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Research Article

Investigation of Burr Formation and Circularity Error in Drilling of PLA Produced at Different Printing Temperatures with Machine Learning-Based Prediction

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ABSTRACT

In this study, it was aimed to investigate the effect of feed (0.1-0.15-0.2 mm/rev) and printing temperature (190-210-230°C) on the formation of burrs and circularity in the drilling of samples produced using polylactic acid (PLA) material with the fused deposition modelling (FDM) technique, which is an additive manufacturing (AM) method. In the results obtained, it was observed that the burr height increased with the increase of the feed in the drilling of the samples, and the burr height decreased with the increase of the printing temperature. The maximum burr height at the hole entrance was 0.32 mm (0.2 mm/rev, 190°C), while the maximum burr height at the hole exit was 0.37 mm (0.2 mm/rev, 190°C). The maximum circularity deviation at the hole entrance was 0.15 mm (0.2 mm/rev, 230°C) and the maximum circularity deviation at the hole exit was 0.1 mm (0.2 mm/rev, 190°C). In addition, prediction modelling for burr height and deviation from circularity was performed with an average success rate of R^2 94%.

Introduction

Additive manufacturing (AM) is an innovative manufacturing technology in which 3D models are built layer by layer [1,2] This technology enables the production of complex geometries and functional parts [3], [4]. Due to the flexible production processes it offers compared to traditional production methods, its use in various fields such as agriculture, biomedical, aerospace, automotive, defence industry is becoming widespread [1,5,6]. In AM technology, the FDM technique is the most popular in the production of polymer-based materials due to its low cost, minimum waste and ease of material replacement [1,3,7]. However this method is a complex process that involves many production parameters such as layer thickness, raster angle, fill density, print speed, fill pattern, raster width, build orientation, etc. [2,8]. Consequently, researchers have concentrated on the alterations in the mechanical characteristics of the final product resulting from varying manufacturing settings. The printing temperature is particularly significant among these characteristics. The literature has examined the impact of printing temperature on mechanical characteristics. Vo et al. (2019) investigated the effects of 3D printing temperature on the mechanical properties of polypropylene [9]. Martinez et al. (2023) reported the effects of machining parameters on the mechanical properties of 3D printed polyhydroxyalkanoate parts [10]. Ulkir et al. (2024) investigated the effects of printing temperature on mechanical properties in the production of Acrylonitrile Butadiene Styrene (ABS) material by additive manufacturing [11]. Lopez et al. (2024) reported the effects of nozzle temperature on mechanical properties in FDM technique [12]. Melo et al. (2024) included the effects of filament extrusion temperature on the mechanical properties of poly (butylene adipate-co-terephthalate) / poly (lactic acid) [13].

Conversely, subsequent to its fabrication via additive manufacturing, other processing steps are applied. These processes like as drilling and milling are necessary in the final assembly stages based on their specific applications. However, issues arise in the hole drilling process contingent upon the machining settings and the substance of the workpiece. One of these problems is the formation of burrs. The burr is a criteria for assessing the machinability of a material, resulting from plastic deformation along the edge of the workpiece during manufacturing operations [14,15]. In drilling, burrs are formed on both the entrance and exit side of the workpiece. Entrance burrs are formed by plastic flow, while exit burrs are formed by elongation of the material on the exit side of the workpiece [14]. Especially in the processing of polymer-based materials, comprehending the correlation between cutting parameters and surface deformation is challenging due to varying viscoelastic behavior [15]. Studies have been carried out in the literature on the burr formation that may occur when polymer-based materials are subjected to different cutting conditions; however, studies are limited. Sundaram et al (2014) concluded that feed has the highest effect on the formation of exit burrs [16]. Kadivar et al. (2012) reported that the burr height increases with both speed and feed in drilling with a conventional drill [17]. Saravanakumar et al. (2015) found that burr height is affected by both feed and drill diameter [18]. Thakre et al. (2016) found that an increase in feed by 100% increased the burr height by approximately 25-50% [19]. Paramanik and Basak (2024) investigated that feed has a strong effect on burr height and chip thickness at the exit of the workpiece [20]. Emir et al. (2024) investigated the burr formation in the drilling of PLA samples with different lattice structures and stated that the lattice structure is an effective parameter in burr formation [21].

When the literature studies are examined, the studies on the burr formation in hole drilling of FDM production parameters are insufficient. In this study, unlike the existing studies, it is aimed to investigate the burr formation and deviation from circularity in the drilling process of PLA samples produced by FDM technique at printing temperatures. For this reason, the samples produced at different printing temperatures were subjected to drilling operations at three different feeds. For each hole, microscope images were taken at both entrance and exit regions and the burr heights and deviation from circularity were measured. In addition, a prediction model was developed by machine learning method using the original measured values.

Material and Method

Fabrication of drilling specimen

Drilling test specimens were produced using FDM technique with Creality Ender V3 SE model 3D printer (Fig. 1a). The device has a print volume of 220 x 220 x 230 mm, a filament diameter of 1.75 mm, a layer thickness of at least 20 microns and a maximum print speed of 24 mm^3/sec. Nine specimens were fabricated at three distinct printing temperatures (190°C, 210°C, and 230°C) with a constant scan angle of 0° to examine burr creation and deviations from circularity during the drilling process (Fig. 1b).

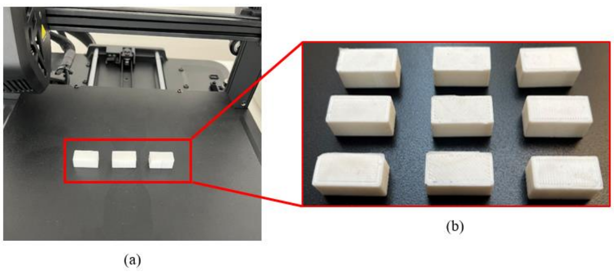


Figure 1. a) Production of test specimens, b) drilling test sample

Drilling test

Drilling operations were carried out on a Chevalier QP2040-L CNC vertical machining machine. The experiments were carried out under dry machining conditions using a Φ5 mm diameter HSS cutting tool produced at different printing temperatures and at different feeds given in Table. 1. For the precision of the experimental results, a different HSS drill was used for each hole due to the chip plastering and chip entanglement problems encountered in PLA drilling. Fig. 2 shows the hole images after drilling process.

Table 1. Drilling test parameters.

Feed (mm/rev)	Printing temperature (°C)	Spindle (rpm)
0.1 - 0.15 - 0.2	190 - 210 - 230	1500

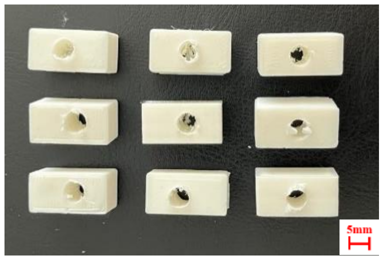


Figure 2. Drilling test.

Burr height and circularity error measurement

For each hole, measurements were taken from both the hole entrance and the hole exit. In addition, for the accuracy of the imaging, the average was calculated over the profile images of the part from four directions (Fig. 3). The burr height was measured with a Euromax brand streo microscope. Burr height was calculated as given in Equation (1) by subtracting the average value (h_2) from the nominal value (h_1). The deviation from circularity during drilling was measured at all hole entrances and exits. For measurement accuracy, each hole was divided into eight equal parts and the hole diameter values were determined. The equations given in Equation (2) and Equation (3) were used to calculate the deviation values.

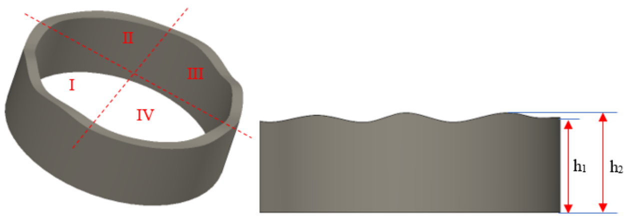


Figure 3. Burr height measurement zones.

$$\text{Burr height} = h_2\text{-}h_1 \qquad (1)$$

$$\text{Average dim.} = \frac{\sum Hole\ diameter}{Number\ of\ measurements} \tag{2}$$

$$\text{Deviation value} = |\text{Nom. dim-Avr. dim.}| \tag{3}$$

Machine learning

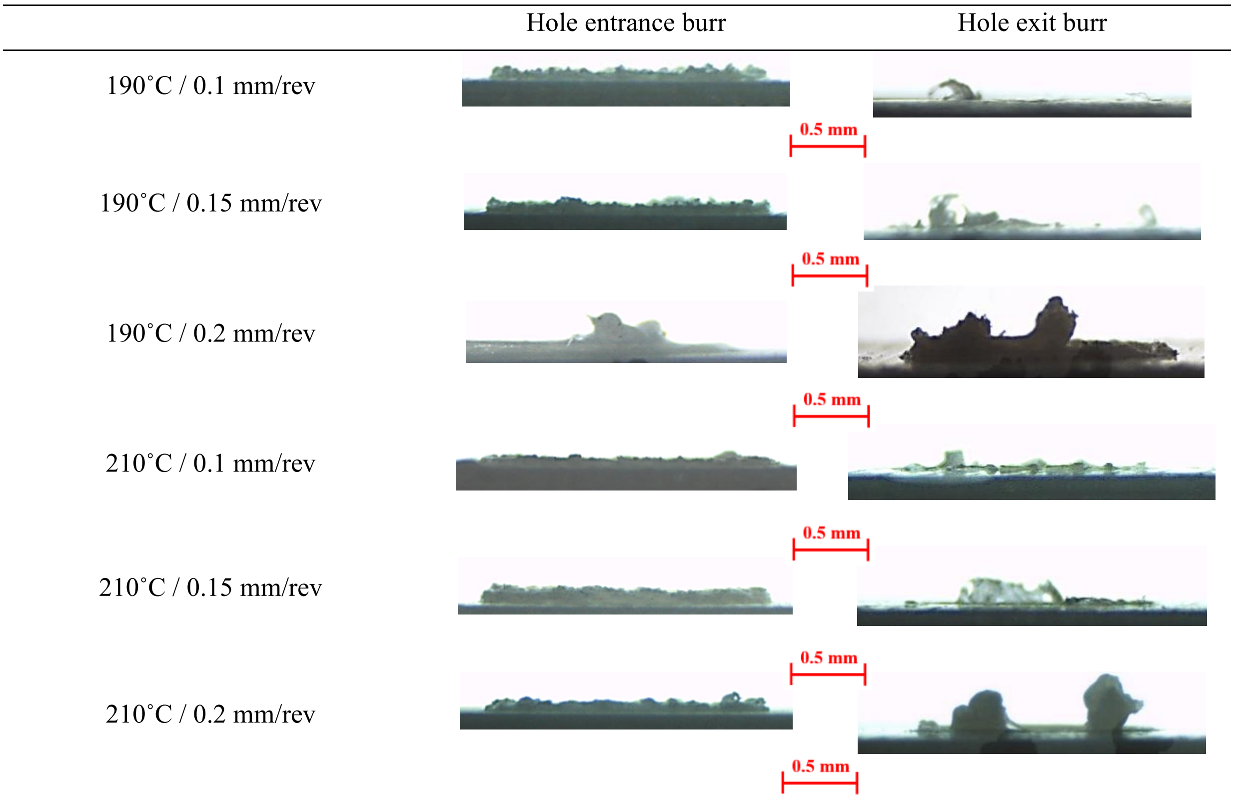
The study employed a machine learning approach to produce predictions based on the original data acquired from the experiments. The research favored this approach due to its efficacy in concurrently evaluating quantitative and qualitative data sets. This strategy is effective and readily adaptable for multivariate prediction models, particularly in natural nonlinear modeling tools. By concentrating on the paramount factors and disregarding the less significant ones, the approach diminishes the size of the forecasting dataset while enhancing both forecasting efficacy and velocity. The model was utilized to forecast the target variable. The anticipated value, error rate, and model performance (R^2) values were acquired.

Results and Discussion

Effect of feed on burr formation

Fig. 4 shows the burr images generated at the entrance and exit of the hole due to drilling PLA samples produced at various printing temperatures and feed. In the images obtained, it was observed that the burr formation at the hole entrance increased with the increase in feed and decreased with the increase in printing temperature. At high feeds, the cutting tool pushes the material instead of cutting it, making it difficult to cut at an adequate rate [22,23]. Consequently, insufficient chip removal arises from suboptimal cutting conditions on the PLA sample, leading to an increased production of burrs. In addition, with the increase in feed, the temperature increase due to the increase in friction is effective in the formation of burrs at the hole entrance. Melting occurs especially in drilling operations due to the low melting temperatures of polymer-based materials and therefore being sensitive to temperature. The microscope pictures captured at the entrance of the hole, as seen in Fig. 5a, were obtained subsequent to the drilling operations. A certain degree of melting buildup and burr creation at the hole's edge was proven to occur, contingent upon the feed following the initial contact of the cutting tool with the material. As a result of melting, the cutting tool could not cut in the desired way, resulting in an increase in burr formation.

When the burr formation at the exit of the hole was examined, a more pronounced formation was observed compared to the hole entrance. Fig. 5b shows the microscope images taken from the holes produced at 230°C printing temperature and drilled at different feed. In the images, the effect of feed on the burrs occurring at the exit of the hole is more evident. In the cutting process, the material weakens as it approaches the end of the drilling depth due to the increase in feed. Due to the rapid pushing of the material, it was observed that the material was torn or broken at the exit edges before the cutting process was completed (Fig. 5b). This resulted in larger and irregular burrs at the exit of the hole than at the entrance of the hole. In addition, a higher feed will increase plastic deformation due to the increased thrust force [16]. As a result, the optimum cutting process was obtained at a lower feed.



230˚C / 0.1 mm/rev

230˚C / 0.15 mm/rev

230˚C / 0.2 mm/rev

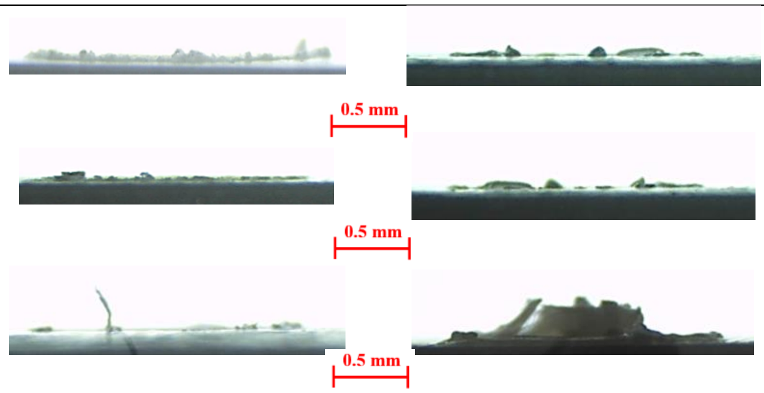


Figure 4. Burr images taken from the hole entrance and exit after drilling.

Feed (mm/rev) 0.1 0.15 0.2

(a) Hole entrance

(b) Hole exit

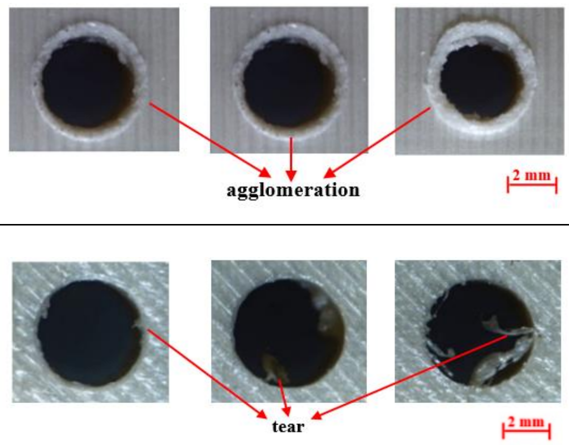


Figure 5. Produced at 230°C printing temperature a) hole entrance, b) hole exit images of PLA samples.

Effect of printing temperature on burr formation

With the increase in printing temperature, burr formation decreased. Especially with the increase in printing temperature, the viscosity of PLA decreases and provides a more stable layer bonding during printing compared to low printing temperatures [13,24]. If the printing temperature is low, it causes poor bonding properties in the previous laid layer and between the layers arranged side by side and loss of internal structure [24-27]. For this reason, the polymer material produced at low printing temperature (190°C) has a harder and fragile structure and causes burrs to remain on unevenly cut parts during drilling. At 0.1 mm/rev feed, microscope images taken from the hole entrance and exit of the samples produced at different printing temperatures are given in Fig. 6. It was noted that when the printing temperature increased, irregular forms such as melting aggregation at the hole entry and cutting at the hole exit happened less frequently. Consequently, elevated temperatures provide superior adhesion between layers, resulting in a more efficient drilling operation with fewer burrs compared to lower printing temperatures.

Effect of production and machining parameters on burr height

Fig. 7a and Fig. 7b shows the results of burr height measurements taken from PLA samples produced at different printing temperatures and drilled at different feed. The results showed that the burr height increased with the increase in feed and decreased with the increase in printing temperature. The increase in feed increases the cutting force for both hole entry and hole exit [22,28]. The sudden increase in temperature, along with the increased force at the hole entrance, resulted in the melting of PLA and the formation of deposits in the form of agglomeration near the hole's borders (Fig. 5a, Fig. 6a). In the drill exit area along the hole line, it was noted that interlayer adhesion, influenced by the printing temperature and the volume of material removed, resulted in tears at the hole exit and the formation of burrs (Fig. 5b, Fig. 6b). The maximum burr height measured for hole entrance was 0.32 mm at 0.2 mm/rev feed and 190°C printing temperature, while the minimum burr height was 0.168 mm at 0.1 mm/rev feed and 230°C printing temperature. The maximum burr height at the hole exit was 0.377 mm at a feed of 0.2 mm/rev and a printing temperature of 190°C, while the minimum burr height was 0.285 mm at a feed of 0.1 mm/rev and a printing temperature of 230°C.

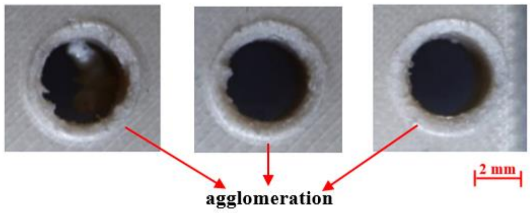
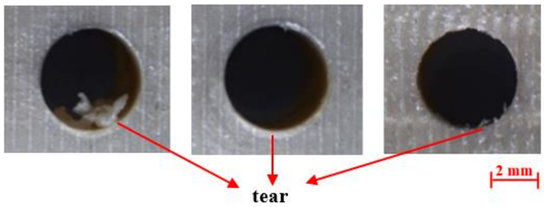
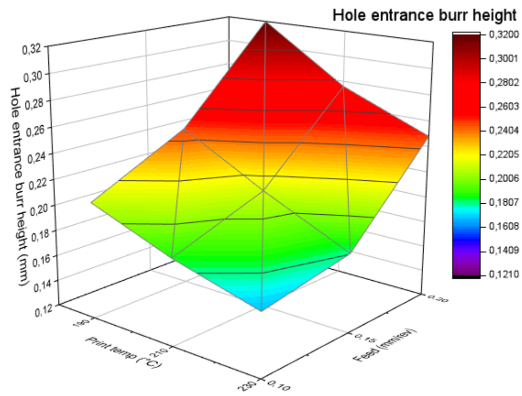
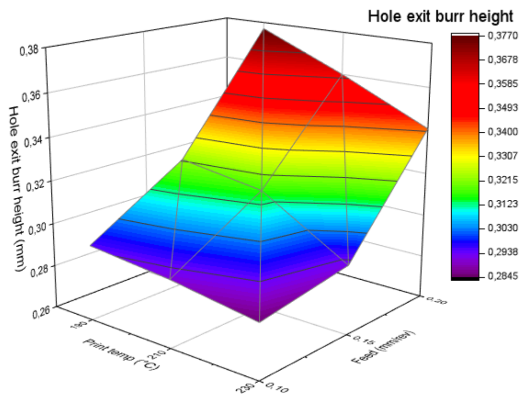
	Printing temp.	190°C	210°C	230°C
(a)	Hole entrance			
(b)	Hole exit			

Figure 6. Produced at 0.1 mm/rev feed a) hole entrance, b) hole exit images of PLA samples.



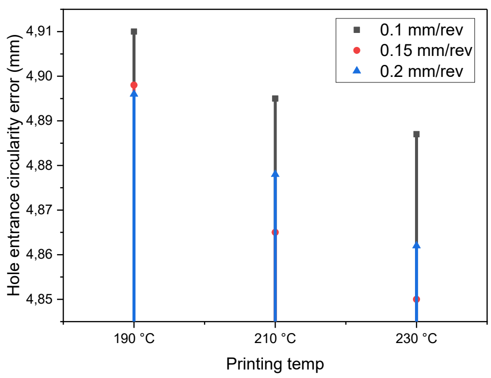
(a)



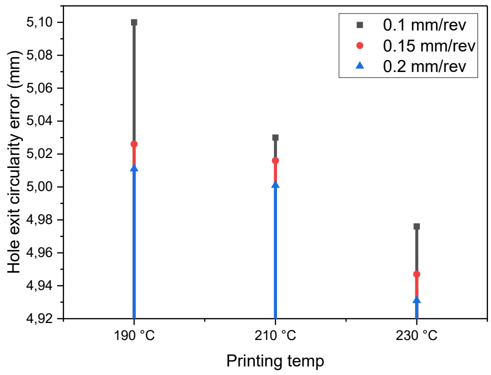
(b)

Figure 7. Burr height measurement results; a) hole entrance, b) hole exit.

Fig. 8a and Fig. 8b shows the results of the circularity measurements taken from both entrance and exit regions for each hole. It is seen that the deviation from the circularity at the entrance and exit of the hole increases with the increase in feed. The increase in feed prevents the chip removability from being at the desired level. This situation prevents the increase in the chips to be removed per unit time and the cutting tool from removing homogeneous chips by making an irregular feed [21]. On the other hand, it is seen that the amount of deviation from circularity decreases with increasing printing temperature. Increased interlayer bonding and lower brittleness with higher stamping temperature provide a more stable cutting environment during chip removal. Thus, since the cutting zone becomes more regular, the cutting tool pierces close to the desired shape instead of pushing the material. In the regularized cutting zone, the cutting tool performs the cutting process with less force during chip removal.



(a)



(b)

Figure 8. Circularity deviation measurement results; a) hole entrance, b) hole exit.

Machine learning results

Machine learning prediction results of burr height and circularity values are given in Table. 2 and Table. 3. R^2 values were calculated as 94% (6% error rate) on average in the experiments performed for the prediction results. In the results obtained, both the experimentally calculated values and the machine learning prediction model gave results proportional to each other.

Fig. 9 and Fig. 10 show the deviations of the burr height and circularity predicted using the machine learning method from the values obtained from the experimental study. It was seen that the deviation amounts were consistent between the values obtained from both the hole entrance and the hole exit and the values predicted by machine learning. While a maximum deviation of 8% was calculated for the burr height at the hole entrance (Fig. 9a), a maximum deviation of 6.78% was calculated at the hole exit (Fig. 9b). In the circularity measurement, a maximum deviation of 0.37% was calculated between the experimental data and the prediction data in the hole entrance diameter (Fig. 10a), while it was calculated as 1.54% at the hole exit (Fig. 10b).

Table 2. Machine learning burr height prediction results.

No	Feed (mm/rev)	Printing temp (°C)	Hole burr height (mm)			
			Entrance	R^2	Exit	R^2
1	0.1	190	0.21407	0.95822	0.29202	0.93763
2	0.1	210	0.19586	0.94988	0.29017	0.94986
3	0.1	230	0.17492	0.93873	0.28141	0.94909
4	0.15	190	0.24045	0.94914	0.32456	0.93876
5	0.15	210	0.21896	0.94911	0.32164	0.95871
6	0.15	230	0.1956	0.94988	0.31182	0.95907
7	0.2	190	0.29684	0.95817	0.36443	0.94975
8	0.2	210	0.27598	0.94091	0.35541	0.93765
9	0.2	230	0.25354	0.94761	0.34137	0.94415

Table 3. Machine learning circularity estimation results.

No	Feed (mm/rev)	Printing temp (°C)	Hole circularity (mm)			
			Entrance	R^2	Exit	R^2
1	0.1	190	4.90337	0.95265	5.018	0.93473
2	0.1	210	4.88285	0.94034	5.01207	0.94256
3	0.1	230	4.87888	0.93686	4.9787	0.94364
4	0.15	190	4.89664	0.94239	5.03303	0.93796
5	0.15	210	4.87586	0.94754	5.02096	0.95564
6	0.15	230	4.86805	0.94796	4.97428	0.95269
7	0.2	190	4.89631	0.95935	5.06864	0.94984
8	0.2	210	4.87248	0.94259	5.03953	0.93765
9	0.2	230	4.86821	0.94236	5.007	0.94347

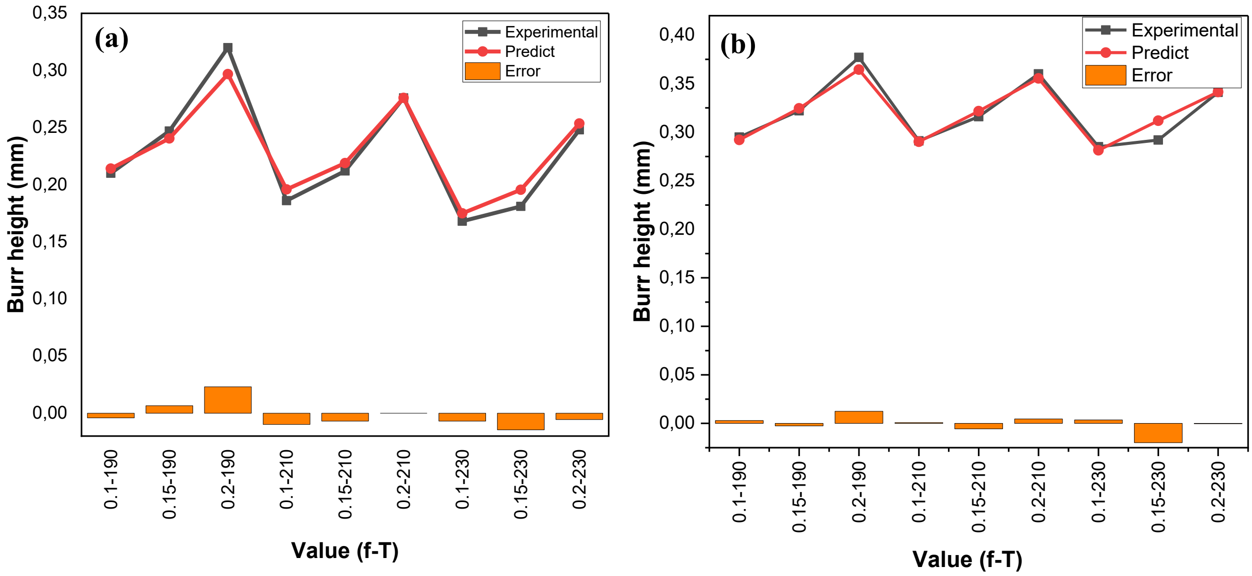


Figure 9. Circularity deviation measurement results; a) hole entrance, b) hole exit.

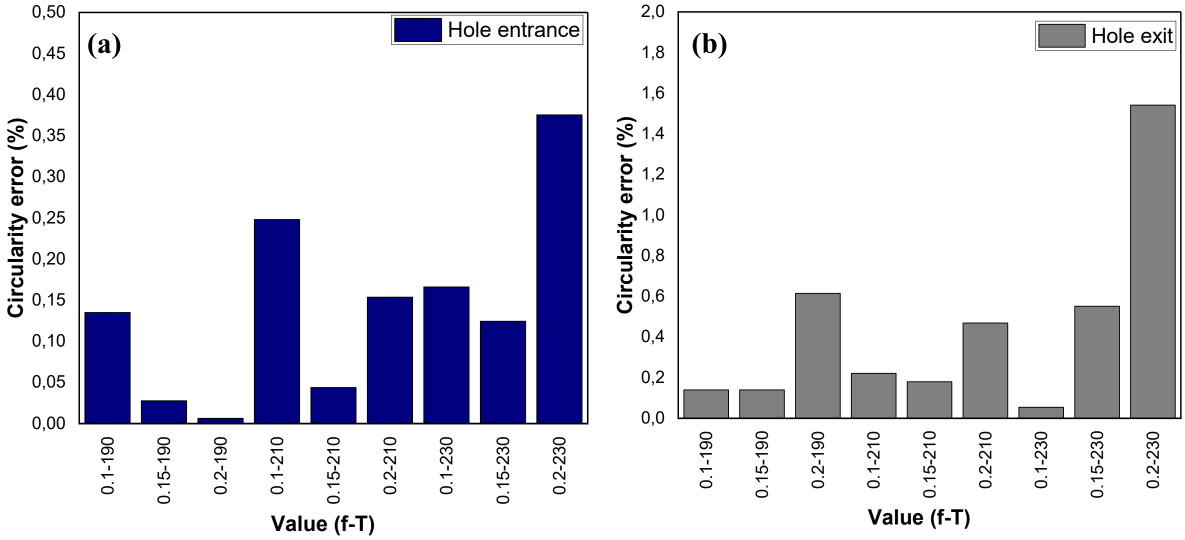


Figure 10. Circularity deviation measurement results; a) hole entrance, b) hole exit.

Conclusions

This work examined the correlation between burr development and deviations from circularity due to drilling operations at varying feeds of PLA samples generated at different printing temperatures using the FDM process, and a predictive model was developed utilizing machine learning methods. In this perspective, the data acquired from drilling experiments can be enumerated as follows:

1. During hole drilling operations, it was noted that the quantity and height of burrs generated due to enhanced interlayer bonding from elevated printing temperatures were significantly reduced compared to those at lower printing temperatures.

2. As the feed increases, the volume of chips removed per unit time also rises, resulting in an observable increase in burr height owing to chip removal occurring by pushing rather than cutting. Burr formation was identified as material accumulation at the hole entry and material extension at the hole exit. Consequently, the burr height at the hole exit was recorded as greater than that at the hole entry.

3. As a result of the increase in feed, the amount of chips removed per unit time increases and it becomes difficult to realise homogeneous cutting process. Therefore, deviation from circularity increases. By increasing the printing temperature, good bonding between the layers is achieved and brittleness is reduced. This decreased the deviation from circularity.

4. The success of the prediction method prepared with the machine learning method is around 94% on average. In addition, it was observed that there was a low deviation between the experimental data and the data obtained with

the prediction model. In this respect, the machine learning model provides effective prediction results.

The results show that printing temperature and feed have significant effects on burr formation and circularity in the production and perforation of PLA. Controlling these parameters to minimise defects would make both AM production and post-production post-processing more efficient. This study will be important for future studies on the drilling of PLA in a wider range of AM production parameters and drilling parameters, as well as for future studies by applying different processing techniques and different production materials.

Interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

Ender Emir: Conceptualization, Acquisition of data, Methodology, Supervision, Validation, Writing

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