

A Study on Milling Parameters for Enhanced Surface Quality of FDM-Printed PLA Parts

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DOI: <https://doi.org/10.30880/ijie.2024.16.06.024>

Article Info

Received: 1 March 2024

Accepted: 24 November 2024

Available online: 29 December 2024

Keywords

3D printing, FDM, post-processing, surface quality, machinability, milling

Abstract

Fused Deposition Modeling (FDM) is a mostly used additive manufacturing method known for its cost-effectiveness and ease of use in producing parts with complex geometries. However, there are also several challenges such as surface roughness which limit its applications where surface quality is a critical factor. Post-processing methods - including milling, have been analyzed to improve the surface quality of FDM-printed parts. This paper focused on optimizing milling parameters for PLA thermoplastic parts manufactured via FDM. A series of systematic experiments changing spindle speed, feed rate, and tool radius were investigated to determine optimal combination for getting optimal milling results. The gathered results showed that a spindle speed of 1500 RPM and a feed rate of 500 mm/min with a 4 mm radius milling tool represented optimal surface quality and dimensional accuracy. Practical applications include streamlined manufacturing processes and improved part quality, improving the usability of FDM-based manufacturing. Further research works are recommended to investigate advanced processing techniques and parameter optimization methods to unlock the full potential of this technology.

1. Introduction

Fused Deposition Modeling, also known as Fused Filament Fabrication (FFF), is a widely utilized and cost-effective additive manufacturing technology. It operates by extruding thermoplastic materials, such as polylactic acid (PLA), layer by layer to create three-dimensional parts from CAD models. FDM has become increasingly popular in various industries due to its ability to produce parts with complex geometries and with reduced cycle times, which doesn't require expensive tooling [1]. The technology is not only used for prototyping but has also found applications in end-use products, including medical implants [2], parts for automotive [3] and robotics [4] industries, and even aerospace [5] systems. Although it has a high number of advantages, the FDM technique has some challenges in terms of mechanical properties, surface quality, and dimensional accuracy, which can limit its application where precision and strength are crucial [6].

To solve the limitations of FDM, post-processing methods such as milling, chemical treatment, and various forms of surface treatments have been developed to improve the surface quality and dimensional accuracy of printed parts. These analysed methods can significantly reduce surface roughness and improve the mechanical properties of the parts. For instance, chemical treatments, like acetone vapor smoothing, represent significantly reduced surface roughness and improve functional qualities of the parts [7]. In addition to chemical treatments, thermal post-processing techniques, such as controlled heating and pressure, have also been employed to improve the dimensional accuracy and surface reflectivity of FDM parts. These methods can be particularly beneficial for creating optical elements or parts that require precise dimensions [8]. Moreover, the application of coatings, such

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as aluminum, can not only improve surface roughness but also enhance thermal properties, with making FDM parts suitable for high-temperature applications. This expands the potential use cases for FDM parts into areas that were previously inaccessible due to material limitations [9]. The optimization of FDM process parameters, such as layer thickness and nozzle diameter, can also contribute to better surface quality and dimensional accuracy. However, achieving optimal combination of parameters is challenging and needs several research works. That's why post-processing steps are still necessary process for many applications [10].

Moreover, the machining of printed polymers is a critical step in improving the surface quality of the final product. This process is especially utilized for applications where precision and friction behavior are critical, such as in mechanical components and decorative finishes. Conventional machining parameters like cutting speed, feed rate, and etc. significantly influence the machinability and the surface roughness of printed plastics. Optimal machining parameters are varying for different materials and machining processes. Mechanical finishing, such as CNC milling, can substantially improve the surface roughness of printed polylactic acid thermoplastic material, achieving smoother and more consistent surfaces [11], [12].

According to the wide adaptation of additive manufacturing technology to several industries, lots of research works were performed to improve final part quality by applying several post-processing methods. For instance, this study [12] investigated the potential of hybrid manufacturing (AM + milling) to improve the surface quality of FDM-produced polyamide parts. The paper analyzed the effects of machining parameters such as cutting depth, feed rate, and rotation speed, by applying the end milling process to the printed polyamide samples. It highlighted the importance of optimizing milling parameters to get improved surface quality in post-AM processes. The results suggested that low rotation speed and high feed rates should be applied for achieving better surface quality for polyamide parts. In addition, the research work [13] investigated the machinability of 3D printed carbon fiber reinforced polymer (CFRP) composites, analyzing the effects of different matrix arrangements and machining parameters on surface finish, burr formation, and tool wear. Experimental results showed that post-process machining improved surface quality, while minimum quantity lubrication (MQL) techniques reduced burr formation and improve tool wear during the machining process. The next paper [14] used orthogonal cutting tests to investigate the machinability of 3D printed PEEK, both with and without short carbon fiber reinforcement. It analyzed that how force generation, superficial damage, and temperature were affected by printing orientations and machining parameters. It provided insights into the feasibility and challenges of machining reinforced PEEK components. Furthermore, in order to improve the surface finish quality of 3D printed objects, this study [15] looked into the optimization of machining parameters. The full factorial method was utilized in a series of experiments to identify optimal parameters to get the necessary surface roughness levels along the x and y-axes. Findings suggested specific parameter combinations for each axis, emphasizing the importance of customized optimization techniques in surface finishing for printed parts.

The article [16] proposed a mechanical finishing process via CNC milling to get better the surface quality of printed continuous carbon fiber reinforced polymer composites. The study investigated the surface roughness and morphology of samples produced using the FDM technique and laser-assisted laminated object manufacturing (LA-LOM). As a result of performed machining processes, smooth and consistent surface morphology was achieved by applying various cutting depth values while surface roughness improved by 70% for FDM and 60% for LA-LOM components. Additionally, there is a review research paper [17] that analyzed the significance of several post-processing methods to improve the properties and characteristics of printed polymer materials. It discussed several different techniques, their advantages and disadvantages, cost results, and future prospects as well. It investigated all the mentioned things by emphasizing the critical role of post-AM processes in industrial applications.

As mentioned before, although FDM easy to easy-to-use and cost-effective method for producing complex geometries with thermoplastic materials, FDM-printed parts often show surface irregularities and dimensional inaccuracies due to inherent process limitations. Post-processing techniques such as milling offer a viable solution to improve the surface quality of printed parts by using the FDM technique. The main objective of our study was to optimize milling parameters specifically used for PLA thermoplastic parts manufactured by FDM. By systematically changing them, our goal was to find optimal combination of machining parameters such as spindle speed, feed rate, and tool radius that results in optimal surface finish. To improve surface roughness and overall quality of samples, the most efficient milling approach had to be determined through extensive experimentation and analysis as a part of the optimization process. Our aim in performing this research study was to maximize the performance and usability of printed parts by offering useful post-processing recommendations. Manufacturers can increase the precision, reliability, and functionality of FDM based printing processes by optimizing the milling parameters. This will also increase the potential applications for this exciting new manufacturing technology.

2. Experimental Setup and Methodology

The Fused Deposition Modeling printing process was utilized to produce PLA plastic sample using a Qidi Tech X-CF Pro 3D printer machine. PLA is a commonly used thermoplastic material known for its ease of printing and

biodegradability. FDM printing technology (illustrated in Fig. 2) works by melting and extruding thermoplastic filament through a heated nozzle, and using layer by layer method to create a three-dimensional part. The first step in the procedure is to create a digital 3D model, either by utilizing computer-aided design software or by getting an already-existing model. Then the 3D model is sliced into thin horizontal layers by using slicing software (Qidi Tech slicer software for our case). The thickness of each layer is determined by the required resolution and the capabilities of the printer machine. Then, during the printing process, the printer's nozzle is heated to the melting temperature of the filament material. The nozzle moves along the predetermined path and deposits molten material onto the build platform. Each upcoming layer is deposited to the previously printed layer by bonding to it. Then the molten material quickly cools and solidifies to form each layer. The mentioned process repeats continuously until the final part is produced [6].

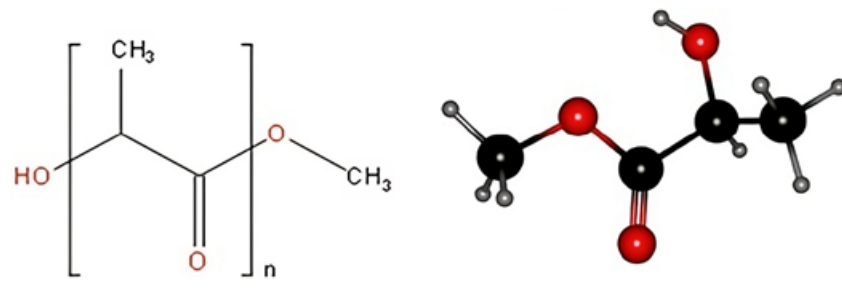


Fig. 1 Chemical structure of polylactic acid [18]

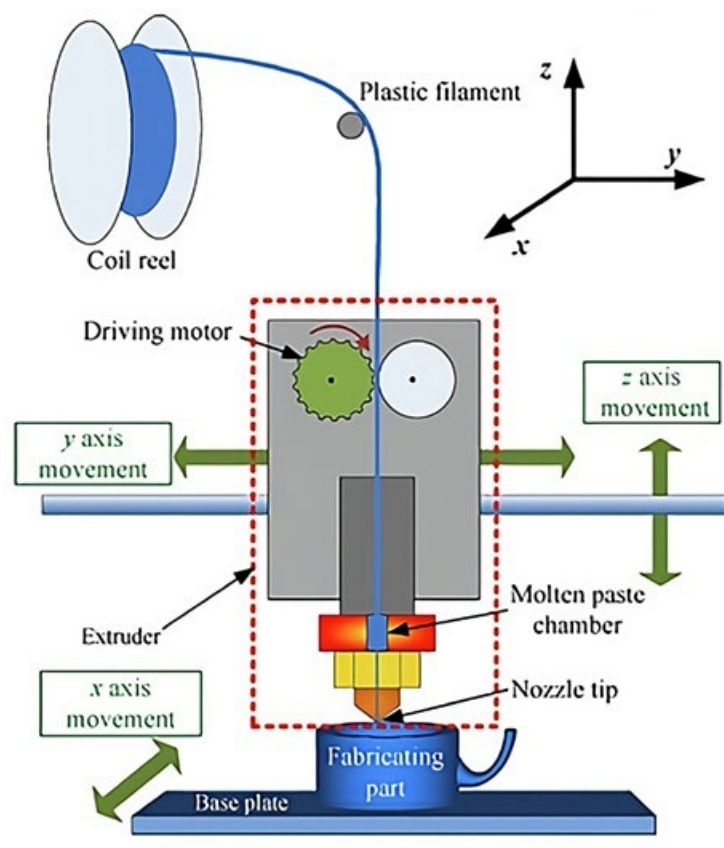


Fig. 2 Diagrammatic representation of working principle of the FDM process [19]

The printer's build volume allowed for the production of parts with dimensions up to 300 mm in length, 250 mm in width, and 300 mm in height. The printer has a heated build plate and a single extruder capable of reaching temperatures up to 300 degrees Celsius. To receive optimal print quality and dimensional accuracy, the printer should be prepared accurately before the 3D printing process. In addition, the build plate was also levelled to get optimal possible layer deposition and adhesion. Test specimen with dimensions of 80 mm (length) × 30 mm (width) × 30 mm (height) was designed using computer-aided design (CAD) software and then sliced into layers

using Qidi Tech slicing software which is suitable with the used printer machine. The modelled part was then printed from PLA material by using the following printing parameters - Table 1.

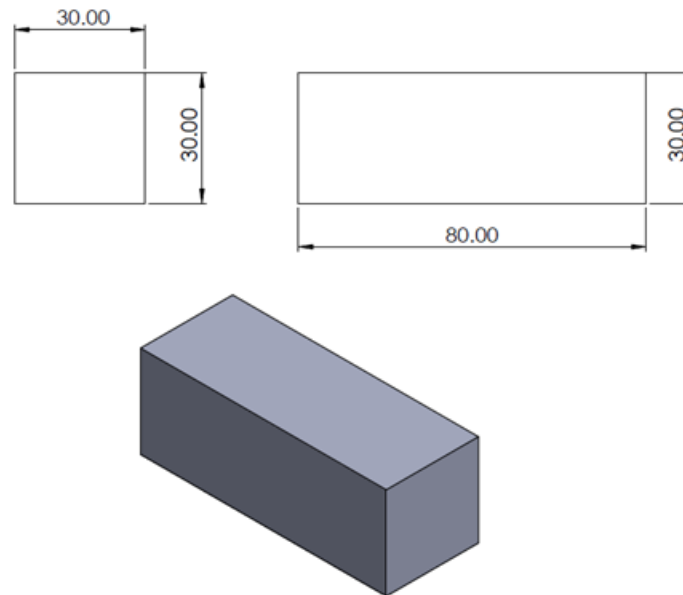


Fig. 3 Geometric characteristics of the sample

Table 1 The applied printing parameters

| Parameters | Value |
|-------------------------------|---------|
| Filament diameter, [mm] | 1.75 |
| Nozzle diameter, [mm] | 0.4 |
| Line width, [mm] | 0.4 |
| Layer height, [mm] | 0.2 |
| Infill density, [%] | 25 |
| Printing speed, [mm/s] | 60 |
| Nozzle temperature, [°C] | 210 |
| Build plate temperature, [°C] | 60 |
| Number of top layers | 25 |
| Number of bottom layers | 5 |
| Top/Bottom pattern | Lines |
| Infill pattern | Zig Zag |

After the finishing of 3D printing, see Fig. 4. the manufactured PLA specimen was carefully checked for any surface defects or irregularities. Before the planned machining (milling) process, the sample was securely mounted onto the worktable of the machine using appropriate fixtures to provide stability during the machining process. A CNC (Computer Numerical Control) milling machine (Emco PC Mill 55) with a 4 mm radius milling tool ($\varnothing 8 \times 13 / R1$ solid carbide shoulder/slot mill; type number: H4038217-8-1; 4 cutting edges; 49° flute helix angle) was used for the machining trials. The milling machine offered control over feed rate and spindle speed along with precise movement in the X, Y, and Z axes. In addition, a secondary milling test was carried out utilizing a milling tool with a 6 mm radius (HSS CO8 TiN coated four flute end mill) in order to investigate the impact of tool diameter change on milling results. Multiple milling trials were performed, changing parameters such as spindle speed and feed rate while keeping other factors constant. The milling parameters for each trial were carefully documented. This experimental setup simplified the systematic analysis of the effect of milling parameters on the post-processing quality of specimens. It was also aimed at the optimization of milling operations to improve surface finish.



Fig. 4 Sample of 3D-printed PLA part before any post-processing

Milling Tests and Evaluation Criteria: Spindle speed, measured in revolutions per minute (rpm), is a critical parameter that affects the cutting efficiency and heat generation during milling. In our experiments, milling trials were performed on the top surface of the samples, and spindle speed was varied to analyze its impact on the surface quality of machined parts. Additionally, all milling trials were conducted using the up-milling method. In up-milling, the workpiece is fed against the direction of the rotation of the cutting tool. This method was chosen for its benefits in terms of tool wear and surface finish. Three different spindle speed parameters were tested: 1000 rpm, 1500 rpm, and 2000 rpm. The feed rate represents the linear speed at which the milling tool moves along the workpiece surface during machining, which was another critical parameter under investigation. It affects material removal rate and chip formation, which also influences surface finish and tool wear.

Two feed rate values were tested: 250 mm/min and 500 mm/min which were systematically set to optimize the milling performance. These feed rates were selected to study the effect of cutting speed on material removal rate and surface finish while providing the stability of the milling process. The radius of the milling tool determines the width of the cut and the amount of material removed per pass and for our case, it was changed to evaluate its influence on machining (milling) performance. Two different tool radiuses were utilized in our experiments: 4 mm and 6 mm. The selection of these tool sizes was made while considering the geometry of the printed PLA samples. It was aimed at discovering the trade-off between machining efficiency and surface quality. Table 2 summarizes performed various trials and their corresponding spindle speed, feed rate, and tool radius.

Table 2 Summary of milling trials and cutting parameters

| Trial | 1 | 2 | 3 | 4 | 5 |
|----------------------|------|------|------|------|------|
| Spindle speed, [rpm] | 2000 | 1500 | 1500 | 1500 | 1000 |
| Feed rate, [mm/min] | 250 | 250 | 500 | 500 | 500 |
| Depth of cut, [mm] | 1 | 1 | 1 | 1 | 1 |
| Tool radius, [mm] | 4 | 4 | 4 | 6 | 6 |
| Cutting width, [mm] | 8 | 8 | 8 | 12 | 12 |

A visual inspection was performed to evaluate the surface quality of the milled PLA sample. Any visible defects, such as tool marks, surface imperfections, or material melting/burning, were identified and documented. This qualitative investigation gave insight into the effects of various milling parameters on surface finish and material integrity. Caliper and digital micrometer were utilized to measure the dimensional correctness of machined features. Any deviations from the specified dimensions were recorded for analyzing of milling precision. A detailed evaluation of milling results was carried out, taking into consideration visual inspection findings. As a result of visual inspections, the machining quality was determined based on which the milled trials addressed the better surface quality.

3. Results and Discussion

In this section, the gathered outcomes from several trials to optimize the milling parameters are presented. The realized trials focused to determine optimal combination of spindle speed, feed rate and tool radius for milling PLA plastic parts. Each mentioned trial was evaluated based on surface quality and observed defects. The initial trial, see Fig. 5. presented significant challenges in which the surface of the printed part exhibiting noticeable melting. This happened most likely because of the high spindle speed that was generated excessive heat during the milling process. Thus, it led to material deformation and a very poor surface finish. Recognizing the need to reduce heat generation, the spindle speed was reduced in the second trial (Fig. 5.) while keeping all other parameters constant. While this change improved the surface quality slightly compared to the initial trial, surface quality still didn't meet our expectations. Although it was in reduced level, the melting was still present, and it

indicated that further parameter optimizations were still required to get the expected milling results. Based on the insights gained from the previous two trials, the amount of feed rate was increased in the third trial (Fig. 5.) to accelerate material removal and dissipate heat in a more effective way. This change represented notable improvement in surface quality and the result of performed milling process generally (fewer distortions and defects). This third trial provided optimal results among the initial attempts which also indicated that optimizing the feed rate played a crucial role in achieving desired milling outcomes.

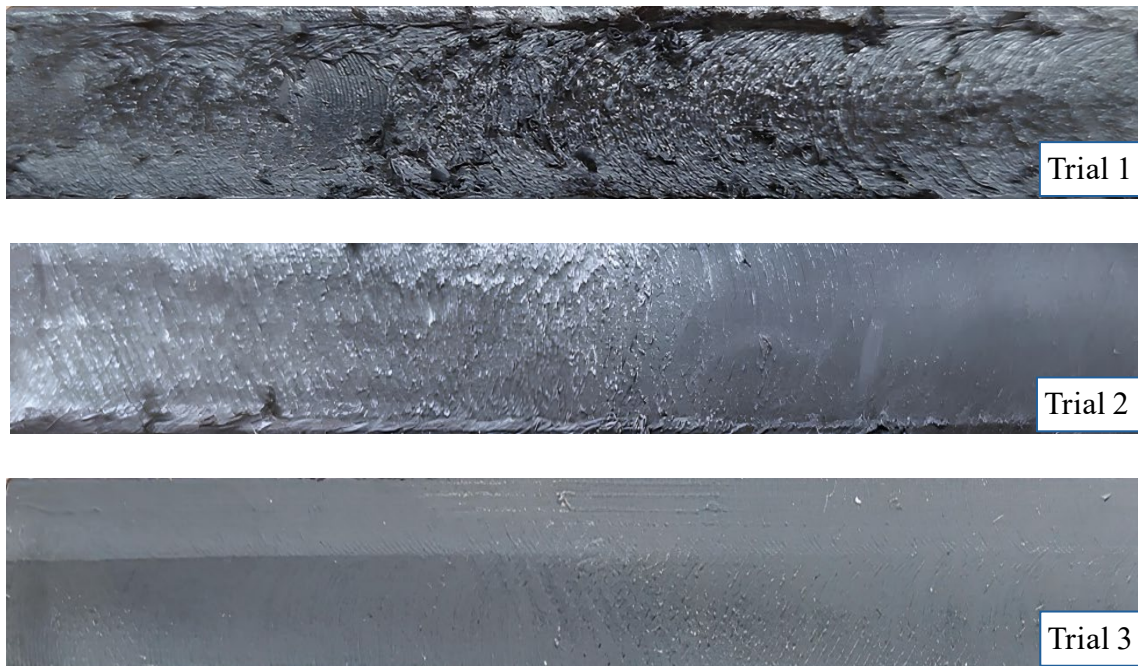


Fig. 5 Comparison of milled surfaces from trials 1-3 (4 mm tool radius)

In the next step, see Fig. 6. a new milling tool with a larger radius (6 mm) was used aiming to distribute cutting forces more evenly and reduce the risk of surface melting. However, despite maintaining the same spindle speed and feed rate as the third trial, the results were unsuccessful. The change to the larger tool radius resulted in unexpected challenges - because the bigger tool diameter increased heat generation and material deformation, surface quality disrupted again, and melting reoccurred. This trial highlighted the importance of considering tool geometry (diameter) together with other parameters to achieve better milling post-processing results. Based on the challenges that were faced in the larger tool radius, additional strategic modifications had to be made to the milling parameters. Considering the influence of tool diameter on cutting forces and at the same time, the importance of balancing cutting forces with spindle speed, the amount of spindle speed decreased to reduce heat generation during machining. It was clearly seen (Fig. 6.) that this modification represented notable results and an improvement in surface quality. But the acquired surface quality was not enough if we compare it with the result of the third trial.

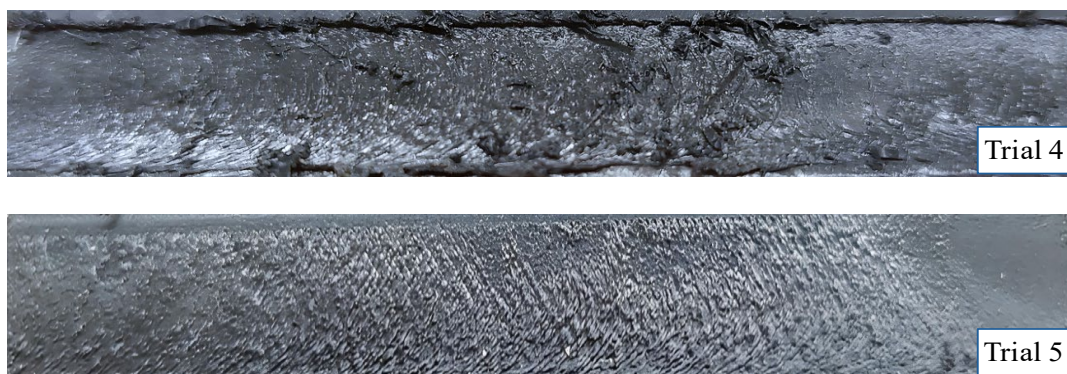


Fig. 6 Comparison of milled surfaces from trials 4-5 (6 mm tool radius)

4. Conclusion

In this study, a detailed investigation was performed to optimize milling parameters for parts printed from PLA thermoplastic material. Through a systematic series of machining experiments, different spindle speeds, feed rates, and tool radiuses were used while keeping other parameters constant to determine optimal combination for achieving the planned milling results. The findings clearly showed that the milling process for PLA plastic samples is extremely sensitive to differences in spindle speed, feed rate, and tool geometry. Among the parameters investigated, we determined that a spindle speed of 1500 rpm and a feed rate of 500 mm/min with a 4 mm radius milling tool provided optimal results in terms of surface quality and dimensional accuracy. This combination resulted in improved machining (milling) performance that led to smoother surface finishes. The practical implications of these findings are significantly important for researchers and several industries which are actively using milling as a post-printing process. By using optimized machining parameters, researchers and manufacturers can make their production process simplified and smooth which will be able to improve the overall quality and consistency of PLA printed parts. In addition, it is known from the current research study that there are complex relationships between the machining parameters and material properties of printed plastics that should be analyzed carefully. Further research works in advanced machining and process optimization are highly recommended to perform especially considering that additive manufacturing continues to be popular in recent years. Future investigations could analyze the effects of different parameters (milling tool geometries, cooling strategies and etc.) on the different types of plastic materials to get better surface integrity and machining efficiency. As additive manufacturing continues to develop, optimizing post-processing techniques like milling is important for unlocking the full potential of this transformative technology.

Acknowledgement

The project No. 2020-1.2.3-EUREKA-2022-00025 was realized with financial help of the National Research Development and Innovation Fund of the Ministry of Culture and Innovation of Hungary.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

References

- [1] Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., & Haq, M. I. U. (2022) 3D printing–A review of processes, materials and applications in industry 4.0, *Sustainable Operations and Computers*, 3, 33-42, <https://doi.org/10.1016/j.susoc.2021.09.004>
- [2] Okolie, O., Stachurek, I., Kandasubramanian, B., & Njuguna, J. (2020) 3D printing for hip implant applications: a review, *Polymers*, 12(11), 2682, <https://doi.org/10.3390/polym12112682>
- [3] Yadav, D. K., Srivastava, R., & Dev, S. (2020) Design & fabrication of ABS part by FDM for automobile application, *Materials Today: Proceedings*, 26 (2), 2089-2093, <https://doi.org/10.1016/j.matpr.2020.02.451>
- [4] Walia, K., Khan, A., & Breedon, P. (2021) Polymer-based additive manufacturing: process optimisation for low-cost industrial robotics manufacture, *Polymers*, 13(16), 2809, <https://doi.org/10.3390/polym13162809>
- [5] Martinez, D. W., Espino, M. T., Cascolan, H. M., Crisostomo, J. L., & Dizon, J. R. C. (2022) A comprehensive review on the application of 3D printing in the aerospace industry, *Key engineering materials*, 913, 27-34, <https://doi.org/10.4028/p-94a9zb>
- [6] Mehdiyev, Z., & Felhő, C. (2023 April 4–6). *Polymer 3D Printing: A review of techniques with their advantages, limitations, and industrial application* [International Conference on Engineering, Natural and Social Sciences]. All Sciences Proceedings, Konya, Turkey. <https://as-proceeding.com/index.php/icensos/article/view/528/477>
- [7] Beniak, J., Križan, P., Šooš, L., & Matúš, M. (2017, December 12–15). *Roughness and compressive strength of FDM 3D printed specimens affected by acetone vapour treatment* [IOP Conference Series: Materials Science and Engineering]. IOP Publishing, Bangkok, Thailand. <https://doi.org/10.1088/1757-899X/297/1/012018>
- [8] Mayville, P. J., Petsiuk, A. L., & Pearce, J. M. (2022) Thermal post-processing of 3D printed polypropylene parts for vacuum systems, *Journal of Manufacturing and Materials Processing*, 6(5), 98, <https://doi.org/10.3390/jmmp6050098>
- [9] Nguyen, T. K., & Lee, B. K. (2018) Post-processing of FDM parts to improve surface and thermal properties, *Rapid Prototyping Journal*, 24(7), 1091-1100, <https://doi.org/10.1108/RPJ-12-2016-0207>

- [10] Mehdiyev, Z., Felhő, C., & Zoltán, K. P. (2022, September 8–9). *Investigation on 3D Printing Parameters of PLA Polymers for Gear Applications* [Vehicle and Automotive Engineering]. Springer Cham, Miskolc, Hungary. https://doi.org/10.1007/978-3-031-15211-5_55
- [11] Parandoush, P., Deines, T., Lin, D., Zhang, H., & Ye, C. (2019, June 10–14). *Mechanical finishing of 3D printed continuous carbon fiber reinforced polymer composites via CNC machining*, [International Manufacturing Science and Engineering Conference 58745]. American Society of Mechanical Engineers, Erie, Pennsylvania, USA. <https://doi.org/10.1115/MSEC2019-2972>
- [12] Tezel, T. (2021) The effect of machining parameters on the surface quality of 3D printed and cast polyamide, *Machining Science and Technology*, 25(5), 703-720, <https://doi.org/10.1080/10910344.2021.1971704>
- [13] Cococetta, N. M., Pearl, D., Jahan, M. P., & Ma, J. (2020) Investigating surface finish, burr formation, and tool wear during machining of 3D printed carbon fiber reinforced polymer composite, *Journal of manufacturing processes*, 56, 1304-1316, <https://doi.org/10.1016/j.jmapro.2020.04.025>
- [14] Gómez-García, D., Díaz-Álvarez, A., Youssef, G., Miguélez, H., & Díaz-Álvarez, J. (2023) Machinability of 3D printed peek reinforced with short carbon fiber, *Composites Part C: Open Access*, 12, 100387, <https://doi.org/10.1016/j.jcomc.2023.100387>
- [15] Setyadarma, P. B., & Mastriswadi, H. (2019, September 18–19). *Surface finish machining optimization for 3D print* [Journal of Physics: Conference Series]. IOP Publishing, Purwokerto, Indonesia. <https://doi.org/10.1088/1742-6596/1367/1/012035>
- [16] Parandoush, P., Deines, T., Lin, D., Zhang, H., & Ye, C. (2019, June 10–14). *Mechanical finishing of 3D printed continuous carbon fiber reinforced polymer composites via CNC machining* [International Manufacturing Science and Engineering Conference]. American Society of Mechanical Engineers, Erie, Pennsylvania, USA. <https://doi.org/10.1115/MSEC2019-2972>
- [17] Dizon, J. R. C., Gache, C. C. L., Cascolan, H. M. S., Cancino, L. T., & Advincola, R. C. (2021) Post-processing of 3D-printed polymers, *Technologies*, 9(3), 61, <https://doi.org/10.3390/technologies9030061>
- [18] Martínez Villadiego, K., Arias Tapia, M. J., Useche, J., & Escobar Macías, D. (2022) Thermoplastic starch (TPS)/polylactic acid (PLA) blending methodologies: a review, *Journal of Polymers and the Environment*, 30(1), 75-91, <https://doi.org/10.1007/s10924-021-02207-1>
- [19] Solomon, I. J., Sevel, P., & Gunasekaran, J. (2021) A review on the various processing parameters in FDM, *Materials Today: Proceedings*, 37, 509-514, <https://doi.org/10.1016/j.matpr.2020.05.484>