Indian Journal of Engineering & Materials Sciences
Vol. 31, April 2024, pp. 276-283
DOI: 10.56042/ijems.v31i2.623

# Experimental investigation on abrasive flow finishing of FDM printed polymeric spur gear

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*Received: 17 April 2023; Accepted: 14 January 2024*

Recently the use of polymers has seen significant growth in manufacturing industries. Polymeric gear is applied in automation, material handling systems, toys and some household applications. At the same time, there are numerous benefits of additive manufacturing techniques. Three dimensional (3D) printed products and components have a wide range of applications, which are growing day by day. The outer surface of the 3D printing process suffers from poor finishing due to layer addition. In this study, abrasive flow machining (AFM) is utilised to assess how well polymeric gears created using fused deposition modelling are finished (FDM). In this study, abrasive flow machining (AFM) is utilised to assess how well polymeric gears created using fused deposition modelling are finished (FDM). The study develops an AFM medium from coal-ash powder, EDM oil, and glycerin. AFM medium viscosity and process parameters have been improved to improve surface quality. Using the statistical program Minitab, a Taguchi L9 Design of Experiments (DOE) has been generated to optimize parameters and establish a functional relationship between the output parameter, surface roughness, and the input variables, which included layer thickness, abrasive concentration, mesh size of abrasive, and finishing time. An analysis has been carried out to optimize the parameters of the abrasive flow machining (AFM) medium in order to improve the surface quality of polymeric gears that are created using fused deposition modeling (FDM) technology. The ideal parameters have been determined to be 33% abrasive concentration, 220 abrasive mesh size, 60% liquid synthesizer, 0.46 Pa/sec media viscosity, 0.1 layer thickness, and 90 minutes completion time. An improvement of 95.37%, from 10.80 µm to 0.50 µm, in the surface imperfection of FDM-printed polymeric gears has been achieved through the efficient optimization of the AFM medium and process parameters. Surface quality of FDM-printed polymeric gears can be enhanced using AFM as a post-processing approach.

**Keyword:** Additive manufacturing (AM), Fused deposition modelling (FDM), Abrasive flow machining (AFM), AFM media

## 1 Introduction

The production of polymer products, such as gears, typically involves the costly creation of moulds or the use of advanced machinery for machining. However, additive manufacturing methods, particularly 3D printing, offer a cost-effective and practical alternative for creating polymer gears with high precision and accuracy in low volumes. This approach eliminates the need for expensive moulds and advanced machinery, making it a viable option for small-scale production runs. In summary, additive manufacturing provides a solution for manufacturing polymer gears without the drawbacks of traditional manufacturing methods[1-2]. The use of additive manufacturing to create machine components out of polymeric materials has skyrocketed in the last decade[3].

Experimental data analysis with machine learning revolutionizes research by swiftly revealing patterns, uncovering insights, and making predictions from complex datasets, propelling scientific discovery across disciplines[4-8].

Fused deposition modeling (FDM) is a 3D printing technique that uses CAD software to build complex components by molding thermoplastic material layer by layer. However, poor surface quality and an uneven finish can be outcomes of FDM[9]. Polymeric gears offer significant advantages over metallic gears in specific applications, such as automotive and aeronautical engineering. These advantages include

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being cost-effective, lightweight, highly efficient, and reliable. Additionally, polymeric gears can operate without external lubrication, making them even more desirable in certain situations. Earlier studies have examined the wear and thermal behavior of injection-molded gears[10].

Additive manufacturing methods, like VAT Photopolymerization, are employed for the purpose of rapid prototyping. Surface quality can be compromised in additive manufacturing processes like 3D printing due to the staircase effect. Improving surface quality and decreasing irregularity can be achieved by using post-processing processes and regulating AM process parameters. The good news is that there is a plethora of options for improving the 3D-printed parts' surface quality[11]. Boschetto *et al.*[12] conducted an1experiment to finish FDM printed parts using barrel finishing and discovered a 72% improvement in surface quality. However, the investigators only tested on flat surfaces, and this method isn't suitable for complex surfaces.

Additive manufacturing (AM) processes, notably 3D printing, face the common challenge of the stair-stepping or stair-casing effect, as illustrated in Fig. 1 (a-c). This effect can generate surface roughness, harming both the mechanical characteristics and visual appeal of the final printed product. Therefore, addressing this issue is vital to enhance the overall quality of AM products[13-14]. Various finishing methods can be used to improve the surface quality of 3D-printed polymer products and minimize the stair-stepping effect. These methods include traditional techniques like polishing, grinding, and honing, as well as advanced approaches such as AFM, MAF, MRF, and MFP. These techniques have been proven to effectively reduce surface roughness in polymer gears, resulting in enhanced quality and expanded possibilities for AM applications[15].

Using one-way AFM, Mali *et al*. investigated how well abrasive gel medium made of polymers enhanced the surface quality of 3D-printed parts[16]. After analyzing numerous post-processing methods for AM components, Hashmi *et al.* concluded that abrasive flow polishing is the most efficient[17-19]. Magnetic Finishing (MF) uses magnetic fields to direct abrasive particles for precise, uniform surface finishes, ideal for intricate materials in aerospace and medical industries. Recent improvements have enhanced its efficiency and effectiveness[20-23]. The surface quality of FDM-produced parts was enhanced by Hashmi *et al.*, who also used AFF and created an AFM medium from natural waste materials for FDM component finishing [24-25].

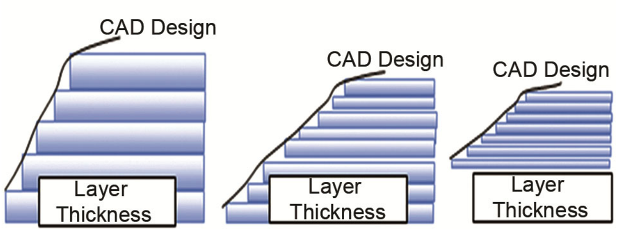


Fig 1 — Stair-stepping/Stair-casing effect occurs during the layer AM process (a) Maximum layer thickness, (b) Medium layer thickness, and (c) Minimum layer thickness.

In order to improve the surface smoothness of polymeric spur gears made using Fused Deposition Modeling (FDM), this study set out to investigate the feasibility of using unconventional Abrasive Flow Machining (AFM) methods. The researchers accomplished this by creating a polymeric spur gear and tools that could be used for one-way AFM finishing. The spur gear was first fabricated using FDM technology, and then AFM was used for processing. In terms of surface quality, mechanical properties, and other aspects, this study's findings may have a substantial impact on the overall performance of polymeric components manufactured with FDM.

## 2 Materials and Methods

### 2.1 Materials and equipment

This research's goal was to investigate how abrasive flow finishing (AFM) might be utilized with the intention of enhancing the surface quality of spur gears manufactured via fused deposition modeling (FDM). The study employed various methods and materials, as illustrated in Fig. 2. Both the spur gear pattern and the AFM tooling were created using FDM. For the media viscosity, a rheometer was used, and for the surface texture of the workpiece, a profilometer. The design was optimized using Minitab'21, Autodesk Fusion 360, and KISSlicer. An FDM filament made of ABS was used, with a finishing media of coal ash powder.

The findings of this study are highly significant since they demonstrate the effectiveness of non-traditional finishing technologies, such as AFM, in improving the surface polish of components that are FDM produced. These methods could revolutionize manufacturing by making FDM technology more accessible for the mass manufacture of flawless, precisely engineered parts.

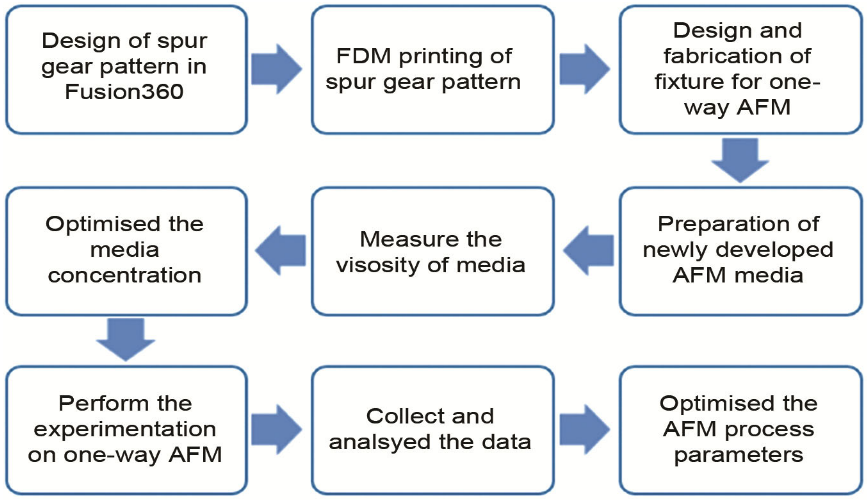


Fig. 2 — Flow chart of proposed methodology.

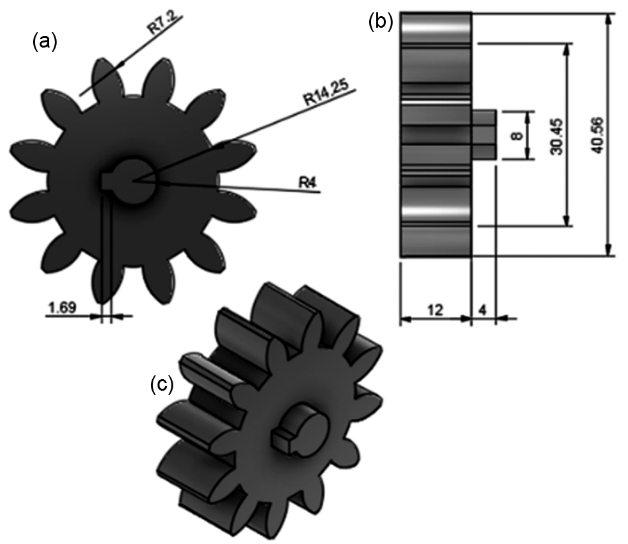


Fig. 3 — CAD model of spur gear (a) front view, (b) dimensions, and (c) side view.

**2.2 Polymeric spur gear design and manufacturing using the FDM technique**

In this research, the authors used AUTODESK Fusion360 software to design a spur gear with 12 teeth, a 40.28 mm addendum circle diameter, and a width of 12 mm. After designing the spur gear, on a fused deposition modelling (FDM) machine, Acryliconitrile butadiene styrene (ABS) was the substance used for its production. You can see the finished spur gear's size, characteristics, and CAD model (in Fig. 3 (a-c) of the research report) in the side view design. The results of this study show that FDM technology may be used to make polymeric parts and to polish their surfaces using non-standard methods like Abrasive Flow Finishing (AFF).

The authors followed a series of steps to fabricate the spur gear pattern and AFM tooling using FDM technology. First, a CAD model was created using Autodesk Fusion 360® software. From this model, an STL file was generated and imported into the KISSlicer software. In KISSlicer, the infill percentage and other essential parameters were adjusted as required. The STL file was then sliced, and the resulting file was saved to a memory card, which was inserted into the printer's card reader. The extruder and bed were preheated to 235°C and 112°C, respectively. The spur gear and AFM tooling were fabricated using FDM technology by running the G-code of the printing sample on the FDM machine. These steps demonstrate the process of using FDM technology to fabricate complex components like spur gears, which can be subsequently finished using non-traditional techniques like Abrasive Flow Finishing (AFF). Figure 4 depicts the processing sequences involved in the FDM process used for fabricating the spur gear and AFM tooling. These results demonstrate the practical application of FDM technology for producing intricate geometries and developing tooling for non-conventional finishing processes like Abrasive Flow Finishing (AFF).

The feasibility and effectiveness of FDM technology in producing polymeric components with complex geometries are demonstrated in the results of the FDM process for fabricating polymeric spur gears presented in Fig. 5. This figure depicts nine samples of the fabricated gears. These findings emphasize the potential of FDM technology in manufacturing complex polymeric components, which can be finished using non-traditional processes like abrasive flow finishing (AFF).

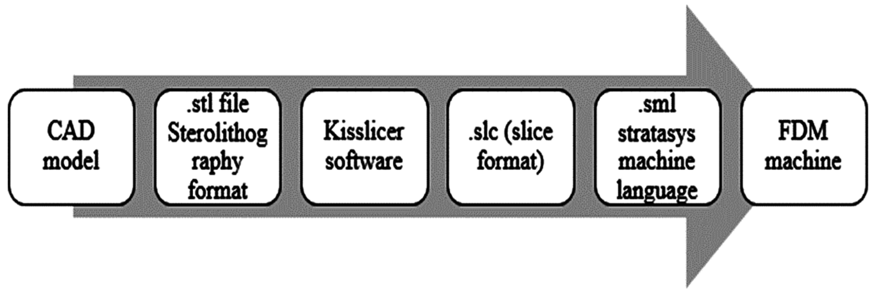


Fig. 4 — Data processing in FDM.

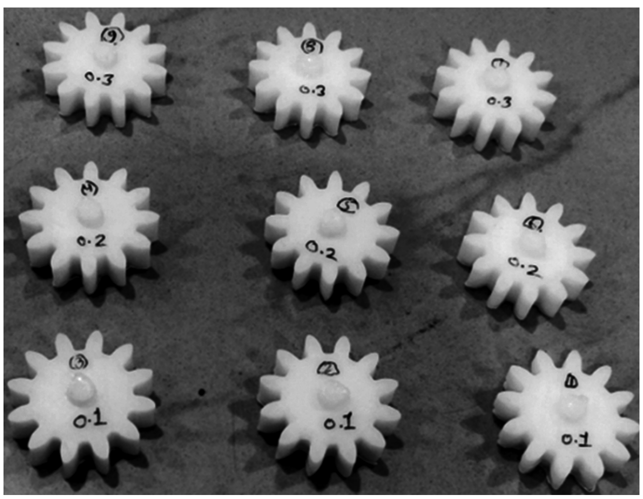

Fig. 5 — FDM printed polymeric spur gear.

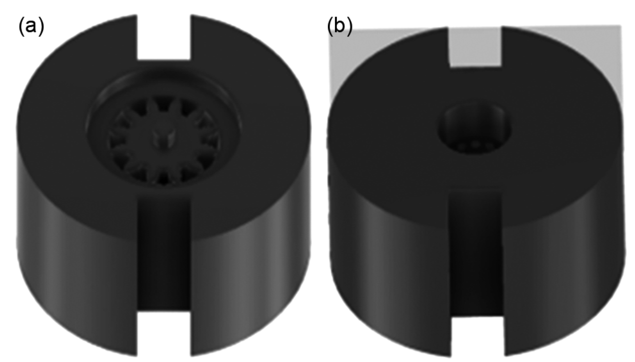


Fig. 6 — CAD model of fixture for spur gear (a) top fixture, and (b) bottom fixture for spur gear.

## 2.3 Development and design of an AFM fixture

Autodesk Fusion 360® software was utilized to design and FDM machine was employed to fabricate a specialized fixture that would facilitate the Abrasive Flow Finishing (AFF) procedure on the ABS spur gear sample. The custom fixture was created to support the AFF process and optimize the finishing of the polymeric spur gear. The research paper describes the design and production of the fixture in detail. The fixture consisted of two parts the top and the bottom that were accurately aligned to securely hold the spur gear component. As illustrated in Fig. 6, the abrasive flow finishing (AFF) fixture's computer-aided design (CAD) model was specifically developed for the spur gear. In order to properly support the polymeric spur gear throughout the AFF procedure, the custom fixture was engineered to optimize its finishing. As an effective method for holding and sustaining components securely during the AFF procedure, the paper emphasizes the design and fabrication methodology of the fixture.

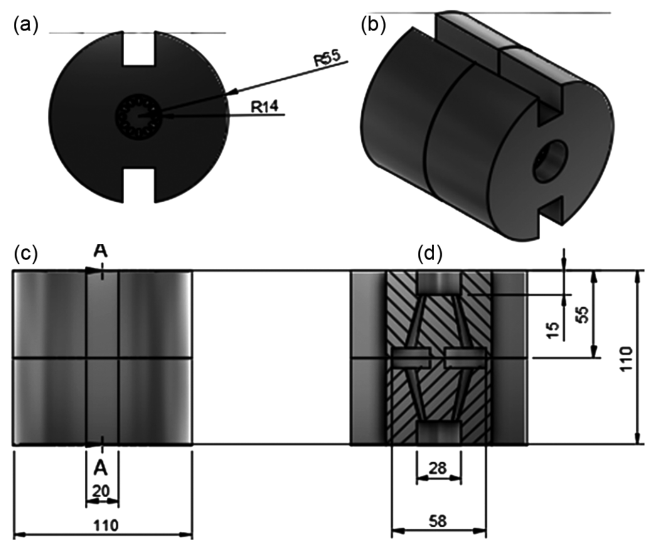


Fig. 7 — Various view with dimensions of top and bottom fixtures for spur gear; (a) Top view, (b) Assembled fixtures, (c) Side view, and (d) Internal sectional view.

In order to maintain and bolster the ABS spur gear specimen during the AFM process, a bespoke fixture was fabricated in this investigation utilizing FDM technology and Autodesk Fusion 360® software. The fixture consists of a top and a bottom component, as illustrated in Fig. 7. The dimensions of each component are 110.00 mm in diameter and 55.00 mm in thickness. An illustration of the fixture's CAD model is presented in Fig. 7(a-b). The model features an opening in the center to facilitate accurate sample alignment and has an outer diameter of 110.00 mm. The cross-sectional view of both components is depicted in Fig. 7(c-d). Their purpose is to ensure alignment with the inline spur gear component that is situated between them. These bespoke fixtures provide a streamlined and efficacious approach to maintain components in a secure position throughout the AFM procedure.

ABS material was used in the FDM process to fabricate the one-way AFM fixture for the polymeric spur gear. The fixture was designed using FDM technology and subsequently printed. This printed fixture was used to hold and support the circular spur gear during the finishing process and was fixed onto the one-way AFM. Figure 8 shows the FDM printed fixture designed for the spur gear.

## 3 Results and Discussion

### 3.1 Rheological investigation of AFM media

#### *3.1.1 Abrasive media preparation*

The abrasive flow finishing (AFF) media utilized in this investigation consisted primarily of coal-ash powder compounded in precise proportions with EDM oil, glycerine, and guar gum powder, as illustrated in Fig. 9. By integrating numerous constituents into the AFF media, one can attain the intended surface treatments on polymeric components in a comprehensive manner.

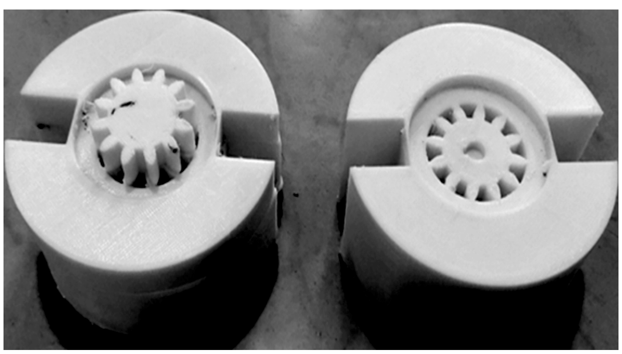

Fig. 8 — FDM printed fixture for spur gear.

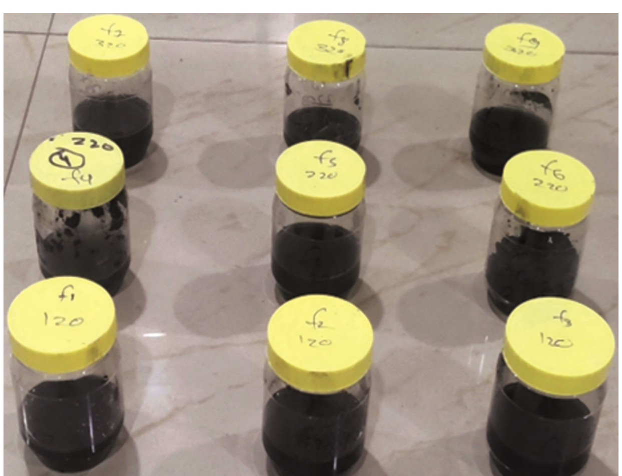

Fig. 9 — Coal-ash-based media samples.

#### *3.1.2 AFM finishing media viscosity optimization*

The experimental design considered three factors with three levels, namely mesh size of abrasives (120, 220, and 320), abrasive concentration (33%, 50%, and 67%), and liquid synthesizer (30%, 45%, and 60%), as shown in Table 1. In order to optimize the viscosity of abrasive flow finishing (AFF) media for enhancing the surface finishing of polymeric components, we utilized the Taguchi L9-based experimental method. This involved preparing nine samples of coal-ash-based media, as detailed in Table 2, and measuring their viscosity using an Anton Par rheometer.

The research team determined, via the Taguchi L9 experimental design and Minitab 21 software analysis, that the particle size of abrasives had the greatest impact on the viscosity of Abrasive Flow Finishing (AFF) media, with the abrasive concentration percentage following suit. The team determined the optimal media concentration, which consisted of 220 grain size abrasives, 33% concentration of abrasives, and 60% liquid synthesizer, based on the signal-to-noise ratio for media parameters. Based on the findings, it can be inferred that an increase in viscosity decreases surface irregularity due to the

Table 1— Process levels and input parameters for the experimental design (Media – Coal-ash-based media).

| Process Parameters | Levels | | |
|---|---|---|---|
| | I | II | III |
| Abrasive mesh size (A) | 120 µm | 220 µm | 320 µm |
| Abrasive con.1(B) | 33%1 | 50%1 | 67%1 |
| Liquid synthesizer1(C) | 30%1 | 45% | 60% |

Table 2 — Experimental results for the viscosity of coal-ash-based media.

| Sample No. | Abrasive Mesh Size(µm) | % of Abrasive Concentration | % of Liquid Synthesizer | Viscosity (Pa-Sec) |
|---|---|---|---|---|
| 1 | 120 | 33 | 030 | 0.56 |
| 2 | 220 | 50 | 045 | 0.52 |
| 3 | 320 | 67 | 060 | 0.26 |
| 4 | 1220 | 33 | 045 | 0.66 |
| 5 | 1220 | 50 | 060 | 0.46 |
| 6 | 1220 | 67 | 030 | 0.26 |
| 7 | 1320 | 33 | 060 | 0.18 |
| 8 | 1320 | 50 | 030 | 0.10 |
| 9 | 1320 | 67 | 045 | 0.80 |

deeper penetration of the rigid AFF medium into the workpiece surface, consequently improving the overall surface quality. Utilizing the Taguchi L9-based experimental method to systematically optimize the viscosity of AFF media in order to enhance the surface finishing of polymeric components is demonstrated to be effective in this study. The research paper illustrates the signal-to-noise ratio for media parameters in Fig. 10.

### 3.2 Experimental investigation for AFM of FDM printed gear

The research team utilized Minitab 21 software to evaluate the regression coefficient for the experimental results. To conduct the experiments, the Taguchi L9 methodology was used to design a set of nine experiments. The study focused on three input parameters as control factors: AFM media viscosity, workpiece layer thickness, and finishing time, each varied at three levels: low, medium, and high. Table 3 in the research paper presents the details of the experimental design. Overall, the Taguchi L9 methodology proved to be an effective approach for systematically evaluating the impact of different control factors on the surface finishing of polymeric components using AFM.

Where:

A-Media viscosity (Pa-sec)
B-Layer thickness (mm)
C- Duration to finish (min.)
D-Preliminary surface roughness (µm)
E-Surface roughness (µm) (Post finishing)
F-Percentage improvement of Ra

To improve the surface roughness of the spur gear samples after AFM, an experimental design based on

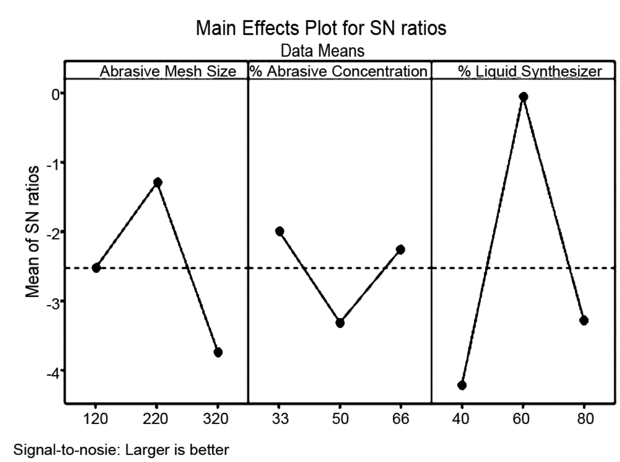


Fig. 10 — S/N ratio for media parameters.

Taguchi L9 was used. This design involved fabricating nine samples using the FDM machine, as detailed in Table 4. The samples were then finished using a one-way AFM machine with three factors and three levels. To measure the surface roughness of the samples before and after AFM, a Taylor Hobson® surface finish tester was used. The experimental results were analyzed to optimize the improvement in surface roughness.

The results of the nine experiments conducted on a one-way AFM machine are presented in Table 4, showing the improvement in surface roughness. The analysis revealed that the media viscosity, finishing time, and layer thickness had a significant impact on the surface quality of the spur gear pattern, with media viscosity and finishing time being the most influential parameters in improving surface roughness, as demonstrated in Fig. 11. Based on the signal-to-noise ratio, the optimal parameters for improving surface roughness were determined to be 0.46 Pa-sec media viscosity, 0.1-layer thickness, and 90-minute finishing time.

#### *3.2.1 Effect of media viscosity*

Optimizing the viscosity of AFM media is critical to achieving high-quality surface finishing of 3D-printed polymeric spur gears. Higher viscosity levels generate increased shear force during the finishing process, leading to improved surface quality. These findings have important implications for enhancing the performance of 3D-printed polymeric gears and optimizing the finishing process.

Table 3 — Process levels1and parameters for finishing of FDM printed polymeric spur gear

| Process Parameters | Levels | | |
|---|---|---|---|
| | I | II | III |
| Media viscosity (Pa-sec) (A) | 0.26 | 0.46 | 0.66 |
| Layer thickness (mm) (C) | 0.1 | 0.2 | 0.3 |
| Finishing time (Min) (D) | 30 | 60 | 90 |

Table 4 — Surface improvement experimentation on FDM-printed polymeric spur gear

| Sample. No | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | 0.26 | 0.1 | 60 | 6.26 | 4.32 | 30.99 |
| 2 | 0.46 | 0.2 | 30 | 8.60 | 4.26 | 50.46 |
| 3 | 0.66 | 0.3 | 90 | 4.80 | 1.24 | 74.16 |
| 4 | 0.26 | 0.2 | 90 | 8.24 | 4.67 | 43.32 |
| 5 | 0.46 | 0.3 | 60 | 10.03 | 4.24 | 57.72 |
| 6 | 0.66 | 0.1 | 30 | 5.24 | 1.80 | 65.64 |
| 7 | 0.26 | 0.3 | 30 | 9.32 | 7.26 | 22.10 |
| 8 | 0.46 | 0.1 | 90 | 10.80 | 0.50 | 95.37 |
| 9 | 0.66 | 0.2 | 60 | 7.68 | 2.80 | 63.54 |

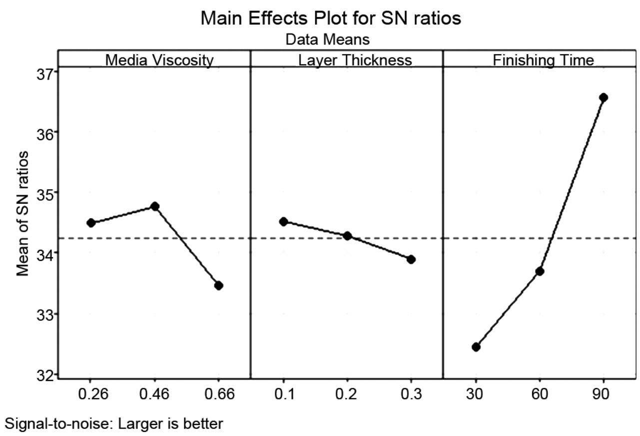


Fig. 11 — Surface roughness improvement as a percentage measured by the S/N ratio.

*3.2.2 Effect of finishing time*

Optimizing the finishing time is crucial for achieving high-quality surface finishing of 3D-printed polymeric spur gears. The second most significant factor after increasing the viscosity of the AFM media is the optimal finishing time. The study found that increasing the finishing time up to 90 minutes led to a noticeable enhancement in surface quality by reducing surface roughness. The maximum percentage improvement in surface roughness was observed after reaching the optimal finishing time level. These findings have important implications for optimizing the finishing process and improving the performance of 3D-printed polymeric gears.

*3.2.3 Effect of layer thickness*

Layer thickness was found to be the third least influential parameter in the finishing process of additive-manufactured polymeric spur gears. While the most significant improvement in surface quality was observed when using a layer thickness of 0.1, its effect was secondary to that of viscosity and finishing time. Therefore, optimizing viscosity and finishing time should be prioritized to achieve superior surface quality, while layer thickness should be considered a secondary parameter in the finishing process of additive-manufactured polymeric gears.

## 4 Conclusion

This study aimed to investigate abrasive flow finishing (AFM) of additively manufactured polymeric spur gears. The research identified media viscosity as the most important factor in achieving high-quality surface finishing of 3D-printed polymeric spur gears. The study determined that the optimal finishing time of 90 minutes led to noticeable improvements in surface quality, and layer thickness had the least influence on the process. To achieve superior surface quality, the study recommends optimizing viscosity and finishing time as primary parameters.

An eco-friendly finishing media for additively manufactured polymeric spur gears was developed using coal-ash powder as a polymer base and EDM oil as a solvent synthesizer. This reduced waste and provided a low-cost alternative to conventional polymer bases while enhancing the performance of the finishing media. The study found that abrasive concentration, abrasive mesh size, and liquid synthesizer percentage were critical factors affecting viscosity, which significantly influenced the surface quality of additively manufactured polymeric gears.

Optimal AFM input parameters were determined to be 0.46 Pa-sec media viscosity, 90 minutes finishing time, and 0.11-layer thickness, resulting in a significant improvement in surface quality. These findings are important for optimizing the finishing process of additively manufactured polymeric gears and enhancing their performance in various applications. The study highlights the significance of media viscosity in achieving optimal surface finishing in additive manufacturing applications.

## Acknowledgement

The authors express their gratitude to the Department of Science and Technology, Government of India, for their support of this research through the DST-SERB EMR/2016/003372 grant.

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