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INVESTIGATION OF WEAR BEHAVIOR OF FDM PRINTED ABS AND CARBON FIBER REINFORCED ABS COMPONENTS

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Abstract: The present study investigates the wear behavior of acrylonitrile butadiene styrene [ABS] and carbon fiber reinforced ABS [ABS + CF] composites printed with FDM, by testing it in three-body abrasive wear machine. Taguchi experimental design is also applied for optimization of experimental trials. The 3D printing process parameters effects such as layer height, printing temperature, and printing speed on material loss due to wear was investigated using Taguchi L9 orthogonal array and Analysis of variance [ANOVA]. This experimental results in layer height significantly influenced the wear resistance compared to pure ABS. The optimized printing conditions resulted in minimum wear loss with enhanced tribological performance.

Keywords: FDM, ABS, ABS+CF, Wear Behavior, Taguchi Method, ANOVA, Additive Manufacturing.

I. INTRODUCTION

1. Additive Manufacturing

In additive manufacturing [AM], 3D printing has a very common manufacturing method to build the component directly from solid CAD model in which components are fabricated layer-by-layer. Unlike any other traditional manufacturing methods where material is removed from a work piece, additive manufacturing used to build the component by depositing material only where required.

In last few years AM has gained attention in various industrial sectors, especially in biomedical, consumer products, defense, automotive and aerospace because of its flexibility and cost effectiveness. This technology supports in rapid prototyping and direct manufacturing of functional components. This entire process and flexibility completely depends on 3D printing of material and type of process. Fused Deposition Modelling [FDM] still remains commonly chosen techniques for thermoplastic materials because of its simplicity, affordability, and ease of operation.

The increase in demands for lightweight and high-performance engineering components has further encouraged to choose reinforced polymer composites in additive manufacturing. However, the properties of FDM printed components related to mechanical and tribological behavior mainly relies on the parameters opted during FDM process and composition along with filament quality.

2. Fused Deposition Modelling(FDM)

It is very commonly used AM techniques for building a polymer-based component. The process operates by continuous feeding a thermoplastic filament through a heated nozzle, where the material is melted and deposited layer-by-layer as per the toolpath generated by the slicing software. After deposition, the material solidifies and bonds with its earlier layer to complete the final component.

This process of FDM generally consists of several stages including CAD modelling, slicing, toolpath generation, filament extrusion, and layer deposition. From converting of a CAD software model into STL file and then processing with help of slicing software and define the parameters for printing such as height of each layer, printing speed, and nozzle temperature are all considered as preprocessing before the actual printing. The process parameters are crucial in deciding the quality of the printed component. To overcome these limitations, inclusion of CFs (CF) as reinforcements into polymer matrices will enhance strength, stiffness, and tribological performance.

3. Acrylonitrile Butadiene Styrene(ABS)

ABS is most commonly used and selected thermoplastic polymers in FDM because of its mechanical, thermal, and processing characteristics. ABS is an amorphous polymer composed of three monomers namely acrylonitrile, butadiene, and styrene. The acrylonitrile component provides the chemical resistance and thermal stability, butadiene contributes toughness and impact resistance, where as styrene improves its rigidity and surface finish. because of this combination of properties, ABS is extensively utilized in engineering applications such as automotive components, consumer products, electronic housings, and prototype development.

4. Carbon Fiber Reinforced ABS (ABS + CF)

ABS+CF is a composite material developed by incorporating CFs into the ABS polymer matrix to enhance its mechanical and tribological properties. Since CF is having high strength, good stiffness with less density and very good thermal stability, which makes it an ideal choice for various applications. The inclusion of CF improves the performance characteristics of ABS components significantly.

The inclusion of CF into ABS enhances stiffness, hardness, tensile strength & dimensional stability of the printed components. CF also reduces the thermal shrinkage and warping during the printing process, which results in improving dimensional accuracy and print quality. Due to their lightweight nature and high specific strength, ABS+CF composites are increasingly preferred in aerospace, automotive, robotics, and structural engineering applications, where the weight reduction and mechanical performance are important considerations.

5.Need for Wear Analysis

In FDM fabricated components, the layer-by-layer deposition process introduces anisotropic characteristics and interlayer bonding defects which adversely affect tribological performance. The surface quality, strength of bonding between layers, porosity, and internal structure of the printed component are strongly influenced by the process parameters like layer height, printing temperature, and printing speed. Variations in these process parameters may lead to changes in wear resistance and material removal mechanisms during operation.

Among different wear mechanisms, three-body abrasive wear is commonly encountered in practical engineering environments where loose abrasive particles exist in between two contacting surfaces. Under such conditions, abrasive particles slide or roll between the surfaces and remove material progressively, leading to wear damage. Hence this is critical to understand the wear behavior of the 3D printed component using three-body abrasive wear to predict their actual life in real-world applications. The incorporation of reinforcement materials such as CF will enhance the wear resistance of polymer composites.

The present study focused on the evaluation of wear, and tribological performance of Fused Deposition Modelling printed ABS and ABS+CF specimens under controlled three-body abrasive wear conditions. In order to determine the most influential parameters and determine the optimum printing conditions for minimizing wear loss.

II. OBJECTIVE

The aim of this study focused on the evaluation of wear, and tribological performance of Fused Deposition Modelling printed ABS and ABS+CF specimens under controlled three-body abrasive wear conditions. In order to determine the most influential parameters and determine the optimum printing conditions for minimizing wear loss.

- The objective of this study is to fabricate ABS and ABS+CF composite specimens in FDM with different process parameter combinations.
- The objective is to assess and study the three-body abrasive wear behavior of printed sample (specimens) and investigate the influence of the layer height, printing temperature, and printing speed on wear performance.
- The objective is to apply the Taguchi method for this design, Signal-to-Noise (S/N) ratio analysis using the smaller-the-better criterion, and optimization of printing parameters.
- The objective is to identify the significant process parameters affecting wear behavior and comparison of wear performance of ABS and ABS+CF specimens by applying Analysis of Variance (ANOVA) study.

III. Methodology

1. Pure ABS Filament

Acrylonitrile Butadiene Styrene (ABS) is a widely used thermoplastic polymer in additive manufacturing because of its balanced mechanical and thermal properties. ABS exhibits good impact resistance, toughness, thermal stability, and ease of processing, making it suitable for engineering and functional applications. The material also offers good dimensional stability and moderate wear resistance under operating conditions. The commercially available Filament of ABS is shown in Fig.1.

Fig.1 Filament of Neat ABS

In the present study, commercially available ABS filament of standard diameter was used for specimen fabrication through the FDM process. The filament was supplied in spool form and stored under dry environmental conditions to prevent moisture absorption before printing.

2. CF Reinforced ABS (ABS + CF)

Carbon reinforced ABS [ABS+CF] filament is a polymer composite material developed by incorporating short CFs into the ABS matrix and in the form of filament. The inclusion of CF significantly enhances stiffness, hardness, dimensional stability, and wear behavior of the material. Due to these advantages, ABS+CF composites are increasingly used in lightweight structural and engineering applications. The commercially available Filament of ABS+CF is shown in Fig.2.

Fig.2 Filament of ABS + CF

In the present investigation, commercially available ABS+CF filament is used in FDM for specimen fabrication. The composite filament contained uniformly distributed CF reinforcements within the ABS matrix to improve mechanical and tribological performance.

3. Printing Parameters

The quality and performance FDM fabricated components are significantly influenced by process parameters selected during printing. Parameters such as layer height, printing temperature, and printing speed affect interlayer bonding, dimensional stability, quality of surface, mechanical properties, and wear behavior of the printed specimens. Therefore, appropriate selection of process parameters is essential for obtaining defect-free components with improved tribological performance.

In this investigation, the printing parameters are choosen based upon previous literature studies and machine operating limitations. Each parameter was considered at three different levels to study its influence on the three-body abrasive wear behavior of neat ABS and CF reinforced ABS (ABS+CF) composites. The corresponding levels chosen and their selected process parameters are depicted in Table 1.

Table 1. Printing Parameters and Their Levels

Parameter	Level 1	Level 2	Level 3
Layer Height (mm)	0.16	0.20	0.24
Printing Temperature (°C)	220	230	240
Printing Speed (mm/s)	30	60	90

4. Fabrication of Specimens

The specimens required for this present investigation are produced using the FDM process. The fabrication process involved several stages including CAD modelling, STL conversion, slicing, parameter selection, and layer-by-layer printing of the specimens. The printing process of ABS and ABS+CF is shown in Fig.3.

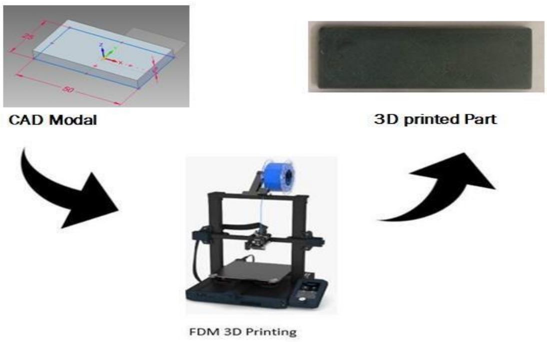

Fig.3 3D Printing Process of ABS and ABS+CF

Initially, the specimen geometry for three-body abrasive wear testing was designed using computer-aided design (CAD) software according to the required dimensions and testing standards. The CAD model was carefully prepared to ensure dimensional accuracy and uniform geometry for all experimental samples. After completion of the design process the designed model in CAD was converted into STL (Standard Tessellation Language) format, which is standard in AM applications. The STL file represents the component geometry using a triangular mesh structure and enables communication between the CAD software and the slicing software.

The generated file, which is STL file was moved into slicing software for preprocessing and toolpath generation. The slicing software converted the three-dimensional model into a series of thin horizontal layers and generated machine instructions in the form of G-code for the FDM printer. During this stage, important process parameters such as layer height, printing temperature, and speed of printing were selected depending on the Taguchi L9 experimental design. Additional settings including nozzle diameter, infill pattern, raster orientation, and cooling conditions were also configured to ensure proper fabrication of the specimens.

Before printing, the build platform of the FDM printer was properly leveled and cleaned to ensure good adhesion of the first layer. Both pure ABS and CF reinforced ABS (ABS+CF) filaments were loaded separately into the extrusion system of the printer. The filaments were maintained under dry environmental conditions prior to printing in order to avoid absorption of moisture otherwise it would affect print quality and mechanical performance.

During the printing process, the thermoplastic filament was continuously poured in to a heated extrusion nozzle where it melted at the selected printing temperature. The molten material was deposited layer-by-layer onto the build platform following the programmed toolpath generated by the slicing software. After deposition, each layer solidified and bonded with the previously deposited layer to gradually form the complete specimen geometry.

The movement of the nozzle in the X and Y directions controlled the deposition path of the material, while the vertical movement in the Z direction determined the layer stacking sequence. The selected layer heights of 0.16 mm, 0.20 mm, and 0.24 mm were carefully maintained throughout the printing process to ensure consistency among all specimens. Similarly, printing temperatures of 220°C, 230°C, and 240°C and printing speeds of 30 mm/s, 60 mm/s, and 90 mm/s were used according to the experimental design matrix.

Special attention was given to avoid common FDM defects such as warping, poor interlayer bonding, under-extrusion, and porosity. The conditions of printing environment were controlled to minimize dimensional inaccuracies and thermal distortion. After completion of printing, the specimens were naturally cooled. The fabricated specimens were visually inspected to identify any surface defects, cracks, or layer separation. Dimensional measurements were also performed to ensure uniformity and consistency among the printed samples. Only defect-free specimens with acceptable dimensional accuracy were selected for three-body abrasive wear testing.

Both pure ABS and ABS+CF specimens were produced with similar printing conditions to facilitate a comparative investigation of their tribological performance. The fabricated samples subjected to wear analysis, statistical optimization, and SEM examination to understand the effect of FDM printing parameters on the specimen.

5. Wear Testing Conditions

To assess the tribological performance of FDM fabricated pure ABS and CF reinforced ABS (ABS+CF) specimens three body abrasive wear tests are conducted under controlled operating conditions and it is shown Fig.4.

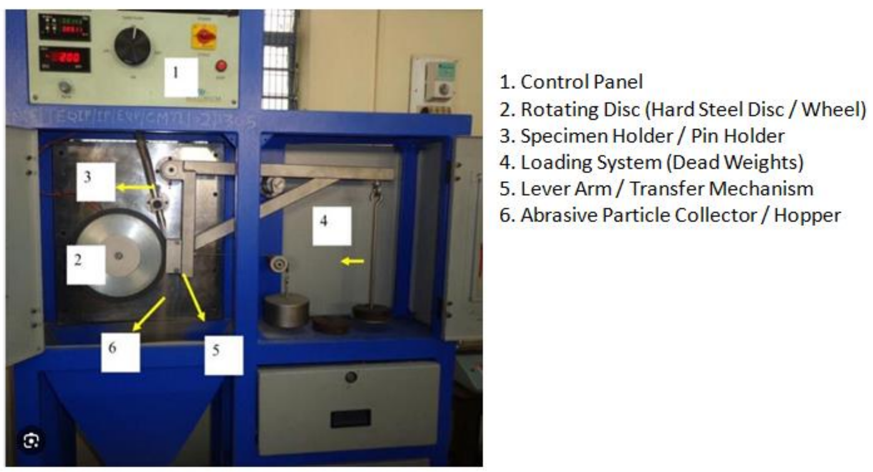

Fig.4 3-Body Abrasive Wear Testing Equipment

The wear experiments were designed to simulate practical engineering environments in which loose abrasive particles exist between the contacting surfaces during relative motion. These problems are commonly comes in applications involving conveyor systems, gears, bearings, agricultural equipment, and mechanical components operating in dusty or abrasive environments.
The parameters selected for wear testing are depicted in Table 2.

Table 2. Wear Testing Conditions

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

6. Taguchi Experimental Design

To assess the tribological performance of FDM fabricated pure ABS and CF reinforced ABS (ABS+CF) specimens three body abrasive wear tests are conducted under controlled operating conditions. The wear experiments were designed to simulate practical engineering environments in which loose abrasive particles exist between the contacting surfaces during relative motion. These problems are commonly comes in applications involving conveyor systems, gears, bearings, agricultural equipment, and mechanical components operating in dusty or abrasive environments.

The Taguchi approach provides an efficient method for studying the effect of multiple parameters on a response characteristic with reduced experimental cost and time. In this study, the response parameter considered was wear loss, and the selected process parameters were layer height, printing temperature, and printing speed. Each parameter was studied at three different levels. The selected process parameters and levels used in the Taguchi design are depicted in Table 3.

Table 3 Process Parameters considered in this study and levels

Parameter	Symbol	Level 1	Level 2	Level 3
Layer Height (mm)	A	0.16	0.20	0.24
Printing Temperature (°C)	B	220	230	240
Printing Speed (mm/s)	C	30	60	90

With number of process parameters considered as three with three levels an L9 orthogonal array was opted for the experimental design. This method allows investigation of three different factors at three varying levels using only nine experimental runs instead of conducting a full factorial experiment involving twenty-seven trials. Based on these parameters and levels the array was formulated as presented in Table 4.

Table 4. Taguchi L9 Orthogonal Array

Run	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)
1	0.16	220	30
2	0.16	230	60
3	0.16	240	90
4	0.20	220	60
5	0.20	230	90
6	0.20	240	30
7	0.24	220	90
8	0.24	230	30
9	0.24	240	60

Each experimental run represented a unique combination of parameters and was used to print the corresponding wear test specimen using the FDM process. After fabrication, three-body abrasive wear tests are conducted under similar operating conditions to identify the wear loss for each experimental trial. The Taguchi method also utilizes Signal-to-Noise (S/N) ratio analysis to identify the optimum printing parameters for improved performance. Since the main focus of the study was to minimize wear loss, the "smaller-the-better" criterion was selected for S/N ratio analysis. The S/N ratio for wear loss was evaluated using the following relation:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

where:

- y_i= observed wear loss value
- n= number of observations

Fig.5 3D printed ABS Specimens according to the L9 Array

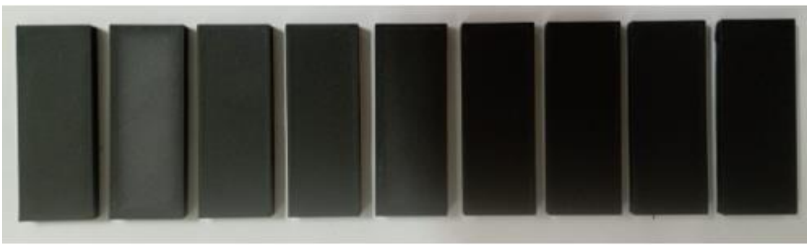

Fig.6 3D printed ABS + CF Specimens according to the L9 Array

Analysis of variance [ANOVA] was further employed to determine the statistical significance and percentage contribution of each process parameter affecting wear behavior. The combined use of Taguchi optimization and ANOVA enabled systematic evaluation of the influence of FDM parameters on the tribological performance of pure ABS and ABS+CF composites.

The experimental design methodology chosen in this study provided an effective approach for identifying the optimum printing conditions that resulted in minimum wear loss and improved wear resistance of the printed specimens.

IV. RESULTS AND DISCUSSION

1. Wear Behavior of Neat ABS

The wear behavior of pure ABS specimens printed using the Fused Deposition Modelling (FDM) process was checked by various combinations of printing parameters. The wear performance was evaluated depending on the wear loss measured after conducting abrasive wear tests under controlled operating conditions. The selected process parameters included layer height, printing temperature, and printing speed, each considered at three different levels according to the Taguchi L9 orthogonal array. And the 3D printed ABS worn specimens are shown Fig.7.

Fig.7 3D Printed ABS worn Specimens

The experimental wear loss values obtained for pure ABS specimens are presented in Table 5. From the experimental observations, it is obvious that the wear behavior of pure ABS specimens was strongly influenced by the selected FDM process parameters. Significant variation in wear behavior was witnessed with changes in layer height, printing temperature, and printing speed.

The least wear loss of 0.982 mg was obtained for the specimen fabricated with:

• Layer Height = 0.20 mm
• Printing Temperature = 240°C
• Printing Speed = 30 mm/s

The improved resistance to wear witnessed in these conditions may be attributed to enhanced interlayer bonding and better structural consolidation of the printed specimen. The higher printing temperature of 240°C improved melting and flow characteristics of the ABS material, resulting in stronger adhesion between adjacent deposited layers. In addition, the lower printing speed of 30 mm/s provided sufficient time for proper material deposition and fusion, thereby minimizing internal voids and porosity within the structure.

Table 5. Experimental Wear Loss Values for Pure ABS

Run	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)	Wear Loss (mg)
1	0.16	220	30	1.365
2	0.16	230	60	1.298
3	0.16	240	90	1.912
4	0.20	220	60	1.342
5	0.20	230	90	1.965
6	0.20	240	30	0.982
7	0.24	220	90	2.978
8	0.24	230	30	2.215
9	0.24	240	60	2.346

On the contrary, the maximum wear loss of 2.978 mg was observed for the specimen fabricated with:

- Layer Height = 0.24 mm
- Printing Temperature = 220°C
- Printing Speed = 90 mm/s

The results clearly indicate that layer height had a substantial influence on wear behavior. Lower layer heights generally improved wear resistance due to better layer adhesion and reduced surface irregularities. As the layer height increased from 0.16 mm to 0.24 mm, the wear loss also increased considerably. This behavior may be attributed to increased void formation and weak interfacial bonding at higher layer thicknesses.

Printing temperature also played an important role in determining wear performance. Higher temperatures improved interlayer diffusion and bonding, thereby reducing wear loss. However, inadequate heating at lower temperatures resulted in weak bonding and poor structural integrity. Similarly, lower printing speeds contributed to improved wear resistance because slower deposition allowed sufficient time for proper material fusion and layer consolidation. Higher printing speeds reduced bonding quality and increased porosity, which accelerated wear under abrasive conditions.

The results of the wear tests highlights that there is need for optimization of FDM printing parameters for improving the tribological performance of pure ABS components. Proper selection of layer height, printing temperature, and printing speed can significantly reduce wear loss and enhance the durability of FDM fabricated polymer components under abrasive operating conditions.

2. Main effect plot for SN ratio for ABS

The main effects plot for S/N ratios illustrates(Fig.8), the effect of layer height, printing temperature, and printing speed on the wear behavior of FDM printed ABS specimens. Since the "smaller-the-better" criterion was selected for wear loss analysis, a greater S/N ratio shows that better resistance to wear and much lesser loss of material due to wear.

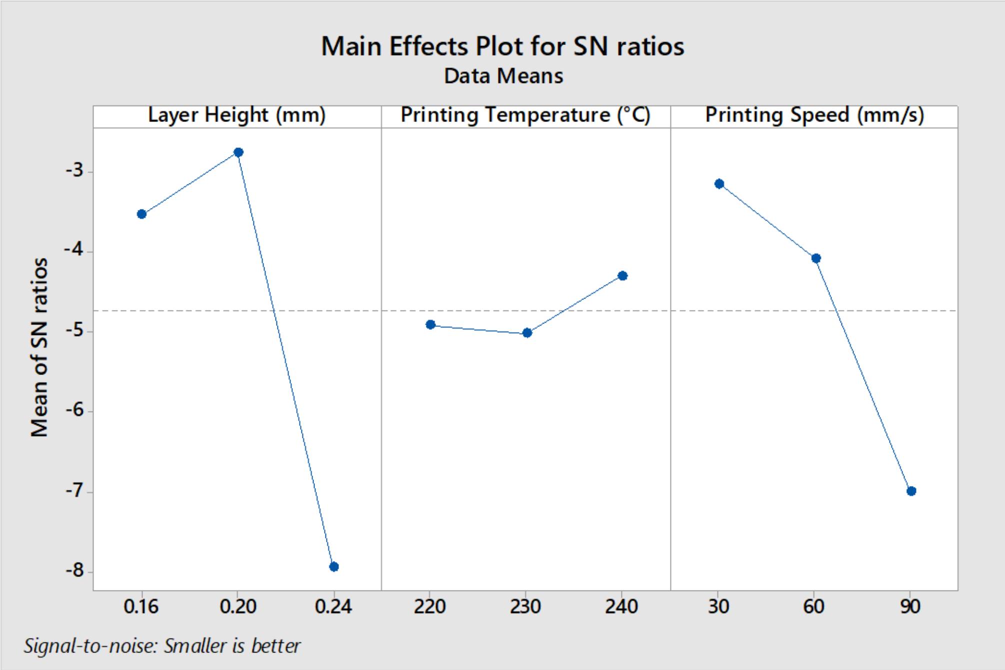

Fig.8 Main effect plot for SN ratio for ABS

Based on the analysis of S/N ratio, the combination of parameters which is optimum for lesser loss of material due to wear of ABS specimens was identified as:

- Layer Height = 0.20 mm
- Printing Temperature = 240°C
- Printing Speed = 30 mm/s

The results indicate that lower printing speed and optimized layer deposition conditions improve tribological performance of FDM printed ABS components by enhancing interlayer bonding and reducing internal defects.

3. ANOVA Analysis for Pure ABS

In order to find the statistical significance and % contribution of the selected FDM printing parameters on the three-body abrasive wear behavior of pure ABS specimens the Analysis of Variance (ANOVA) was used. The printing parameters opted in the present analysis were layer height, printing temperature, and printing speed.

The results ANOVA study for wear loss of pure ABS specimens are presented in Table 6.

Table 6. Result of ANOVA study for pure ABS Wear loss

Parameter	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution (%)
Layer Height	2	2.1588	1.0794	74.13	0.013	67.18
Printing Temperature	2	0.0331	0.0165	1.14	0.468	1.03
Printing Speed	2	0.9923	0.4962	34.07	0.029	30.88
Residual Error	2	0.0291	0.0146	—	—	0.91
Total	8	3.2133	—	—	—	100

The ANOVA analysis validated the experimental observations and confirmed that optimization of layer height and printing speed is essential for improving the wear resistance of FDM fabricated pure ABS components.

4. Wear Behavior of ABS+CF

The three-body abrasive wear behavior of CF reinforced ABS (ABS+CF) composites fabricated using the FDM printing was studied and reported by various combinations of printing parameters. The wear behavior of the composite specimens was checked in terms of wear loss measured after abrasive wear testing under controlled operating conditions. Similar to pure ABS specimens, the process parameters considered in the present investigation were layer height, printing temperature, and printing speed. The 3D printed ABS+CF worn specimens is shown in Fig.9.

Fig.9 3D Printed ABS+CF worn Specimens

The values of experimental material loss due to wear got for ABS+CF composite specimens are depicted in Table 7.

Table 7. Experimental Wear Loss Values for ABS+CF Composites

Run	Layer Height (mm)	Printing Temperature (°C)	Printing Speed (mm/s)	Wear Loss (mg)
1	0.16	220	30	1.051
2	0.16	230	60	1.012
3	0.16	240	90	1.258
4	0.20	220	60	0.915
5	0.20	230	90	1.320
6	0.20	240	30	0.758
7	0.24	220	90	1.850
8	0.24	230	30	1.657
9	0.24	240	60	1.723

From the experimental results, it is evident that the wear behavior of ABS+CF composites was significantly influenced by the selected FDM process parameters. However, compared to pure ABS specimens, the ABS+CF composites exhibited considerably lower wear loss in all experimental trials with all varying parameters md this is attributed towards the CF reinforcement in the ABS matrix.

The minimum wear loss of 0.758 mg was noted for the specimen fabricated with:

- Layer Height = 0.20 mm
- Printing Temperature = 240°C
- Printing Speed = 30 mm/s

The superior wear resistance under these conditions attributes to enhanced in interlayer bonding and enhanced in structural integrity resulting from higher printing temperature and lower printing speed. The presence of CFs further improved the hardness and load-bearing capability of the composite material, thereby reducing material removal during abrasive interaction.

The maximum wear loss of 1.850 mg was obtained for the specimen fabricated with:

• Layer Height = 0.24 mm
• Printing Temperature = 220°C
• Printing Speed = 90 mm/s

The increased of material due to wear in all of the conditions considered in this study can be associated with poor layer adhesion, increased porosity, and insufficient fusion between deposited layers caused by higher layer height and lower printing temperature. The higher printing speed may also have reduced quality bonding and increased structural defects within the printed specimen.

This results indicate that layer height significantly affected the wear behavior of ABS+CF composites. Lower layer heights improved wear resistance due to enhanced bonding and reduced surface roughness. As this layer height increased to 0.24 mm, wear loss increased considerably because of weaker interlayer adhesion and increased void formation.

Printing temperature also played a important part in finding the tribological behavior of the composites. Higher printing temperature improved material flow and interfacial bonding between the polymer matrix and CF reinforcement, thereby reducing wear loss. Lower printing temperatures resulted in insufficient material fusion and poor structural consolidation.

Similarly, lower printing speeds enhanced wear resistance due to better deposition quality and reduced porosity. Higher printing speeds produced weaker bonding between layers and accelerated material removal under abrasive conditions. The comparison in between pure ABS and ABS+CF specimens revealed that CF reinforcement significantly improved wear behavior of the polymer material. The CFs acted as load-bearing reinforcements and minimized plastic deformation and surface damage during abrasive interaction. The improved hardness and stiffness of the composite reduced groove formation and material removal under three-body abrasive wear conditions.

Overall, the ABS+CF composites demonstrated superior tribological performance compared to pure ABS specimens under all experimental conditions. The results confirm that CF reinforcement and proper optimization of FDM process parameters can effectively enhance the wear characteristics and durability of additively manufactured polymer components.

5. Main effect plot for SN ratio for ABS+CF

The main effects plot for S/N ratios(Fig.10) represents the effect of layer height, printing temperature, and printing speed on this wear behavior of FDM printed ABS+CF composites. Since the "smaller-the-better" criterion was used for wear analysis, higher S/N ratio values indicate lower wear loss and better wear resistance.

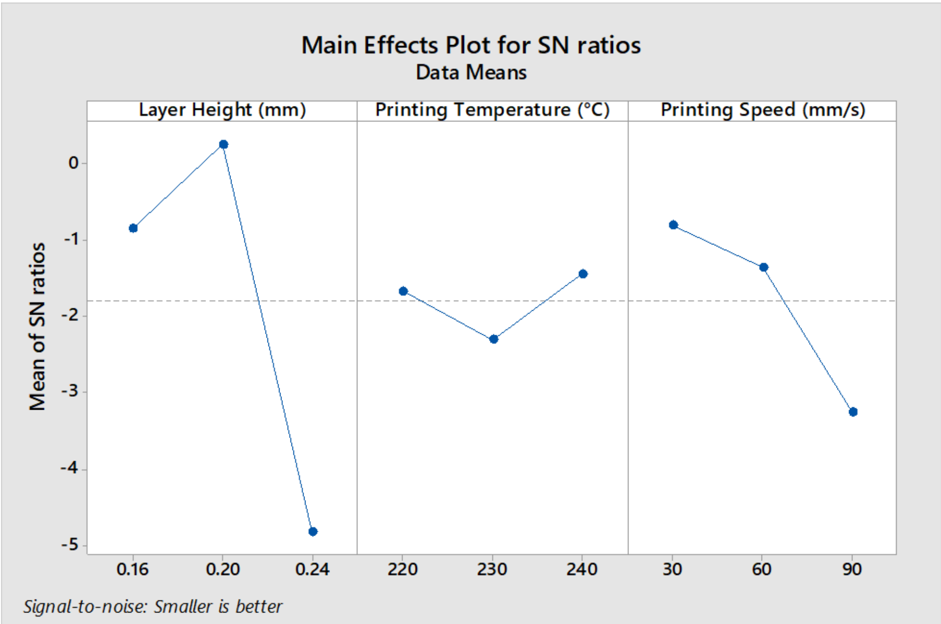

Fig.10 Main effect plot for SN ratio for ABS+CF

Based on the analysis of S/N ratio, the optimum printing parameters for reducing wear loss of ABS+CF composites were identified as:

• Layer Height = 0.20 mm
• Printing Temperature = 240°C
• Printing Speed = 30 mm/s

The results indicate that CF reinforcement improved the wear resistance of ABS composites by enhancing hardness and load carrying capability.

6. ANOVA Analysis for ABS+CF Composites

ANOVA analysis study was conducted to assess the statistical significance and influence of the selected FDM parameters on the three-body abrasive wear behavior of CF reinforced ABS (ABS+CF) composite specimens. The parameters considered for the analysis were layer height, printing temperature, and printing speed. The ANOVA results obtained for wear loss of ABS+CF composites are presented in Table 8.

Table 8. Result of ANOVA study for ABS+CF Wear loss

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution (%)
Layer Height	2	0.9446	0.4723	61.84	0.016	64.52
Printing Temperature	2	0.0416	0.0208	2.72	0.269	2.84
Printing Speed	2	0.4632	0.2316	30.33	0.032	31.64
Residual Error	2	0.0153	0.0076	—	—	1.00
Total	8	1.4647	—	—	—	100

The analysis from the ANOVA study highlights that optimization of layer height and printing speed is essential for improving the tribological performance of ABS+CF composites fabricated using the FDM process.

7. Scanning Electron Microscopy Analysis

SEM analysis study was conducted to examine the worn surfaces of pure ABS and CF reinforced ABS (ABS+CF) specimens after conducting the three-body abrasive wear tests.

- **Worn Surface Morphology of Pure ABS:** The SEM micrographs of pure ABS specimens(Fig.11) showed, severe abrasive wear damage characterized by deep grooves, ploughing marks, surface scratches, and material peeling. These wear features were mainly produced due to continuous interaction between the silicon carbide abrasive particles and the polymer surface during sliding motion.

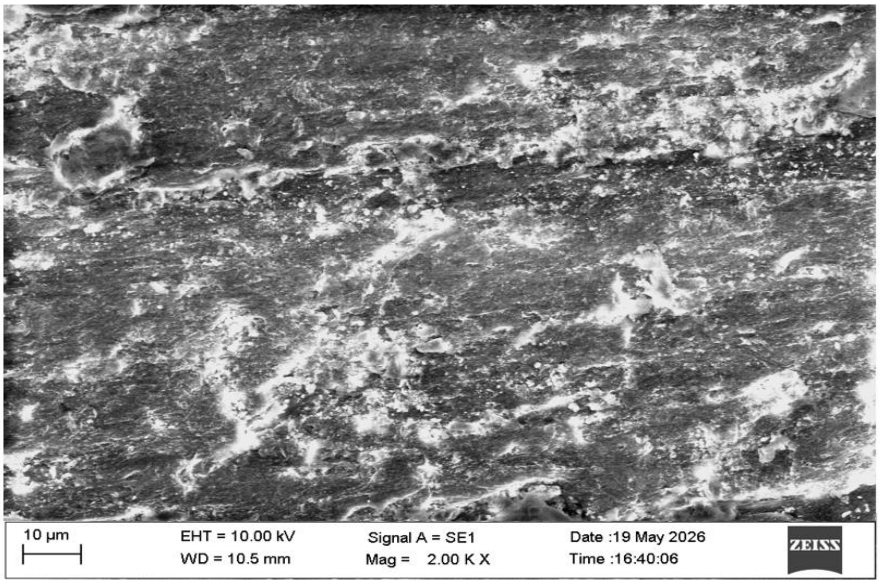

Fig.11 SEM micrographs of pure ABS specimens

- **Worn Surface Morphology of ABS+CF Composites:** The SEM micrographs of ABS+CF composite specimens(Fig.12) revealed comparatively lower surface damage than pure ABS specimens. The worn surfaces exhibited shallower grooves, less severe ploughing marks, and reduced material removal due to the reinforcing effect of CFs.

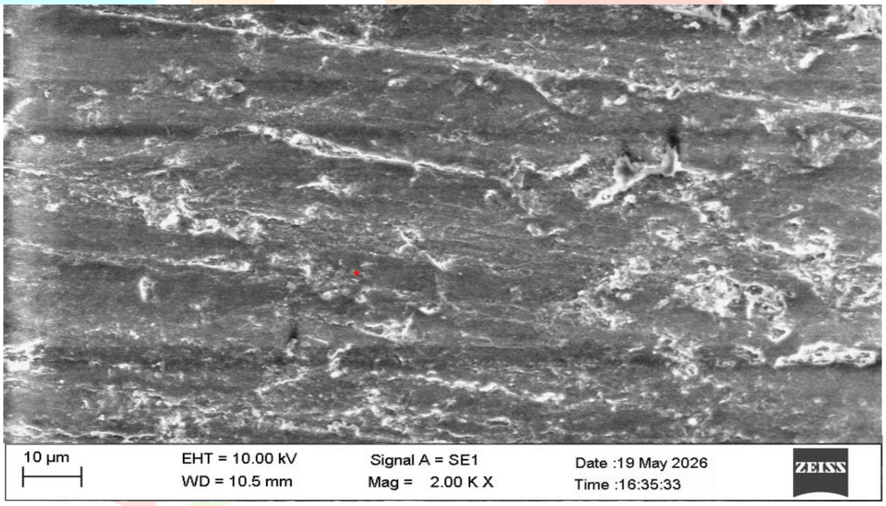

Fig.12 SEM micrographs of ABS+CF specimens

V. CONCLUSION

The present investigation focused on the three-body abrasive wear behavior of FDM fabricated pure ABS and ABS+CF specimens under different printing conditions. The effect of process parameters such as layer height, printing temperature and speed of printing on wear behavior was systematically investigated using Taguchi L9 orthogonal array and ANOVA analysis.

Based on these experimental results, statistical analysis, and SEM observations, the following conclusions were drawn:

1. The wear behavior of FDM fabricated specimens was substantially affected by the selected process parameters, namely layer height, printing temperature, and printing speed.
2. Layer height was identified as the most influential parameter affecting abrasive wear behavior for both pure ABS and ABS+CF composites. Lower layer heights improved interlayer bonding and reduced material removal during wear testing.
3. Lower layer height produced smoother surfaces, reduced porosity, and enhanced structural integrity, thereby improving wear resistance of the printed specimens.
4. Higher printing temperature improved material flow and interlayer fusion, resulting in lower wear loss and enhanced tribological performance.
5. Lower printing speed improved deposition quality and bonding between adjacent layers, thereby reducing abrasive wear damage.

6. CF reinforcement significantly enhanced the wear resistance of ABS composites due to improved hardness, stiffness, and load-bearing capability of the material.
7. ABS+CF composite specimens exhibited lower wear loss compared to pure ABS specimens under all experimental conditions.
8. The minimum wear loss for pure ABS was observed at:
   - Layer Height = 0.20 mm
   - Printing Temperature = 240°C
   - Printing Speed = 30 mm/s
9. The minimum wear loss for ABS+CF specimens under the same optimized process conditions:
   - Layer Height = 0.20 mm
   - Printing Temperature = 240°C
   - Printing Speed = 30 mm/s 10.

10.SEM analysis revealed abrasive grooves, ploughing marks, crack formation, and material removal mechanisms on worn specimen surfaces. ABS+CF specimens showed comparatively reduced surface damage due to the reinforcing effect of CFs.

11. Taguchi optimization and ANOVA analysis justifies to be effective statistical tools for identifying significant printing parameters & obtaining optimum printing conditions for improved wear resistance.

12. The present investigation confirmed that optimization of FDM process parameters and incorporation of CF reinforcement can meaningfully enhances the tribological behavior and durability of polymer components fabricated using additive manufacturing.

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