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HYBRID MANUFACTURING: OPTIMIZING LATHE FINISHING PARAMETERS FOR IMPROVED SURFACE QUALITY AND DIMENSIONAL PRECISION IN FDM-PRINTED COMPONENTS

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Abstract: *Additive Manufacturing (AM), particularly the Fused Deposition Modelling (FDM) technique, is gaining traction in industrial applications due to its versatility and cost-effectiveness. However, components produced by FDM often presents poor dimensional accuracy, geometric deviations, and inferior surface quality. This study investigates the effects of lathe turning post-processing on enhancing these properties. Using a Taguchi design of experiments, critical manufacturing parameters affecting dimensional accuracy and surface roughness were analysed. Results lead to significant improvements in dimensional precision and surface quality post-turning. Optimal finishing conditions identified include a spindle speed of 1200 RPM, cutting depth of 0.3 mm, and feed rate of 0.1 mm/rev, offering valuable insights into the hybrid AM-finishing approach.*

Keywords: *Additive Manufacturing, Fused Deposition Modelling, Surface Roughness, Dimensional Accuracy, Lathe Turning, Hybrid Manufacturing.*

1. INTRODUCTION

AM, particularly FDM, has revolutionized the way prototypes and functional components are produced. Initially developed in the 1980s by Charles Hull with the invention of stereolithography, AM has expanded across industries such as aerospace, construction, and medicine due to its capability to create complex geometries and reduce lead times. FDM, a common form of 3D printing, constructs parts by depositing material layer-by-layer based on a CAD design. This technique allows for rapid prototyping and the production of unique, high complexity shapes without the need for molds or extensive tooling, making it indispensable in engineering and design processes. The key advantages of FDM include reduced production costs and flexibility in material choice, as seen with common options like ABS, PLA, and PETG. Despite its benefits, FDM is often criticized for its inherent limitations in surface quality and dimensional precision. The layer-by-layer deposition process typically results in visible layer lines and surface roughness, which can compromise both the aesthetic and functional properties of printed components. This "staircase effect" and variability in geometric accuracy are influenced by factors such as layer height, print speed, and nozzle diameter. To meet the stringent requirements of certain applications, additional post-processing is often necessary to refine these printed parts.

To fulfil these challenges, traditional machining methods like lathe turning can be integrated with 3D printing as a post-processing step. This hybrid approach combines the design freedom of FDM with the precision of subtractive manufacturing, enabling smoother surfaces and tighter tolerances. The aim of this study is to explore the effectiveness of lathe machining as a method of improving the surface finish and geometric accuracy of FDM-printed parts, thereby enhancing their quality and expanding their application potential.

Setting up of the feeds and speeds parameters for turning manufacturing of parts obtained through FDM technologies consists in a very interesting but challenging topic. As previously stated, setting up the suitable manufacturing parameters is a necessary step in obtaining functional prototypes or parts starting from a 3D printed semi-finished product.

Through our bibliographic study, plenty of data was found on the milling approach of 3D printed parts, but slim to none on the turning process, therefore, an approach could consist in collecting and centralising the milling data regarding the feeds and speeds, especially the cutting speed, and further extrapolate for the turning process.

During the bibliographic study, we remarked that most of the researchers that approached this thematic had a similar starting point within the process of setting up the cutting parameters, consisting in the material's characteristics, especially the hardness of the studied materials, but also the Tensile Strength, the Yield Strength, the Young Modulus, the Poisson coefficient and the Density. There is important to be mentioned that very few of the papers approached the problematic from an analytic calculus of the feeds and speeds, and even in those cases, the calculus was rather simplified, not taking into consideration all the parameters and coefficients used in a classical calculus of the feeds and speeds. Another very important mention is that a relatively small number of the research studies took into consideration the FDM particularities, regarding the infill percentage, the deposition strategies, the thickness of the levels etc, perspective which has a high importance in the cutting parameters setup, from our point of view.

A final remark during our current state research is that within none of experimental studies have been used tools with special geometries for manufacturing plastic filament materials, during most of the studies, the researchers used cutting tools for aluminium, cast iron or stainless steel. The link between the cutting speed and the chip formation during the cutting process is highly tight, but the tool geometry is also very important in order to avoid the deterioration of the cutting edge of the tool (overheating, material deposition etc). Furthermore, based on specific machinery's handbooks [1], a summary of the recommended tool parameters has been developed, data centralized in table 1, noticing that for all the materials the tool radius has be a minimum of 0.5mm.

Table 1

Tool parameters for PLA, ABS and PP materials [1]

Material	α - Clearance Angle (°)	ϒ - Rake Angle (°)	X - Side Angle (°)
PLA	5-10	0-5	45-60
ABS	5-15	25-30	15
PP	6-10	0-5	45-60

Within the following paragraph, the most notable papers and their final conclusions are summarized, for the following material: PLA, PP and ABS.

In the research study [2], the researchers approached the cutting data study of the PLA LITE material (4043D), with different printing parameters and printing orientation. Their experimental study focused on obtaining the roughness as small as possible, by using different cutting parameters. The researchers have concluded that for the material approached, the most suitable cutting data is cutting depth: 0.2mm, speed: 5500 rpm, feed rate 400 mm/min.

Another experimental study [3] focused on the milling also the PLA material, concluded with the following data: cutting depth: 1mm, speed 4377 rpm, cutting speed 165 mm/min, feed rate 1000 mm/min, feed per tooth 0.057.

Also, there were several studies approaching the cutting parameters of the Acrylonitrile butadiene styrene (ABS) material [4], [5] and [6]. For this specific material, the researchers suggest cutting depths between 0.35 and 0.7mm and turning speeds ranging from 4400 and 4800 rpm. Regarding the feed rate, for the ABS material the researchers provide the wides range of all the materials, between 500 and 1200 mm/min. The wide range is probably owed to the fact that the semifinished products used in the experiments had different deposition parameters. Researchers also approached the experimental study regarding the machining of the polypropylene (PP) material [7], [8] and [9], concluding with the following data: cutting depth: 0.5mm, speed: 4138 rpm, feed rate: 1241 mm/min.

By summarising the data from [2-9], we managed to set up the parameters intervals, therefore, cutting depth: 0.2-1 mm, speed: 4000-5500 rpm, feed rate: 400-1400 mm/min, data which is further centralised within Table 2.

Table 2

Cutting data parameters for PLA, ABS and PP materials [2-9]

Material	Cutting depth [mm]	Speed [rpm]	Feed rate [mm/min]	Cutting speed [mm/min]	Feed per tooth [mm/t]
PLA	0.2-1	4300-5500	400-1000	130-200	0.04-0.06
ABS	0.35-0.7	4400-4800	500-1200	n/a	n/a
PP	0.4-0.7	4000-4400	1000-1400	n/a	n/a

Nonetheless, within the walked-through papers, several important aspects have been remarked, data that might be useful for our research or for future research directions, as following:

- preheating the material to around 100°C has an important influence on increasing the machinability of the specimen;
- the usage of coolants and emulsions might lead to stress cracking or plastic deformations;
- carbide bits or diamond coating of tools are only recommended for abrasive printed materials, for all the other types of plastics printed materials, HSS - high speed steel tools are suitable;
- chip evacuation and respectively the heat management has a high influence on the final roughness and precision of the part, therefore, solutions regarding those problems must be taken into consideration.

2. EXPERIMENTAL METHODOLOGY

2.1 Design of experiments

The primary objective of this experimental research is to assess and enhance the surface quality, dimensional precision, and geometric accuracy of parts manufactured through a hybrid approach combining Fused Deposition Modelling (FDM) and lathe turning finishing processes. To accomplish this, the experiment investigates the effects of selected printing and machining parameters.

Table 3 outlines the main influence variables (input factors) and their associated response functions (output variables). These variables were identified based on their potential impact on the quality and precision of the resulting components.

Table 3

Main influence variables and response functions

Code	Type	Unit	Variation domain	Output variables
x1	Nozzle diameter	mm	0.4-0.8	Ra (µm), Circularity (µm), Tolerances (µm)
x2	Layer height	mm	0.1-0.3	
x3	Materials	-	PLA, ABS, PETG	
x4	Printing speed	mm/s	60-120	
x5	Rotational speed	rpm	1500-6500	
x6	Feed	mm/rot	0.008-0.015	
x7	Depth of cut	mm	0.1-0.4	

The experimental design adopted three levels of variation for all parameters, except the printing speed, which was analysed at two levels of variation. These levels uniformly cover the domains defined previously and are detailed in Table 4.

Table 4

Levels of variation of the main influence variables

Code	Type	Symbol	Unit	L1	L2	L3
x1	Nozzle diameter	d	mm	0.4	0.6	0.8
x2	Layer height	h	mm	0.1	0.2	0.3
x3	Materials	-	-	PLA	ABS	PET_G
x4	Printing speed	-	-	60 mm/s	120 mm/s	-
x5	Rotational speed	n	rpm	1500	4000	6500
x6	Feed	f	mm/rot	0.008	0.011	0.015
x7	Depth of cut	ap	mm	0.1	0.25	0.4

The Taguchi methodology was selected for designing the experiments due to its efficacy in systematically analysing the influence of multiple independent variables on the response variables, particularly given the relatively high number of levels involved. The experimental design was created using Minitab 18 software, resulting in the Taguchi orthogonal array L18 (2^1 3^6). Table 5 illustrates this matrix with 18 distinct experimental configurations, indicating the specific combination of factor levels.

Table 5

Taguchi Orthogonal Array L18(2^1 3^6) – Codes for Input Variables

Config.	Printing mode	Nozzle diameter	Layer height	Material	Rotational speed	Feed	Depth of cut
1	60 mm/s	0.4	0.1	PLA	4000	0.011	0.4
2	60 mm/s	0.4	0.2	ABS	6500	0.015	0.1
3	60 mm/s	0.4	0.3	PETG	1500	0.008	0.25
4	60 mm/s	0.6	0.1	PLA	1500	0.015	0.25
5	60 mm/s	0.6	0.2	ABS	4000	0.008	0.4
6	60 mm/s	0.6	0.3	PETG	6500	0.011	0.1
7	60 mm/s	0.8	0.1	ABS	6500	0.011	0.25
8	60 mm/s	0.8	0.2	PETG	1500	0.015	0.4
9	60 mm/s	0.8	0.3	PLA	4000	0.008	0.1
10	120mm/s	0.4	0.1	PETG	6500	0.008	0.4
11	120mm/s	0.4	0.2	PLA	1500	0.011	0.1
12	120mm/s	0.4	0.3	ABS	4000	0.015	0.25

13	120mm/s	0.6	0.1	ABS	4000	0.015	0.1
14	120mm/s	0.6	0.2	PETG	6500	0.008	0.25
15	120mm/s	0.6	0.3	PLA	1500	0.011	0.4
16	120mm/s	0.8	0.1	PETG	4000	0.011	0.4
17	120mm/s	0.8	0.2	PLA	6500	0.015	0.1
18	120mm/s	0.8	0.3	ABS	1500	0.008	0.25

2.2 Sample Preparation

Eighteen distinct specimen configurations were fabricated using various combinations of key 3D printing parameters. The parameters selected for the additive manufacturing process are detailed systematically in Table 5, ensuring coverage of variations in nozzle diameter, layer height, material type, and printing speeds.

The specimen presented in figure 1 has a stepped cylindrical geometry, suitable for evaluating the effectiveness of lathe turning post-processing on additive manufactured components. It consists of two distinct cylindrical sections with different diameters—one section with a diameter of 40 mm and a length of 30 mm, and a second narrower section with a diameter of 30 mm and a length of 25 mm used as a fixture surface in the lathe's chuck. This specific geometry allows assessment of dimensional accuracy, circularity, and surface finish, making it particularly relevant for practical evaluations of turning operations on FDM-printed specimens.

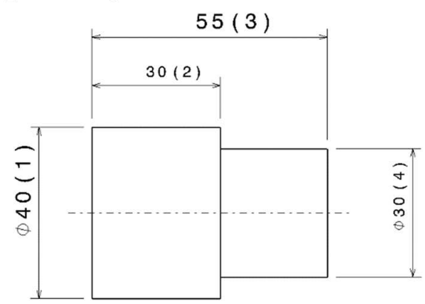

Fig. 1. Specimen's dimensions

All samples were printed using the same 3D printer—Snapmaker A350 equipped with a closed enclosure. The materials utilized in the experiment were stored under controlled environmental conditions, maintaining consistent temperature and humidity levels throughout the printing process. Samples were printed vertically (standing orientation) with a uniform infill density of 15%, employing a triangular internal structure. The top, bottom, and wall thicknesses were uniformly set at 1.5 mm.

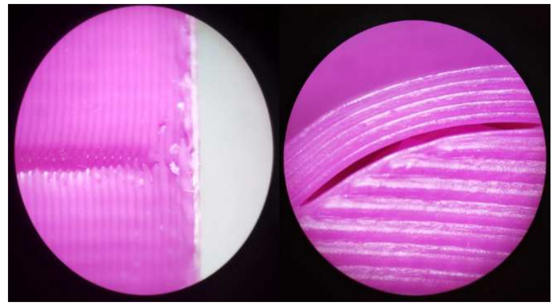

Fig. 2. Specimen fabrication defects

As depicted in figure 2, microscopic analysis of the FDM-printed specimens revealed several characteristic defects, including inadequate interlayer adhesion, visible surface cracks, delamination, irregular edges, and inconsistent extrusion, resulting in pronounced surface roughness, dimensional inaccuracies, and compromised geometric precision. Cylindrical surfaces often presented protrusions, uneven textures, and edge irregularities, whereas the top plane surfaces showed notable layer separation, cracking, and uneven stacking patterns. These observations clearly underscore the necessity and importance of this research in optimizing printing parameters and subsequent post-processing methods to enhance the overall quality and functionality of additive manufactured components.

2.3 Machining process preparation

The finishing operations were carried out using a Haas ST-15Y CNC lathe. The cutting tool utilized for these experiments was a VBMT 16 04 04-UM 4425 insert mounted on a suitable holder characterized by a 0.4 mm radius at the cutting edge, and a maximum depth of cut of 25 mm, and a side rake optimized for plastic materials. Specifically, the lathe setup included the following parameters:

The cutting sequences executed during the turning operation are described through the following G-code sequence:

```
N1 G54 T2 M06;
N2 S(n) M03;
N3 G00 Z0 X45;
N4 G01 X-1 F(f);
N15 G00 X[40 - ap] Z1;
N20 G01 Z-25;
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N35 G00 X45;
N40 G00 Z20 M05;

To ensure that dimensional and geometrical deviations resulting from the additive manufacturing process itself do not interfere with the evaluation of the finishing process, each specimen is initially machined down to a diameter of 39 mm before applying the finishing step. This preliminary machining step establishes a consistent baseline from which the effectiveness of the subsequent lathe turning can be accurately assessed.

3. RESULTS AND DISCUSSION

3.1 Specimen manufacturing deviations

Microscopic and dimensional analysis of the fabricated specimens revealed key insights into the impact of specific 3D printing parameters on dimensional accuracy. All measurements were carried out using a Faro Gage 3D measuring arm equipped with a 3 mm probe, ensuring high precision and repeatability. The results highlighted that ABS material consistently provided the smallest deviations from nominal dimensions, indicating superior dimensional stability compared to PLA and PETG under the tested conditions. Among tested nozzle diameters, the 0.6 mm nozzle demonstrated optimal dimensional control, particularly in length-related dimensions, achieving a balance between accuracy and reliability. The influence of printing speed within the range tested (60 mm/s and 120 mm/s) was found to be minimal, suggesting that other printing parameters surpass speed-related effects. Regarding layer height, lower values (0.1 mm and 0.2 mm) showed significantly improved dimensional accuracy, especially for cylindrical features, whereas higher layer heights (0.3 mm) consistently resulted in greater deviations. These findings emphasise the importance of material choice, nozzle diameter, and layer height optimization to enhance dimensional precision in additive manufacturing processes.

Further, an analysis of the cylindrical deviations resulted after the manufacturing process, is measured across the specimens. A graphical analysis is represented in figure 3.

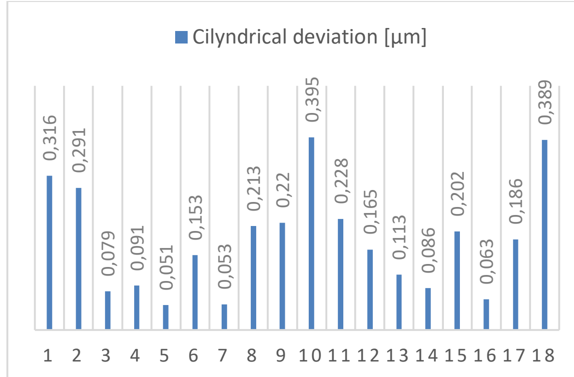

Fig. 3. Cylindrical deviation for each specimen

The analysis linking cylindrical (geometrical) deviations to specific manufacturing parameters revealed distinctive trends compared to the dimensional deviations discussed previously.

PETG emerged as the material with the most consistent and lowest cylindrical deviations, indicating its superior capability to retain accurate geometrical shapes during the printing process. Contrarywise, ABS exhibited considerable variability and higher maximum deviations, emphasizing the material's sensitivity to printing conditions and the necessity of precise parameter control.

Nozzle diameter significantly influenced cylindrical accuracy, with a 0.6 mm nozzle providing optimal precision and minimal deviations. Smaller nozzle diameters, such as 0.4 mm, resulted in higher variability and larger deviations, likely due to difficulties in maintaining consistent extrusion flow. The impact of printing speed within the tested range (60-120 mm/s) was relatively minor; however, higher speeds slightly reduced variability and improved consistency.

Regarding layer height, intermediate values (0.2 mm) provided a balance between print efficiency and cylindrical accuracy, producing the most stable outcomes. Extreme layer heights (0.1 mm and 0.3 mm) introduced higher variability, potentially due to increased challenges in maintaining uniform extrusion and stable cooling conditions.

Surface roughness measurements of the fabricated specimens are carried out using a MarSurf VD 140 with a BFW A 10-45-2 probe. Each specimen was measured three times to determine average values for Ra and Rz. The analysis revealed considerable variations in surface roughness, highlighting the significant impact of printing parameters. Specimens demonstrated average Ra values ranging from approximately 5.6 µm (Specimen 1, optimal surface finish) to over 22 µm (Specimen 12, poorest finish). Similarly, Rz values fluctuated significantly, with the lowest around 23 µm and the highest exceeding 94 µm. These variations indicate sensitivity primarily to layer height and material selection, with larger layer heights and specific materials resulting in notably increased roughness.

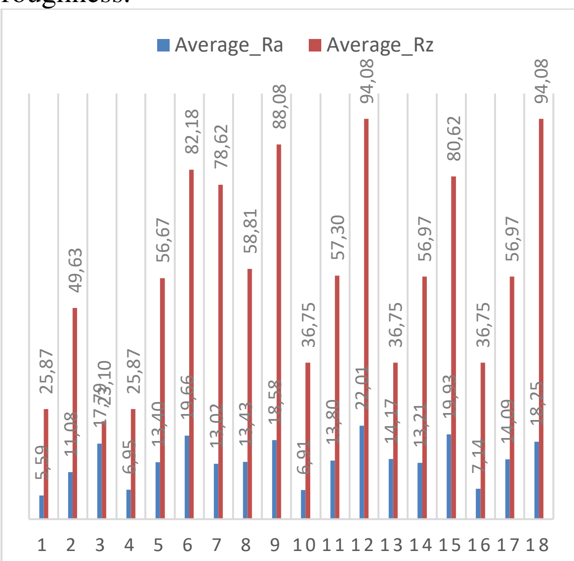

Fig. 4. Resulted roughness after fabrication for each specimen

3.2 Dimensional deviations after finishing process

Some specimens (Specimens 2, 5, 7, 12, and 13) could not be successfully machined during the turning process. This failure occurred due to the excessive clamping pressure exerted by the lathe chuck jaws, causing delamination and structural damage, rendering the specimens unusable for further machining.

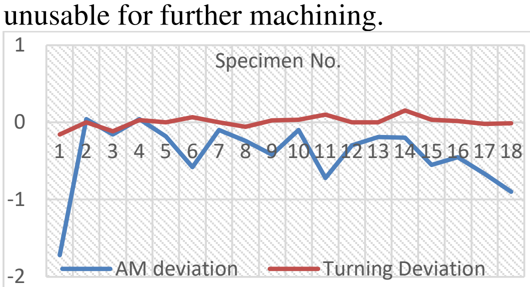

Fig. 5. Dimensional deviation resulted after specimen fabrication and lathe turning finishing process

As depicted in figure 5, for the specimens successfully machined, a comparative analysis of dimensional deviations before (after AM) and after the turning process revealed substantial improvements:

- Before turning, additive manufactured specimens displayed large deviations from the nominal diameter of 40 mm, ranging from slight oversizing (+0.04 mm, specimen 4) to significant undersizing (-1.72 mm, specimen 1).
- The turning process significantly improved dimensional accuracy for all machined specimens. For instance, Specimen 1 improved from an AM deviation of -1.72 mm to only -0.16 mm after turning. Similarly, Specimen 18 improved dramatically from -0.90 mm to just -0.015 mm.
- The turning operation consistently minimized deviations, highlighting its effectiveness as a finishing method. The final deviations after turning were mostly within ±0.1 mm, indicating excellent precision and reliability of the lathe finishing step.

3.3 Surface roughness analysis after turning

Surface roughness measurements were conducted precisely in the machined areas of the specimens to assess the effectiveness of the turning process. Each specimen was measured twice on the surfaces highlighted in figure 6, using a MarSurf VD 140 roughness meter equipped with a BFW A 10-45-2 probe to ensure high accuracy and repeatability of the results.

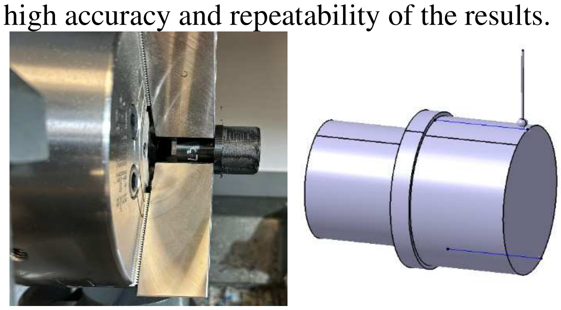

Fig. 6. Roughness measurement

To objectively evaluate the influence of manufacturing parameters on surface roughness, a Taguchi “smaller-is-better” analysis was conducted to determine the influence of turning parameters (spindle speed, feed rate, depth of cut) on surface roughness. The analysis results are presented in the following images.

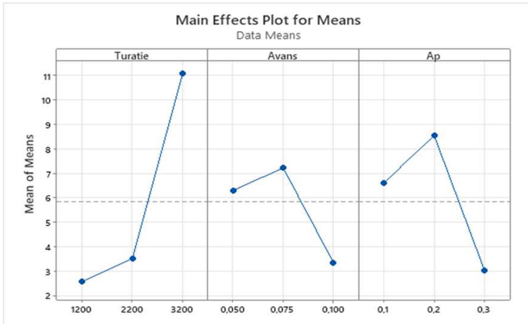

Fig. 7. Turning parameter’s influence on Ra[μm]

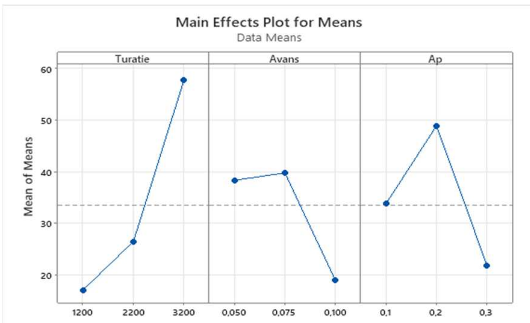

Fig. 8. Turning parameter’s influence on Rz[μm]

The Taguchi analysis identified spindle speed (RPM) as the most influential factor affecting both average roughness (Ra) and maximum height roughness (Rz). Contrary to common expectations that higher spindle speeds produce better surface finishes, the optimal results were achieved at a lower speed of 1200 RPM. This phenomenon is attributed to reduced heat generation at lower spindle speeds, which is crucial when machining plastic materials that are sensitive to elevated temperatures, as excessive heat can cause layer delamination or surface burning.

Depth of cut emerged as the second-most critical factor influencing surface roughness. An optimal depth of 0.3 mm was determined beneficial, as it effectively removes several printed layers in a single pass without applying excessive cutting forces. Nevertheless, it’s important to avoid selecting a depth of cut equal to the nozzle diameter, as doing so could result in tearing of layers rather than achieving a clean, smooth cut.

Lastly, feed rate showed the least influence among the analysed parameters. Interestingly, a relatively higher feed rate of 0.1 mm/rev provided superior roughness results. This improvement is likely due to the reduced contact time between tool and specimen, resulting in minimized vibrations and a more uniform distribution of cutting forces across the specimen surface.

Considering these observations, the recommended turning parameters for achieving optimal surface roughness include a spindle speed of 1200 RPM to minimize heat generation, a depth of cut of 0.3 mm to effectively remove material without excessive force, and a feed rate of 0.1 mm/rev to reduce contact time and prevent vibration-induced deterioration.

4. CONCLUSION

This research focused on improving the surface quality and dimensional accuracy of FDM-printed components through lathe turning finishing. Specimens were initially produced using various additive manufacturing parameters, followed by a systematic evaluation of the turning process using a structured Taguchi experimental approach. Key findings indicate:

The turning process substantially reduced dimensional deviations originally present in FDM-printed specimens. Specifically, turning minimized deviations from nominal dimensions from as high as 1.72 mm to within 0.16 mm, showcasing its effectiveness for precise final sizing of AM-produced parts.

Surface roughness was notably enhanced by the turning process. Analysis revealed that spindle speed was the most influential parameter affecting roughness (Ra, Rz). Despite conventional expectations advocating high spindle speeds, the optimal spindle speed determined was 1200 RPM due to reduced heat generation and prevention of layer delamination in plastic materials.

Depth of cut emerged as the second-most significant factor, with an optimal value identified as 0.3 mm. This depth effectively removes multiple additive layers simultaneously without exerting excessive cutting forces, thus maintaining structural integrity and surface quality. Caution is recommended to avoid matching the depth of cut with nozzle diameter, as it could lead to layer tearing rather than clean cutting.

Feed rate was found to have the least influence on surface roughness, although unexpectedly, a higher feed rate (0.1 mm/rev) provided superior surface finish results. Reduced tool-workpiece contact time and distributed cutting forces help minimize vibrations, positively influencing the surface finish.

In conclusion, lathe turning post-processing significantly enhances the quality of FDM-printed components. The optimal machining parameters—1200 RPM spindle speed, 0.3 mm depth of cut, and 0.1 mm/rev feed rate—ensure improved dimensional accuracy and superior surface finish. Future research should further explore the effects of specialized cooling fluids and investigate the influence of other machining strategies on various AM-produced thermoplastic materials.

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Fabricația hibridă: optimizarea parametrilor de finisare prin strunjire pentru îmbunătățirea calității suprafeței și a preciziei dimensionale a componentelor realizate prin fabricație aditivă FDM

Fabricarea aditivă (AM), în special tehnica FDM, câștigă teren în aplicațiile industriale datorită versatilității și rentabilității sale. Cu toate acestea, componentele produse de FDM prezintă adesea o precizie dimensională slabă, abateri geometrice și o calitate inferioară a suprafeței. Acest studiu investighează efectele finisării prin strunjire asupra îmbunătățirii acestor proprietăți. Folosind metodologia de experimente Taguchi, au fost analizați parametrii critici de fabricație care afectează acuratețea dimensională și rugozitatea suprafeței. Rezultatele demonstrează îmbunătățiri semnificative ale preciziei dimensionale și ale calității suprafeței după strunjire. Condițiile optime de finisare identificate includ o turație a arborelui principal de 1200 RPM, adâncimea de așchiere de 0,3 mm și viteza de avans de 0,1 mm/rot, oferind informații valoroase despre abordarea hibridă de finisare AM.

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