 1980s, when stereolithography was first introduced commercially. Since that period the technology has undergone rapid evolution and is today applied across aerospace, automotive, biomedical, defense, consumer goods, electronics, and architectural sectors. Increasing pressure to compress product development cycles, reduce structural weight, and enable mass customization has pushed AM into mainstream industrial use.

A key practical advantage of AM lies in its material efficiency: subtractive methods remove large quantities of stock from a workpiece, whereas AM uses only the quantity of material that the geometry demands. Tooling requirements are simultaneously reduced, shortening overall manufacturing lead times and making the process particularly attractive for rapid prototyping and small-batch production. Design changes can also be implemented quickly by updating a CAD file rather than reworking costly tooling.

- **PLA and PLA+GF Materials**

Polylactic Acid (PLA) is a widely used thermoplastic material in FDM processing, valued for its biodegradability, ease of extrusion, low warping behavior, and environmentally responsible origin. Derived from renewable agricultural sources such as corn starch, sugarcane, and cassava, PLA offers a more sustainable footprint than petroleum-based polymers. Its good dimensional stability, modest printing temperature requirements, and ability to reproduce fine detail make it a natural choice for rapid prototyping and functional part manufacturing.

The material's advantages over conventional thermoplastics such as ABS include lower shrinkage during printing, negligible toxic emissions, and simpler handling. These properties have driven widespread adoption of PLA in biomedical devices, packaging, educational models, automotive interior components, and everyday consumer goods. In additive manufacturing, PLA is the go-to feedstock for lightweight geometrically complex structures where high print quality is a priority.

That said, neat PLA has inherent limitations that constrain its use in mechanically demanding or tribologically active environments. Its relatively brittle nature, moderate strength, and low thermal resistance are well documented. Of particular concern is its limited resistance to abrasive and sliding wear — a factor that restricts its suitability in tribological applications. In practice, PLA components exposed to continuous abrasive loading may suffer accelerated surface degradation, crack initiation, and elevated material loss rates.

To overcome these shortcomings, researchers have explored various reinforcement strategies. Glass fiber (GF), carbon fiber (CF), and natural fiber inclusions have all been investigated within PLA matrices. Among these, GF reinforcement has emerged as a practical and commercially accessible approach for improving load-bearing capacity, resistance to surface damage, and overall dimensional stability. During abrasive contact, the hard glass fibers support the applied load and shield the surrounding polymer matrix from penetration by abrasive particles, thereby reducing the rate of material removal.

In FDM-based manufacturing, PLA+GF composite filaments are gaining traction for engineering applications where enhanced structural and tribological performance is required. However, the behavior of these composites is strongly influenced by printing parameters — particularly layer height, printing temperature, and printing speed — which collectively govern fiber distribution, interlayer bonding quality, and the degree of void formation within the printed structure. Systematic investigation and optimization of these parameters are therefore critical for producing durable PLA+GF components with reliable tribological characteristics.

- **Objectives**

1. To fabricate PLA and PLA+GF composite specimens using FDM with different printing parameter combinations.
2. To investigate the effect of layer height, printing temperature, and printing speed on the three-body abrasive wear behavior of the printed specimens.
3. To apply the Taguchi method and ANOVA for experimental design, optimization, and identification of significant process parameters affecting wear performance.
4. To compare the wear resistance characteristics of pure PLA and PLA+GF composite specimens and determine the optimum printing conditions for minimum wear loss.

III. MATERIALS AND METHODOLOGY

Materials: The present study considers two thermoplastic filament materials: neat Polylactic Acid (PLA) and Glass Fiber Reinforced Polylactic Acid (PLA+GF). FDM-fabricated specimens of both materials were used for three-body abrasive wear testing.

- **PLA Filament**

A commercial-grade PLA filament of 1.75 mm diameter was used as the primary matrix material. PLA is a biodegradable thermoplastic derived from renewable agricultural inputs including sugarcane and corn starch. It occupies a leading position in FDM feedstock markets on account of its ease of extrusion, low print temperature, reliable dimensional stability, and favorable environmental profile.

The material's technical advantages include a low warping tendency, negligible shrinkage during printing, good surface reproduction, and uncomplicated extrudability. These characteristics have made PLA the default material for rapid prototyping, educational models, biomedical device development, and lightweight engineering components.

- **PLA+GF Filament**

Glass Fiber Reinforced PLA (PLA+GF) filament of 1.75 mm diameter was employed as the reinforced composite material for comparative investigation. The filament consists of a PLA matrix with glass fiber reinforcement incorporated to improve the overall structural and tribological performance of the printed parts.

Glass fibers are among the most widely used reinforcements in polymer composites, offering high tensile strength, good stiffness, excellent thermal stability, and substantial load-bearing capacity. Their incorporation into the PLA matrix improves the composite's structural integrity and abrasive wear resistance.

In FDM processing, the behavior of PLA+GF composites is strongly dependent on layer height, printing temperature, and printing speed. Inadequate processing conditions cause fiber agglomeration, poor interlayer bonding, and void formation, all of which degrade both mechanical and tribological properties. Parameter optimization is therefore essential for realizing the potential performance improvements offered by glass fiber reinforcement.

As with the PLA filament, the PLA+GF material was stored in a moisture-controlled environment prior to printing. Both materials were printed under comparable operating conditions to ensure a meaningful and direct comparison of their wear behavior under three-body abrasive testing

- **Experimental Parameters**

The FDM process parameters selected for this investigation were chosen on the basis of their documented influence on interlayer bonding, surface finish, dimensional accuracy, porosity, and tribological behavior. Three key printing parameters — layer height, printing temperature, and printing speed — were each varied across three levels, as established through preliminary trials, machine operating limits, and guidance from the existing literature. The parameter levels were used to construct the experimental matrix according to the Taguchi L9 orthogonal array design.

- **Layer Height**

Layer height defines the thickness of each individual stratum deposited during FDM printing. It directly governs mechanical performance, dimensional accuracy, surface quality, and interlayer adhesion of the finished component. Smaller layer heights generally yield better interlayer bonding, reduced porosity, smoother surface finish, and improved wear resistance, though at the cost of greater print time. In this study, layer heights of 0.16 mm, 0.20 mm, and 0.24 mm were selected.

- **Printing Temperature**

Printing (nozzle) temperature governs filament melting and flow characteristics during extrusion. Adequate temperature is essential for proper interlayer fusion and uniform material deposition. Insufficient temperature leads to poor layer bonding and void formation, while excessively high temperature risks thermal degradation and dimensional instability of the printed component. Three printing temperatures were selected: 200°C, 210°C, and 220°C.

- **Printing Speed**

Printing speed is the traverse velocity of the nozzle during material deposition. It influences deposition quality, cooling behavior, bond strength, and surface characteristics. Lower speeds allow better material fusion and deposition accuracy, whereas higher speeds may produce incomplete bonding and increased surface defects. In this study, printing speeds of 30 mm/s, 60 mm/s, and 90 mm/s were investigated. The three parameters and their respective levels are summarized in Table 3.1 which governed the systematic experimental combinations generated via the Taguchi L9 orthogonal array.

Table 3.1 Process Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Layer Height (mm)	0.16	0.20	0.24
Printing Temperature (°C)	200	210	220
Printing Speed (mm/s)	30	60	90

- **Fabrication of Specimens**

All specimens required for the experimental program were fabricated using Fused Deposition Modelling (FDM) 3D printing. Both PLA and PLA+GF filaments were used to produce specimens for three-body abrasive wear testing. The fabrication sequence involved CAD model preparation, slicing, printing parameter setup, layer-by-layer deposition, and final specimen removal. All specimens were produced under controlled conditions to ensure dimensional consistency and experimental repeatability.

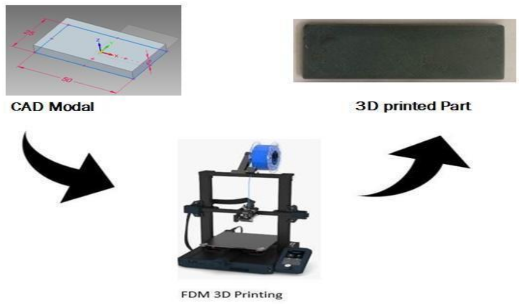

Figure 3.1: 3D Printing Process of PLA and PLA+GF

1. CAD Model Preparation: The specimen geometry for wear testing was designed in CAD software, scaled to meet wear machine requirements and machine limits. The completed design was exported to STL (Standard Tessellation Language) format — the standard exchange format for AM — in which the geometry is represented as a triangulated surface mesh and serves as the input to the slicing software.

2. Slicing Operation: The STL file was imported into the slicing software, which discretized the three-dimensional model into horizontal layers and generated the corresponding toolpath instructions. The resulting G-code file controlled all nozzle motion, extrusion flow rate, layer thickness, and printing speed commands during fabrication. Printing parameters were configured in accordance with the experimental design, and the G-code was transferred to the FDM machine for fabrication.

3. Printer Parameter Setup: Before each print, the selected filament was loaded into the FDM extrusion system. Printer settings were configured to match the specific parameter combination designated by the Taguchi experimental design — nozzle temperature, layer height, and printing speed were each adjusted carefully to ensure uniform material deposition and consistent interlayer bonding. The build platform was cleaned and levelled prior to each print run to avoid first-layer defects such as warping, uneven deposition, and dimensional error. Good bed levelling also improves adhesion between the first deposited layer and the printing surface.

4. Layer-by-Layer Fabrication: With parameter setup complete, the printing process was initiated. Filament was fed continuously into the heated nozzle, melted, and extruded onto the build platform according to the programmed toolpath. Each layer fused thermally with the layer below it. Following completion of each stratum, the build platform descended by the prescribed layer height, and successive layers were deposited until the specimen was completely formed. The process ran automatically until all experimental specimens had been produced.

5. Specimen Removal: After printing, specimens were allowed to cool naturally to room temperature on the build platform before removal, to prevent thermal deformation and residual stress buildup. Each specimen was visually inspected for printing defects such as warping, voids, layer separation, and dimensional irregularities. Only defect-free specimens were taken forward for three-body abrasive wear testing and subsequent experimental analysis.

- **Wear Testing Procedure**

Three-body abrasive wear testing was used to characterize the wear behavior of FDM-printed PLA and PLA+GF specimens under controlled abrasive conditions. In three-body abrasive wear, loose abrasive particles are introduced between two contacting surfaces in relative motion. These particles roll and slide freely between the surfaces, generating continuous material removal via cutting, ploughing, and scratching. Compared to two-body abrasion, three-body abrasion more closely replicates the contact conditions encountered in many practical engineering systems.

Figure 3.2: 3-Body Abrasive Wear Testing Equipment

Silicon carbide (SiC) abrasive particles were chosen as the abrasive medium for this study because of their high hardness and reliable abrasive characteristics. Constant operating conditions were maintained throughout all tests to ensure the reproducibility and consistency of results.

Before each test, all specimens were cleaned thoroughly to remove surface dust, loose debris, and contaminants. Initial specimen mass was recorded using a precision electronic balance. The specimen was then securely mounted on the wear testing machine.

During the test, abrasive particles were continuously fed between the rotating disc surface and the specimen face under the applied normal load. Progressive material removal from the specimen surface resulted from the frictional interaction between the abrasive particles and the polymer. Upon completion of the specified sliding distance, each specimen was carefully removed, cleaned to eliminate adhered abrasive particles, and reweighed. Wear loss was calculated as the difference between initial and final specimen mass.

The resulting wear loss values were subsequently used for Taguchi analysis and process parameter optimization. The wear test conditions are summarized in Table 3.2.

Table 3.2 Wear Test Conditions

Parameter	Value
Load	20 N
Sliding Distance	1000 m
Speed	200 rpm
Abrasive Size	425 µm

A constant normal load of 20 N was maintained throughout all tests to ensure consistent contact pressure between the specimen and the abrasive medium. A total sliding distance of 1000 m was selected to generate measurable and quantifiable wear loss under steady-state conditions. A fixed rotational speed of 200 rpm was maintained to provide uniform sliding conditions. Silicon carbide particles of 425 µm size were used as the abrasive medium. This procedure was applied consistently to every experimental combination from the Taguchi design for both PLA and PLA+GF specimens.

- **Taguchi Experimental Design**

The Taguchi method was employed to systematically examine the influence of FDM process parameters on the three-body abrasive wear behavior of the printed specimens. As a statistical optimization tool, the Taguchi approach analyzes the effects of multiple process variables on a target response while minimizing the number of required experimental runs. In full factorial designs, the experimental burden grows exponentially with the number of parameters and levels; the Taguchi approach uses orthogonal arrays to achieve a balanced and efficient design that keeps the experimental program tractable.

The three FDM process parameters investigated were:

- Layer Height
- Printing Temperature
- Printing Speed

With each parameter considered at three levels, an L9 orthogonal array was selected for the experimental design. This array requires nine experimental runs rather than the 27 that a full factorial approach would demand. The selected parameters and their levels are summarized in Table 3.3, and the L9 experimental matrix is presented in Table 3.4.

Table 3.3 Process Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Layer Height (mm)	0.16	0.20	0.24
Printing Temperature (°C)	200	210	220
Printing Speed (mm/s)	30	60	90

Table 3.4 Taguchi L9 Conformal Array

Run	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)
1	0.16	200	30
2	0.16	210	60
3	0.16	220	90
4	0.2	200	60
5	0.2	210	90
6	0.2	220	30
7	0.24	200	90
8	0.24	210	30
9	0.24	220	60

Wear test data from all experimental runs were analyzed using ANOVA and signal-to-noise (S/N) ratio methods. Since wear loss was the response parameter of interest and lower values are preferable, the 'smaller-the-better' S/N criterion was applied throughout the analysis. The Taguchi method enabled identification of the optimum parameter combination for minimizing wear loss and maximizing tribological performance in both PLA and PLA+GF specimens.

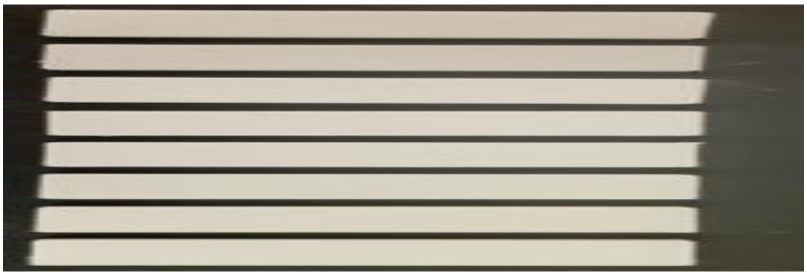

Figure 3.3: 3D Printed PLA Specimens

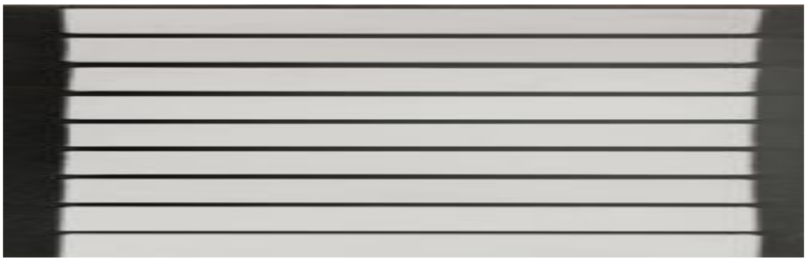

Figure 3.4: 3D Printed PLA+GF Specimens

IV. EXPERIMENTAL RESULTS

- **Wear Loss of PLA**

The FDM-printed PLA specimens prepared across the nine parameter combinations prescribed by the Taguchi L9 orthogonal array were subjected to three-body abrasive wear testing. The investigation aimed to assess the influence of layer height, printing temperature, and printing speed on the wear characteristics of PLA specimens under identical, controlled abrasive conditions.

Material removal from each specimen was quantified by recording the difference between initial and post-test mass. Wear loss values for all nine experimental runs are presented in Table 5.1.

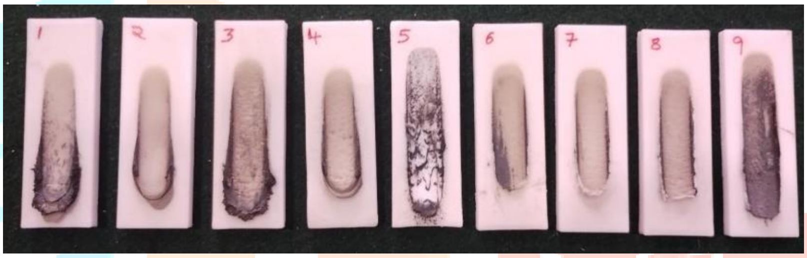

Figure 4.1: 3D Printed PLA Worn Specimens

Table 4.1 Experimental Wear Loss Values for PLA

Run	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)	Wear Loss (g)
1	0.16	200	30	0.912
2	0.16	210	60	0.842
3	0.16	220	90	1.168
4	0.20	200	60	0.965
5	0.20	210	90	1.284
6	0.20	220	30	0.735
7	0.24	200	90	1.942
8	0.24	210	30	1.601
9	0.24	220	60	1.523

The experimental data reveal that wear loss varied considerably across the different parameter combinations. The lowest wear loss value recorded was 0.735 g, obtained from the specimen printed with a layer height of 0.20 mm, printing temperature of 220°C, and printing speed of 30 mm/s. The highest wear loss of 1.942 g was recorded for the specimen printed at 0.24 mm layer height, 200°C, and 90 mm/s printing speed.

The observed trends indicate that lower layer heights and reduced printing speeds generally contributed to improved wear resistance, facilitated by stronger interlayer bonding and reduced surface irregularities. Higher printing temperatures also enhanced the structural cohesion of deposited layers, thereby reducing material loss during abrasive testing. Specimens fabricated at larger layer heights exhibited the highest wear loss values, attributable to increased porosity and weaker interlayer adhesion that accelerate material removal under abrasive loading conditions.

Based on Taguchi signal-to-noise ratio analysis, the optimum parameter combination for minimizing PLA wear loss was identified as:

- Layer Height = 0.16 mm
- Printing Temperature = 220°C
- Printing Speed = 30 mm/s

This combination — a small layer height, elevated printing temperature, and low printing speed — promotes thorough material deposition, strong interlayer fusion, and a minimal density of structural defects, thereby minimizing wear loss during three-body abrasive testing. The experimental results were further analyzed using S/N ratio plots and ANOVA to quantify the individual and combined effects of each process parameter.

- **Taguchi Analysis of PLA**

The main effects plot for S/N ratio captures the influence of layer height, printing temperature, and printing speed on the wear performance of FDM-printed PLA specimens. Because the 'smaller-is-better' S/N criterion was adopted, higher S/N values indicate lower wear loss and therefore better wear resistance.

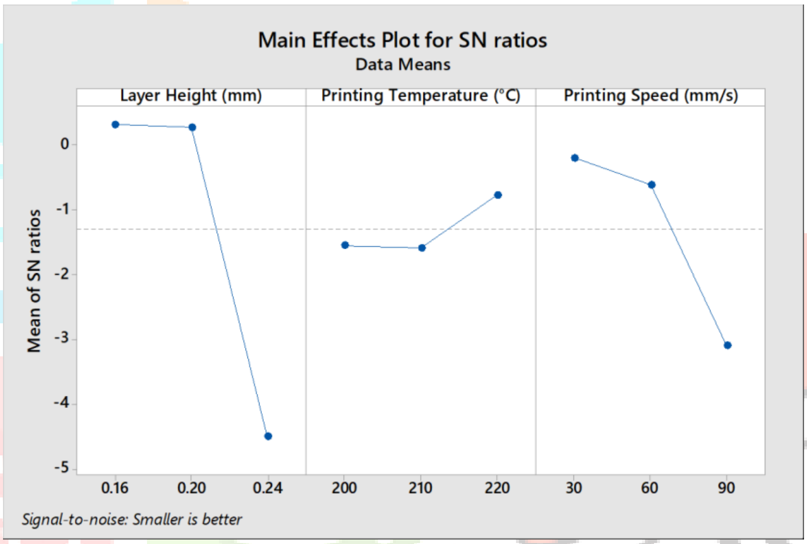

Figure 4.2: Main Effect Plot for S/N Ratio of PLA

Layer height showed the strongest influence on wear performance among all three parameters examined. The S/N ratio values remained relatively high at layer heights of 0.16 mm and 0.20 mm, before declining sharply at 0.24 mm. This pattern confirms that lower layer heights produce stronger interlayer bonding and reduced material removal, leading to improved wear resistance.

Printing temperature exhibited a moderate effect on wear loss. The S/N ratio increased monotonically with temperature and peaked at 220°C, consistent with enhanced interlayer fusion and fewer internal voids at higher nozzle temperatures conditions that collectively improve wear resistance.

Printing speed also had a meaningful impact on wear characteristics. The highest S/N ratio was observed at 30 mm/s, followed by a slight decline at 60 mm/s and a more pronounced reduction at 90 mm/s. Lower printing speeds allow more complete material fusion and stronger interlayer bonding, contributing directly to improved wear resistance. Higher speeds, by contrast, reduce deposition quality and lead to elevated wear loss.

Taken together, the S/N ratio plot confirms that the optimum parameter settings for minimizing PLA wear loss are a layer height of 0.16 mm, printing temperature of 220°C, and printing speed of 30 mm/s.

- **Wear Loss of PLA+GF**

The FDM-printed PLA+GF specimens fabricated across the nine Taguchi L9 parameter combinations were subjected to three-body abrasive wear testing under the same controlled conditions used for PLA. The objective was to assess how layer height, printing temperature, and printing speed influence the wear characteristics of glass fiber reinforced PLA.

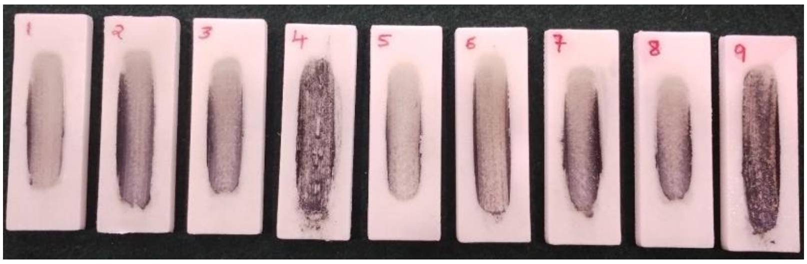

Figure 4.3: 3D Printed PLA+GF Worn Specimens

Material removal was determined from the difference between initial and post-test mass for each specimen. The experimental wear loss values for PLA+GF are presented in Table 4.3.

The experimental data show that PLA+GF specimens recorded substantially lower wear loss than their neat PLA counterparts under identical testing conditions. This improvement is attributable to the glass fiber reinforcement within the PLA matrix, which increases hardness and load-bearing capacity and thereby reduces material removal during abrasive interaction.

Table 4.3 Experimental Wear Loss Values for PLA+GF

Run	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)	Wear Loss (g)
1	0.16	200	30	0.712
2	0.16	210	60	0.654
3	0.16	220	90	0.894
4	0.20	200	60	0.768
5	0.20	210	90	1.012
6	0.20	220	30	0.586
7	0.24	200	90	1.538
8	0.24	210	30	1.284
9	0.24	220	60	1.236

The minimum wear loss of 0.586 g was recorded for the specimen fabricated at a layer height of 0.20 mm, printing temperature of 220°C, and printing speed of 30 mm/s. Maximum wear loss of 1.538 g occurred at a layer height of 0.24 mm, printing temperature of 200°C, and printing speed of 90 mm/s.

The results indicate that lower layer heights and slower printing speeds improved the wear resistance of PLA+GF specimens by enhancing interlayer adhesion and reducing porosity within the printed structure. Higher printing temperatures similarly contributed to improved wear resistance by promoting better filament fusion and strengthening the composite structure. Specimens printed at larger layer heights exhibited greater wear loss due to weaker interlayer bonding and increased surface irregularities that accelerated material removal under abrasive loading.

Overall, the experimental investigation confirms that glass fiber reinforcement substantially enhances the tribological performance of FDM-printed PLA. The PLA+GF specimens showed improved hardness, stiffness, and abrasive penetration resistance relative to neat PLA specimens. The experimental results were further analyzed through Taguchi S/N ratio analysis and ANOVA to identify optimum printing parameters and to quantify the significance of each factor.

- **Taguchi Analysis of PLA+GF**

The main effects plot for S/N ratio characterizes the influence of layer height, printing temperature, and printing speed on the wear performance of FDM-printed PLA+GF composites. The 'smaller-is-better' S/N criterion was applied, so higher S/N values correspond to lower wear loss and better wear resistance.

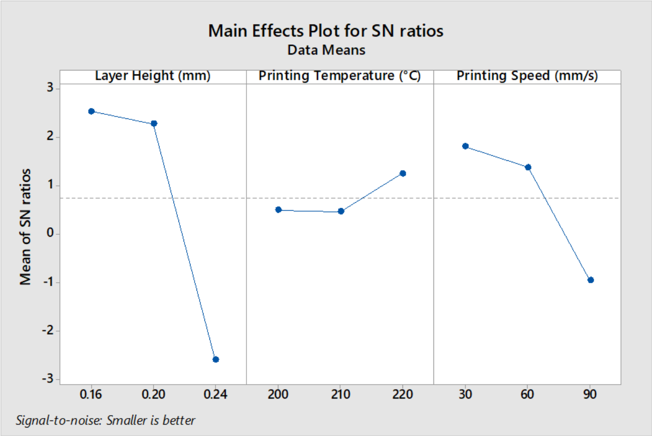

Figure 4.4: Main Effect Plot for S/N Ratio of PLA+GF

Among all three parameters, layer height again exerted the greatest influence on wear performance. The S/N ratio was highest at a layer height of 0.16 mm, slightly lower at 0.20 mm, and declined sharply at 0.24 mm — confirming that smaller layer heights improve interlayer bonding and reduce surface irregularities, thereby improving wear resistance in the composite.

Printing temperature showed a moderate effect on wear behavior, with the S/N ratio increasing progressively with temperature to reach its maximum at 220°C. Elevated temperatures improve interlayer fusion and promote better adhesion between the PLA matrix and glass fiber reinforcement, reducing wear loss.

Printing speed also significantly affected wear characteristics in the PLA+GF composite. The highest S/N ratio was recorded at 30 mm/s, with a slight decrease at 60 mm/s and a more substantial decline at 90 mm/s. Lower speeds allow more time for proper material consolidation, improving structural integrity and wear resistance. Higher speeds result in weaker interlayer bonding and increased wear loss.

The plot therefore confirms that the optimum process parameter combination for minimizing PLA+GF wear loss is: layer height = 0.16 mm, printing temperature = 220°C, and printing speed = 30 mm/s.

V. CONCLUSION

The present investigation examined the three-body abrasive wear behavior of FDM-printed PLA and glass fiber reinforced PLA (PLA+GF) composites across a range of printing conditions using the Taguchi experimental design methodology. The influence of layer height, printing temperature, and printing speed on wear performance was systematically characterized through experimental wear testing, S/N ratio analysis, and ANOVA. The principal conclusions drawn from the work are as follows:

1. Layer height was identified as the most significant process parameter affecting wear behavior in both PLA and PLA+GF specimens. ANOVA analysis showed that layer height contributed markedly more to wear loss variation than either printing temperature or printing speed. Its dominant influence reflects the strong effect it exerts on interlayer bonding quality, internal porosity, and structural integrity of the printed specimens.

2. Lower layer heights improved wear resistance across both material systems. Specimens printed with smaller layer heights exhibited better interlayer adhesion, reduced void fraction, and smoother surface finish, collectively enhancing resistance to abrasive particle penetration and limiting material removal during testing.

3. Higher printing temperatures reduced wear loss by improving interlayer fusion. Elevated nozzle temperatures enhanced filament melting and flow characteristics, producing stronger bonding between deposited layers and reducing the density of internal defects.

4. Lower printing speeds led to improved deposition quality and better tribological performance. Reduced printing speed provided sufficient time for filament fusion and consolidation, strengthening structural integrity and minimizing abrasive wear.

5. PLA+GF composites showed substantially improved wear resistance relative to neat PLA specimens. The inclusion of glass fiber reinforcement significantly enhanced hardness, stiffness, and load-bearing capability of the material. Average wear loss for PLA+GF specimens was approximately 20.84% lower than for neat PLA under identical testing conditions.

Overall, the study demonstrates that a combination of FDM process parameter optimization and glass fiber reinforcement can substantially improve the tribological performance and wear resistance of additively manufactured polymer composites.

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