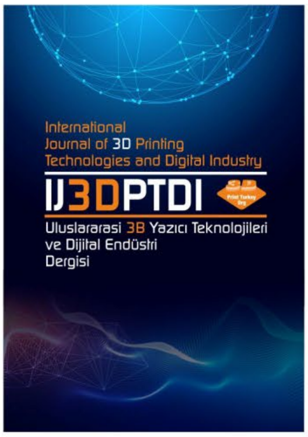

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EXPERIMENTAL DETERMINATION OF THE OPTIMUM CUTTING TOOL FOR CNC MILLING OF 3D PRINTED PLA PARTS

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ABSTRACT

The purpose of this study is to determine the most suitable cutting tool for achieving the desired diameter dimensions in parts produced using PLA material in a 3D printer. A plastic plate in the shape of a rectangular prism with dimensions of 90x40x10 mm was printed without holes with a 100% filling ratio in a 3D printer. A belt-pulley mechanism requiring bearing assembly was designed, manufactured, and tested for applicability. The study successfully identified the optimum parameters for achieving a 15 mm diameter measurement with the desired tolerance in PLA material without causing melt damage. These parameters are spindle speed of 15000 rpm, feed rate of 500 mm/min, cutting depth of 0.5 mm, minimum end mill diameter of 10 mm, and 4 cutting edges. The study also found that the morphological properties of the PLA workpiece were affected by the cutting process of different diameter milling cutters. This study investigated the optimal milling cutter for drilling holes in 3D-printed PLA parts. The method was found successful, allowing for manufacturing flexibility and reduced waste. Results provide insights for improving post-processing efficiency and sustainability in 3D printing.

Keywords: Additive manufacturing, CNC milling, Cutting tool selection, PLA machining, 3D printing.

1. INTRODUCTION

Polymer materials are preferred today, taking the place of many metallic and ceramic materials, especially because of their lightness and ease of processing [1-3]. However, the fact that polymeric materials used in the industry are produced with petroleum and its derivatives brings along various problems [2-5]. The increasing difficulty of access to petroleum resources, the increasing cost of petroleum, and the fact that petroleum-based plastics cannot degrade in nature for many years have made polymer materials produced from petroleum a global problem. For this reason, researchers are conducting studies for the discovery of biopolymers that do not cause environmental problems and are produced from non-petroleum natural resources. Biopolymers are polymeric materials produced from biological sources. Naturally sourced biopolymers do not cause waste and environmental pollution problems, and they dissolve in nature and protect the ecological balance [1-5]. In addition, the production of biopolymers consumes less energy and has a lower carbon footprint compared to the production of petroleum-based polymers. For these reasons, the use of biopolymers in the industry is becoming increasingly common. The usage areas of biopolymers are quite wide. It is used in many sectors such as packaging materials, medical materials, agricultural materials, textile products, construction materials, and the automotive industry [6-8]. For example, biopolymers made from starch and cellulose are used as packaging materials and reduce waste problems [9-11]. In addition, biodegradable materials such as lactic acid are used in the manufacture of medicinal materials. As a result, biopolymers gain importance as an environmentally friendly and sustainable alternative, since petroleum-based polymers do not degrade in nature and cause environmental problems. The uses of biopolymers are expanding and researchers are working to discover more biopolymers using natural resources and renewable resources [12].

Additive manufacturing, also known as 3D printing, has become increasingly popular in recent years due to its flexibility in producing complex and customized parts. ABS, PLA, and PETG filaments are the most preferred filament types, and among these, PLA filaments stand out more than others in terms of some advantages. Depending on the types of filament used to manufacture 3D printed parts, challenges such as surface quality, tensile strength [13] and dimensional accuracy must be overcome. In addition, it is aimed to obtain more durable structures by optimizing manufacturing parameters such as printing speed, fill rate, and scanning angles [14]. This is particularly important for functional parts that require additional post-processing operations such as CNC milling. PLA is one of the most commonly used materials in 3D printing due to its low cost, ease of printing, and biodegradability. However, PLA has a lower hardness and thermal stability compared to other engineering plastics, which can cause difficulties in machining processes such as milling. Therefore, the selection of an appropriate cutting tool and cutting parameters is crucial to achieving a good surface finish and dimensional accuracy of milled PLA parts [1-5].

Additive manufacturing has gained significant attention in recent years due to its ability to produce complex and customized parts [12]. The ease of use and low cost of 3D printing technology has made it an attractive option for rapid prototyping and small-scale production. However, one of the main challenges in 3D printing is achieving the desired surface finish and dimensional accuracy of the printed parts. This is particularly important for functional parts that require additional post-processing operations such as CNC milling.

PLA is a biodegradable thermoplastic polymer that is commonly used in 3D printing due to its low cost, ease of printing, and biodegradability [15]. PLA is derived from renewable resources such as cornstarch or sugarcane, which makes it an attractive option for sustainable manufacturing [16]. However, PLA has a lower hardness and thermal stability compared to other engineering plastics [17], which can cause difficulties in machining processes such as milling. Machining PLA parts requires special considerations due to the low thermal stability of the material, which can result in melting, deformation, and poor surface finish.

To overcome these challenges, selecting an appropriate cutting tool and cutting parameters is crucial to achieving a good surface finish and dimensional accuracy of milled PLA parts. The selection of the cutting tool and cutting parameters can greatly affect the machining performance and efficiency, as well as the quality of the final product. Various types of cutting tools and cutting parameters can be used for milling PLA parts, but their effectiveness and suitability need to be evaluated experimentally.

This study aims to experimentally determine the optimum cutting tool for CNC milling of 3D-printed PLA parts. The conducted a series of experiments using various cutting tools to evaluate their effectiveness in machining PLA parts.

2. MATERIAL AND METHOD

2.1. Materials

The main reason for using PLA material in this study is that 3D printer users around the world tend to prefer this material for printing. As seen in Table 1, it can melt at relatively low temperatures (~150 °C), making the work easier. The possibility of warping during printing is lower. Users mostly operate 3D printers in personal living spaces. Therefore, there are no special ventilation systems in these environments. PLA material is bio-based and does not harm the environment and humans [8]. On the other hand, ABS has a harmful aspect to health due to users inhaling plastic fumes during melting, so the environment must be ventilated or printing should be done in open air, which is not always possible for users.

Table 1. Some properties of PLA material [15].

Features	Symbol	Unit	Value
Polymer density	ρ	g/cm^3	1.21–1.25
Tensile strength	σ	MPa	21–60
Tensile modulus	E	GPa	0.35–3.5
Ultimate strain	ε	%	2.5–6
Glass transition temperature	Tg	°C	45–60
Melting temperature	Tm	°C	150–162
Rockwell hardness	HR	kg/m^2	88

2.2. Preparation of Test Samples

For the production of test samples, the Creality Ender-3-S1 printer and conventional PLA filaments, as shown in Figure 1.a, were used. The plate parts with dimensions of 90x40x10 mm were modeled in Solidworks 2015 software. The created solid models were saved in STL format and transferred to the Simplify 3D slicing program, as shown in Figure 1.b. From there, G-codes were generated for the printing process and defined as input for the printer. After entering the position of the sample on the printer tray, the fill ratio (%100), infill angle offsets (±45°), printer bed temperature (60°C), and other production parameters, the samples were printed. The printing process of a single sample with the given dimensions took 2 hours and 5 minutes. The filament length used was 12.5 m, and the weight of the printed sample was obtained as 37 gram. The printed experimental sample is shown in Figure 1.c. To achieve consistency in the manufacturing parameters of the samples, 9 test samples were printed using the same features and printing technique.

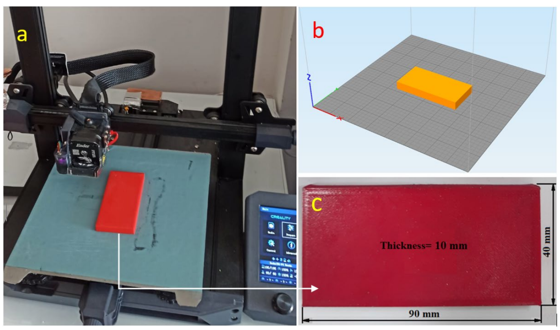


Figure 1. a) Creality Ender-3 S1, where the experimental samples were produced, b) slicing process and G-code generation in Simplify software, c) completed experimental sample

When the necessary times for printing with and without holes (Figure 2.a and Figure 2.b, respectively) were calculated on the 3D printer, very close times of 2 hours 5 minutes and 1 hour 59 minutes were obtained, respectively. The reason for this is that the nozzle spends extra time changing its position and direction to leave the hole area empty. Therefore, it is thought that not creating holes does not cause significant time loss and it would be appropriate to achieve precise tolerances by the final process of CNC milling.

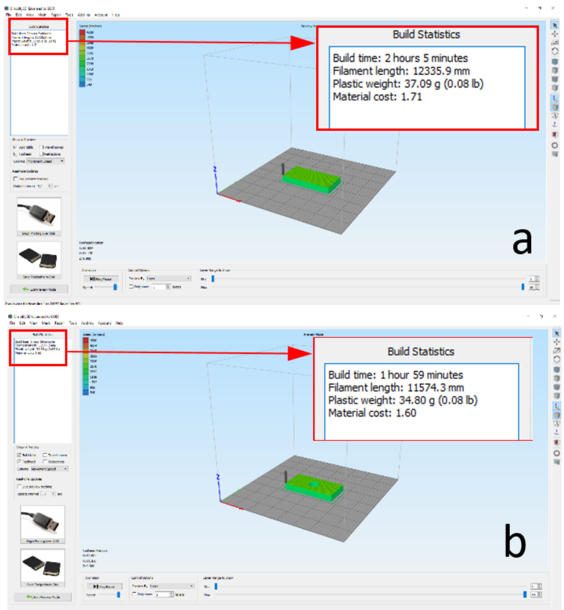


Figure 2. Manufacturing times of PLA printed parts a) without holes b) with holes.

2.3. Pocket Milling

The most preferred method for drilling holes is using a drill bit. However, delamination occurs in wood, composite [9-11], and polymer materials. As seen in Figure 3.a, a damaged formation occurs in a larger diameter than the diameter that needs to be drilled, especially where the drill bit exits. These delamination damages significantly affect the accuracy and also negatively affect the bushing and bearing seats that will be inserted into the hole, shortening the life of the part. Since a similar layering occurs in layered materials, such as the composite material shown in Figure 3.b, it does not seem appropriate to use a drill bit for PLA material.

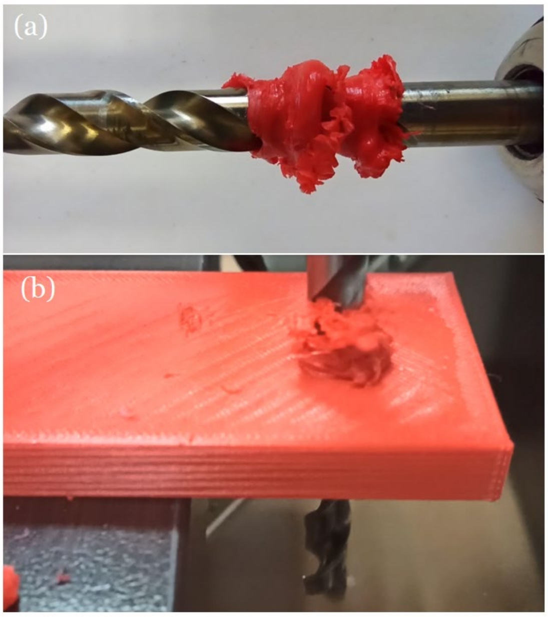


Figure 3. a) PLA melting and sticking to the drill bit. b) melting and delamination formation during drilling.

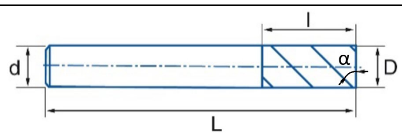
Several milling processes commonly used in industry include surface milling, profile shaping, pocket milling, and drilling. Other processing methods, except for drilling, have been studied in various literature. However, it has been identified that small-diameter (<20 mm) drilling is a topic that needs to be investigated. In assembly processes where positional tolerance is important, the drill cannot provide sufficiently accurate positioning. Therefore, the feasibility of drilling operations with CNC milling has been investigated. The special production CNC milling machine used for surface machining studies, as seen in Figure 4.a, is a 3-axis machine with a processing area of 400 mm on both the x and y axes and 200 mm on the z-axis. The maximum spindle rotation speed is 18000 rpm. It is designed for medium to high-precision manufacturing up to 0.01 mm. Coolants are generally required for processing thermoplastic materials, and petroleum-based coolants can be used for semi-crystalline plastics such as nylon, acetal, polyester, and thermosets. However, if processing any amorphous material such as PLA where it is difficult to determine its interaction with the coolant, avoiding such cooling liquids is generally a good solution [11,12,15]. Therefore, during the experiments, pressurized air was used to benefit from the cooling effect and to prevent chip buildup in front of the milling cutter. Machining of thermoplastics is an effective solution to overcome the challenges encountered in molding and forming processes, such as high cost, time consumption, and difficulties in creating complex shapes. The process of machining can produce high-quality products with close tolerances, whether from plastics, composites, or metals. Advancements in CNC machining have led to increased accuracy and quality, achieved by increasing the number of axes or incorporating jointed-arm robots. In drilling thermoplastics, however, issues such as melting due to high temperature, product cracking, and non-optimized process parameters can arise. Researchers have developed various techniques to mitigate these problems, such as the use of hybrid machines that combine Fused Deposition Modeling (FDM) and CNC milling processes, and increasing cutting speed to drill thermoplastics. In the study, experiments were conducted to open holes with a diameter of 15 mm. In order to perform this operation, 7 different end milling cutters with properties given in Table 2 and numbered, as seen in Figure 4.b, were used. Milling cutters up to 10 mm in diameter have a two tooth cutter. This means that it has more contact with the material being cut and the heat generated during cutting is distributed to two tooth cutter. However, in four tooth cutter tools, the total heat is divided by the number of cutting edges. Thus, it is thought that more effective cooling is achieved by transmitting the heat on the contact surface to the end mill.

In addition, in order to determine the effects of using coated end milling cutters, 2 coated cutters were preferred. Thus, in order to increase the performance of the end mills and to cut faster, Titanium Aluminum Nitride (TiAlN) tip number 3 and Boron Carbide (B_4C) coated insert number 7 were used. TiAIN coating is a type of coating that is widely preferred in carbide end mills that we encounter in the market. It is widely preferred in high-temperature applications. Aluminum in its composition acts as a thermal insulator due to its stability and heat resistance at extremely high temperatures. The aluminum layer on the tool surface not only provides oxidation resistance but also provides a hardness that is resistant to burrs, which are often encountered in other coatings. B_4C coating is preferred for accurate cutting geometries and precise dimensional tolerances, and they are also inserts that provide good heat transfer.

During operations such as surface machining or channel cutting in CNC, the cutting tool moves on different axes on the flat surface, which does not allow the same area of the PLA part to reach high temperatures. However, in the drilling process, as the diameter decreases, the hole is vertically positioned and close to a single center, which heats both the removed debris and the surfaces of the hole that it is in continuous contact with. The rotating movement of the milling cutter in this way creates a risk of damage to the PLA material.

Figure 4. a) Desktop CNC milling machine b) end milling cutters used in processing.

Table 2. Schematic view and characteristics of cutting tools.



Cutting tool number	Tool body diameter (Ød) [mm]	Insert diameter (ØD) [mm]	Tool overall length (L) [mm]	Tool cutter length (l) [mm]	Helix Angle (α) [°]	Number of teeth (z)	Coating
1	10	10	100	60	45	4	Uncoated
2	8	5	130	75	30	2	Uncoated
3	10	7	75	30	45	2	Coated (TiAlN)
4	6	5	60	20	45	2	Uncoated
5	5	4	65	40	45	2	Uncoated
6	5	1.5	70	15	30	2	Uncoated
7	4	6	45	15	45	2	Coated (B4C)

3. RESULTS AND DISCUSSION

Experiments were conducted using the end milling cutters with properties given in Table 2 to observe their effects on the PLA material during processing. The drilling experiments with number 2 and number 5 end mills are shown in Figure 5.a and 5.b, respectively. Although partial drilling was observed in these experiments, the molten workpiece was deformed. In the experiment with the number 6 cutter, as seen in Figure 5.c, the drilling process did not occur at all. The intense melting observed in the workpiece due to the heat generated by the rotation of the small-diameter cutter caused the workpiece to melt before processing. Since a small diameter end mill was used here, a situation similar to the friction stir welding of polymer materials was encountered [18]. The high temperature required for friction stir welding is a disadvantage for drilling holes. Figure 5.d shows the drilling process with cutter number 1. Accordingly, cutters 2, 4, 5, and 6 both melted the workpiece and failed to drill a hole, and their tooth cutter have broken after a while. Cutters 3 and 7 have been able to drill a hole but caused deformation and plastic accumulation at the entry and exit points of the workpiece. It is observed that a successful process that meets all expectations were realized in the workpiece processed with cutter number 1 without causing melting or deformation.

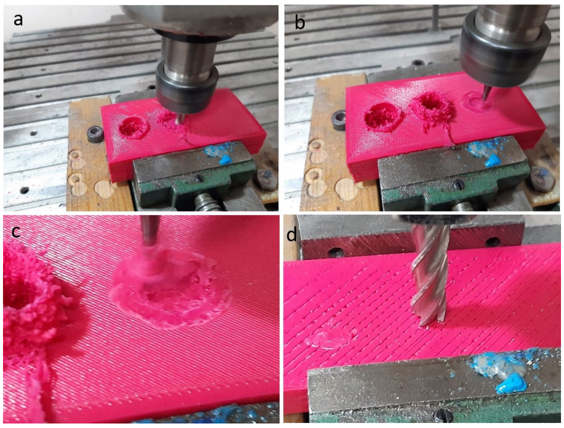


Figure 5. Machining of PLA parts with different characteristics using an end mill.

Each drilling operation was repeated three times with each end mill, using a total of 9 workpieces. In samples where multiple drilling operations were performed on the same workpiece, the workpiece was allowed to cool sufficiently after each drilling attempt. As seen in Figure 6, end mills 2, 5, and 6 were used on one workpiece (Figure 6.a), while mills 4, 3, and 7 were used on another (Figure 6.b). A separate workpiece was used with cutter 1 (Figure 6.c). The surface roughness values were measured for the hole drilled with cutter 1 because it was measurable. Surface roughness values could not be measured for the other processed surfaces because they were overly deformed. The reason why the average surface roughness of the PLA parts could not be measured is that the high values that exceeded the measurement range of the roughness testing device existed before the finishing process. However, even though the surface roughness of the PLA part could be measured, the results were quite high: Rt = 11.7µm, Rz = 6.91µm, and Ra = 2 µm. Figure 6 presents a collective view of the samples subjected to the experiment. This image reflects the fact that each sample has different properties and process parameters, and therefore shows different results after processing. In the image, different diameters, shapes, and surface structures of the samples can be observed. Additionally, both perforated and non-perforated versions of the samples are included. The samples were processed using different milling tools and cutting tools. Some samples were processed using aggressive process parameters such as high speed and feed rate, while others were processed using lower speeds and feed rates. The image demonstrates the different results obtained using different process parameters and milling tools.

Figure 7 displays the scanning electron microscope (SEM) images of the melted surface of PLA plastics that occurred during processing with different cutting tools. The SEM images provide a visual representation of the particle distribution in each compound. The observed macro surface morphological variability in SEM images can be attributed to different temperature distribution patterns exhibited by various cutting tools. It is evident that the type of cutting tool used significantly affects the melting distribution behavior and general viscoelastic properties of the plastics. Since temperatures on the cutting surface reached up to 173 °C, melting and accumulation occurred, and the PLA melt adhered to the cutting tool tip. PLA melts adhering to the cutting tool tip was observed to rotate on the cutting tool for a while before cooling and glassing occurred. Furthermore, leaf-shaped formations and crystalline buds in powder form were observed in SEM images. This resulted in a more brittle structure and a sharper and more difficult-to-correct deformation pile-up. Lambiase et al.'s [8] study showed that laser surface finishing with a 30 W CO_2 laser in continuous wave mode significantly improves the surface roughness of 3D printed PLA components. The study determined the influence of laser treatment parameters on surface morphology and identified surface ablation as the mechanism of interaction. ANOVA, RSM, and MRO were used to determine optimal process conditions, resulting in enhanced surface roughness (Ra = 0.3 µm) and minimized surface recession (0.1 mm). These findings provide valuable insights for improving the surface quality of 3D-printed PLA components. The article by Lalegani Dezaki et al. [10] explores the effect of CNC machining on the surface quality of FDM products. The study investigates the surface roughness of printed and machined samples in various build orientations. The results show that the horizontal surface roughness yielded the best quality compared to perpendicular and vertical specimens. Machining was found to greatly influence thermoplastics, resulting in smoother surfaces. The research emphasizes the importance of surface quality in FDM products for better mechanical properties. Figure 7 presents a SEM image of the melted PLA pockets on the milled surfaces of the processed parts. This image provides a detailed view of the processed surface of the parts and helps determine the size and shape of the damage that occurred after processing. The image shows the melted PLA pockets on the processed surface clearly, and their shape and size can also be observed. Furthermore, the deformation of the pockets during processing can also be seen. This image can be used as a tool to examine the details and deformations of melted PLA pockets on the processed surface of the parts. It provides valuable information for optimizing processing parameters and cutting tools, which ultimately enhances the quality of the processed parts.

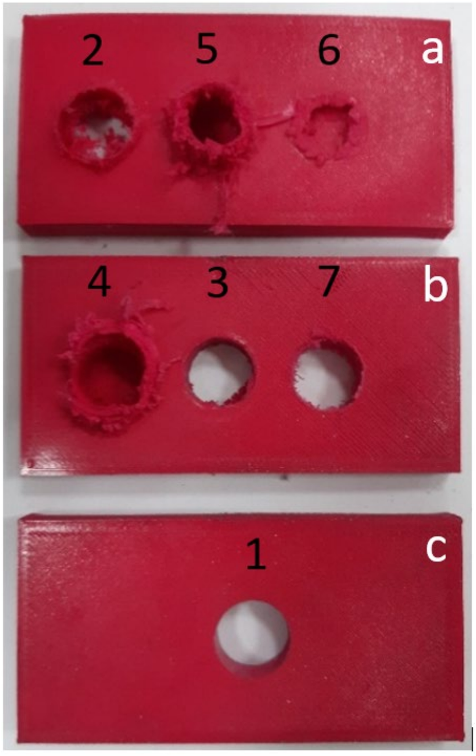


Figure 6. Overview of tested PLA plates processed with 7 different end mill cutting tool samples.

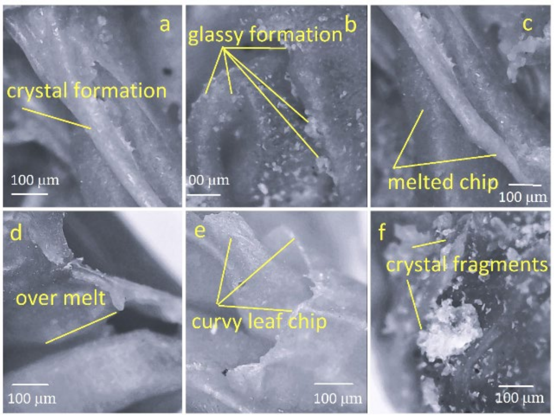
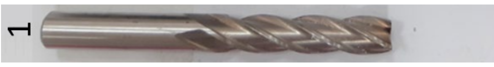
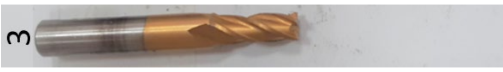
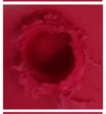
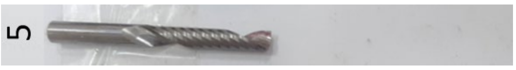
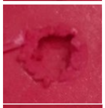


Figure 7. SEM image of melted PLA pocket milled surface of parts.

Table 3 presents the appearance of the drilled holes and the success rate of the drilling process. The table provides information on the appearance of the drilled holes in terms of their shape, diameter, and whether or not they are tapered. In addition, the success rate of the drilling process is presented as the percentage of holes that were drilled successfully without any defects or damage. The data in the table is organized based on the different processing parameters and cutting tools used in the drilling process. This information is important for evaluating the quality and accuracy of the drilled holes and for optimizing the processing parameters and cutting tools for future drilling operations. Overall, Table 3 provides a comprehensive overview of the results of the drilling process and can be used as a reference for future research and development in this area. The results led to the evaluation of CNC machining success in two separate categories as “Melting” and “Burring” as seen in Table 3. Inserts 2, 4, 5, and 6 also failed in terms of burr residue, as they did not melt the material and perform acceptable machining. This is due to the small diameter of these inserts, as well as their inadequacy in heat conduction to the cutting tool body, and it is thought that the heat exerts an effect on the PLA material's melting temperature during machining. Inserts 1, 3 and 7 were able to machine the PLA material without melting, as seen in the "Hole view" column in Table 3. On the other hand, it is seen in Table 3 that although the coated inserts 3 and 7 can process, they cause burr residues. These inserts have been successful at an acceptable level in absorbing the heat generated as a result of machining into their bodies. However, it is thought that they are insufficient in terms of burr-free machining due to the small diameter of the cutting tool and their two tooth cutter.

Table 3 shows that the number 1 cutter is more suitable for processing PLA material without melting and burr-free, since it has a sufficient body diameter and a four tooth cutter.

Table 3. Hole macro views and drilling success status of PLA parts.

End milling cutter	Hole view	Drilling success status	
		Melting	Burring
		✓	✓
		✗	✗
		✓	✗
		✗	✗
		✗	✗
		✗	✗
		✓	✗

A practical model has been designed and manufactured based on the results obtained from experimental studies. To achieve this, a bearing with a diameter of 10 mm and 4 cutting edges, which was successfully processed with a precise end milling cutter measured at 15 mm with a caliper, was used. Drilling is also possible, but drill bits are manufactured with a 1 mm interval. For example, it is not possible to obtain holes that provide the necessary tight fit required in this model with a drill bit and that can be used with standard bearings. In machine elements, there are three types of fits defined as clearance fit, transition fit, and interference fit. The interference fit method should be preferred when the bearing needs to be pressed in. For this, if the hole is slightly larger than the nominal diameter of the shaft, it should be manufactured slightly smaller. Tolerance values have been determined for metal-to-metal fits in standards. However, there is no standard for the combination of PLA and metal. Therefore, a tolerance of 0.25 mm was preferred, and a hole with a diameter of 14.75 mm was processed on the workpiece. The standard bearing with a diameter of 15 mm was pressed (Figure 8.a) in using the interference fit method. In Figure 8.b, a body with the pressed bearing using a hydraulic press is seen. A shaft was attached to the body with a tight fit as shown in Figure 8.c to the bearing. A weight of 1 kg was attached to the shaft at a distance of 100 mm from the bearing to test the durability of the tight fit by causing a jerky movement. A belt-pulley mechanism was placed inside the body. This mechanism, driven by a stepper motor, was tested for 200 hours of operation and no gap or looseness was observed between the bearing and the machined PLA material. Thus, it was concluded that both the drilling and fitting processes were successfully performed. Lalegani Dezaki et al. [1] investigated the effects of drilling parameters on FDM products and examined the surface texture of 3D printed samples to determine the effects of build orientation. Results showed that increasing build orientation worsened surface roughness, with horizontal specimens having the best surface quality. Moderate feed rate and spindle speed values showed the best quality in drilled holes, and the 0º sample had the lowest Ra and Rz values. Build orientation also affected surface quality in the drilling process. Tiwary, Arunkumar, and Malik's [19] paper present a novel classification of joining and welding techniques for 3D-printed parts to create bigger-sized components. Their literature review offers insights into the various techniques, their advantages, disadvantages, and critical challenges. Their work provides a practical approach to selecting and applying suitable joining and welding techniques, enhancing the potential of 3D printing in manufacturing.

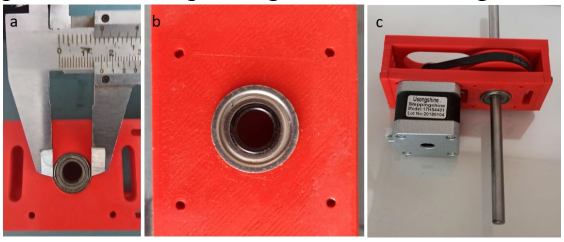


Figure 8. Sample application manufacturing a) rolling bearing on the successfully machined workpiece b) bearing sample view c.) manufacturing completed model.

According to the article by Pămărac and Petruse [20], Optimum milling parameters for face milling and profile contouring operations were determined with different cutting tool diameters for a constant spindle speed of 3500 rpm. It has been determined that slower cutting speeds provide a better surface quality for ABS material, and a better surface quality is obtained when higher cutting speeds are used for PLA material. The article by Moradi et al., [4] presents a thorough investigation of CO_2 laser cutting as a post-processing method for improving the dimensional accuracy of 3D-printed PLA parts. The study highlights the significant impact of process parameters on the quality of kerf dimensions and provides insights into optimal input parameters for achieving high-quality kerf features. The findings of this study offer valuable information for researchers and practitioners in the field of 3D printing.

This study, the article explores the optimal parameters for achieving precise diameter dimensions in PLA material parts produced using 3D printing and CNC milling processes. The study identifies the most suitable cutting tool and process parameters, highlighting the morphological changes induced by different diameter milling cutters. The research findings can help reduce waste material accumulation, and energy-time-raw material losses, and improve the accuracy and efficiency of the manufacturing processes. Moradi et al., [4] investigates the post-processing of 3D-printed poly lactic acid (PLA) parts using CO_2 laser cutting, while Pămărac and Petruse [20] focus on determining the optimal parameters for achieving precise diameter dimensions in PLA material parts produced using 3D printing and CNC milling processes. The article examines the effects of laser-cutting process parameters on the geometrical dimension of the kerf, while this study identifies the most suitable cutting tool and process parameters for achieving the desired diameter dimensions. Overall, the two articles differ in their research objectives, methodology, and findings.

4. CONCLUSION

In this study, the optimal end milling cutter tool selection for drilling holes in 3D-printed PLA parts on a CNC milling machine was investigated. Parameters such as fixed spindle speed, feed rate, and cutting depth were taken into consideration. The results showed that completed PLA-printed parts can be used by drilling holes in them. Additionally, it was determined that PLA-printed parts can be manufactured as a base and then drilled in different positions where needed, providing manufacturing flexibility. Furthermore, it was found that the successful drilling of holes can also provide the possibility of performing similar operations such as channels and bean slots. It was concluded that in cases of faulty printed materials, other processing procedures mentioned in this study, including hole drilling, can be followed to reduce the amount of waste material. The results of this study can serve as a reference for machining studies from a broad perspective.

The optimal end milling cutter tool selection for drilling holes in CNC milling of PLA parts printed on a 3D printer with selected parameters including constant spindle speed (15000 rpm), feed rate (500 mm/min), and cutting depth (0.5 mm) was investigated. Furthermore, the functionality of the workpiece was tested on a sample model based on the findings of the study.

Some important observations from the study can be listed as follows.

- The method followed in this study was found to be successfully applicable when drilling holes in completed PLA printed parts where it is possible to use them.
- PLA printed parts can be manufactured as a base (without holes) and then holes can be drilled in different positions where they may be required, providing manufacturing flexibility.
- Achieving successful hole drilling also allows for the possibility of performing many similar operations (such as channels, bean slots, etc.). The results of this study can be a reference for processing work from a broad perspective.
- By following other machining procedures indicated in this study, such as hole drilling, waste material amounts can be reduced for poorly printed materials.

The results of this study can provide valuable insights into the selection of an appropriate cutting tool and cutting parameters for milling PLA parts. These insights can help to improve the efficiency and quality of post-processing operations for 3D printed parts, especially for functional parts that require high accuracy and surface finish. Moreover, this study can contribute to the development of sustainable manufacturing processes by providing guidance on the use of biodegradable materials in combination with efficient machining methods.

Future work

In this study, no coolant was used during the CNC milling of the PLA part. Therefore, since local heat increases are likely to occur during drilling rather than surface machining, drilling can be considered a critical process. Thus, this study revealed that drilling with a minimum 10 mm diameter milling cutter is possible. In future studies, researchers could examine the machinability of PLA material with smaller diameter milling cutters without deformation by using an additional cooling method.

Another research topic is that, for parts produced with 100% infill rate on a 3D printer, there is no weakening around the drilled hole when the method followed in this study is used. However, for parts produced with lower infill rates, the inner regions of the workpiece are grid-shaped, which inevitably leads to weakening around the drilled hole. Therefore, studies can be conducted to strengthen the planned area around the drilled hole for different infill rates.

REFERENCES

1. Lalegani Dezaki, M., Mohd Ariffin, M. K. A., & Baharuddin, B. T. H. T. "Experimental study of drilling 3D printed polylactic acid (PLA) in FDM process". Fused Deposition Modeling Based 3D Printing, Pages 85-106, 2021.

2. Vidakis, N., Petousis, M., Mountakis, N., & Kechagias, J. D. "Material extrusion 3D printing and friction stir welding: an insight into the weldability of polylactic acid plates based on a full factorial design". The International Journal of Advanced Manufacturing Technology, Vol. 121, Issue 5-6, Pages 3817-3839, 2022.

3. El Mehtedi, M., Buonadonna, P., Carta, M., El Mohtadi, R., Marongiu, G., Loi, G., & Aymerich, F. "Effects of milling parameters on roughness and burr formation in 3D-printed PLA components". Procedia Computer Science, Vol. 217, Pages 1560-1569, 2023.

4. Moradi, M., Karami Moghadam, M., Shamsborhan, M., Bodaghi, M., & Falavandi, H. "Post-processing of FDM 3D-printed polylactic acid parts by laser beam cutting". Polymers, Vol. 12, Issue 3, Pages 550, 2020.

5. Sandhu, K., Singh, G., Singh, S., Kumar, R., Prakash, C., Ramakrishna, S., ... & Pruncu, C. I. "Surface characteristics of machined polystyrene with 3D printed thermoplastic tool". Materials, Vol. 13, Issue 12, Pages 2729, 2020.

6. Sneha, N., & Balamurugan, K. "Micro-drilling optimization study using RSM on PLA-bronze composite filament printed using FDM". IEEE 2nd Mysore Sub Section International Conference (MysuruCon), Pages 1-5, Mysuru, 2022.

7. Borra, N. D., & Neigapula, V. S. N. "Parametric optimization for dimensional correctness of 3D printed part using masked stereolithography: Taguchi method". Rapid Prototyping Journal, Vol. 29, Issue 1, Pages 166-184, 2023.

8. Lambiase, F., Genna, S., & Leone, C. "Laser finishing of 3D printed parts produced by material extrusion". Optics and lasers in engineering, Vol.124, Pages 105801, 2020.

9. Kumar, A., Alam, Z., Khan, D. A., & Jha, S. "Nanofinishing of FDM-fabricated components using ball end magnetorheological finishing process". Materials and Manufacturing Processes, Vol. 34, Issue 2, Pages 232-242, 2019.

10. Lalegani Dezaki, M., Mohd Ariffin, M. K. A., & Ismail, M. I. S. "Effects of CNC machining on surface roughness in fused deposition modelling (FDM) products". Materials, Vol. 13, Issue 11, Pages 2608, 2020.

11. Mathew, A., Kishore, S. R., Tomy, A. T., Sugavaneswaran, M., Scholz, S. G., Elkaseer, A., ... & John Rajan, A. "Vapour polishing of fused deposition modelling (FDM) parts: a critical review of different techniques, and subsequent surface finish and mechanical properties of the post-processed 3D-printed parts". Progress in Additive Manufacturing, Pages 1-18, 2023.

12. Bhattiprolu, V. S., & Crawford, G. A. "Microstructural evolution and mechanical behavior of heat treated Ti-6Al-4V powders". Metallography, Microstructure, and Analysis, Vol. 7, Pages 761-768, 2018.

13. Kuruoğlu Y, Akgün M & Demir H. "Modelling and optimization of surface roughness and tensile strength of ABS, PLA and PETG samples produced by FDM method". International Journal of 3D Printing Technologies and Digital Industry, Vol. 6, Issue 3, Pages 358-369, 2022.

14. Günay M, Gündüz S, Yılmaz H, Yaşar N, & Kaçar R. "Optimization of 3D printing operation parameters for tensile strength in PLA based sample". Politeknik Dergisi, Vol. 23 Issue 1, Pages 73-79, 2020.

15. Nwodu, A. L. "An experimental approach to studying first-layer adhesion in robotic printing operations" Doctoral dissertation, Florida Agricultural and Mechanical University, 2019.

16. Taib, N. A. A. B., Rahman, M. R., Huda, D., Kuok, K. K., Hamdan, S., Bakri, M. K. B., ... & Khan, A. "A review on poly lactic acid (PLA) as a biodegradable polymer". Polymer Bulletin, Pages 1-35, 2022.

17. Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. "Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials". Materials, Vol. 13, Issue 21, Pages 4994, 2020.

18. Karagöz, İ., & Öksüz, M. "Methods for joining thermoplastics by friction stir welding". Journal of Çukurova University Faculty of Engineering and Architecture, Vol. 31, Issue 1, Pages 19-28, 2016.

19. Tiwary, V. K., Arunkumar, P., & Malik, V. R. "An overview on joining/welding as post-processing technique to circumvent the build volume limitation of an FDM-3D printer". Rapid prototyping journal, Vol. 27, Issue 4, Pages 808-821, 2021.

20. Pămărac, R. G., & Petruse, R. E. "Study regarding the optimal milling parameters for finishing 3D printed parts from ABS and PLA materials". Acta Universitatis Cibiniensis. Technical Series, Vol. 70, Issue 1, Pages 66-72, 2018.