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Research Article

Investigation of Delamination in the Drilling of PLA Specimens with Different Lattice Structures

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Abstract: Aim of this study examines the impact of processing parameters and lattice structures on delamination during the drilling of cylinder PLA (Polylactic acid) parts. The parts were designed with four different lattice structures (gyroid, I-WP, nevoius, and diamond) and produced using a 3D printer. A 5 mm HSS drill was used to drill from the center point. After drilling, images of the entrance and exit holes were captured using a digital microscope. The delamination, burr, and circularity around the hole were analyzed. The results showed that the Gyroid and I-WP lattice structures had the lowest delamination at the entrance and exit holes. No burr was observed at the entrance of the specimens. The Nevoius lattice structure exhibited the lowest burr value at the hole exit and entrance, as well as the lowest exit circularity deviation. Among the samples, the highest delamination was observed at the hole entrance in I-WP (0.5601), while the lowest delamination was observed in Gyroid (0.5423). At the hole exit, the highest delamination was observed in Gyroid (0.6229), and the lowest delamination was observed in I-WP (0.5426).

Farklı Kafes Yapılarına Sahip PLA Numunelerin Delinmesinde Delaminasyonun İncelenmesi

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Anahtar Kelimeler
Delaminasyon,
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Kafes yapıları,
PLA

Öz: Bu çalışmanın amacı, kafes yapıların delinmesinde işleme parametrelerinin ve farklı kafes yapılarının delaminasyon üzerindeki etkilerinin araştırılmasıdır. Bu kapsamda dört farklı (gyroid, I-WP, nevoius ve elmas) kafes yapısında tasarlanan silindir PLA (Polilaktik asit) parçalar 3D yazıcıda üretilmiş ve 5 mm HSS matkap ile merkez noktadan delinmiştir. Delme işleminden sonra dijital mikroskop ile giriş ve çıkış delik görüntüleri alınmış ve delik çevresinde delaminasyon, çapak ve dairesellik analizleri yapılmıştır. Elde edilen sonuçlara göre deliğin girişinde en düşük delaminasyon Gyroid ve çıkışında I-WP kafes yapısında ölçülmüştür. Numunelerin delik girişinde çapak oluşmamıştır. Delik çıkışında çapak, giriş ve çıkış dairesellik sapması açısından en düşük değere sahip numunenin Nevoius kafes yapısı olduğu görülmektedir. Delik girişinde en yüksek delaminasyon I-WP'de (0.5601), en düşük delaminasyon ise Gyroid'de (0.5423) gözlemlenmiştir. Delik çıkışında en yüksek delaminasyon Gyroid (0.6229) numunesinde, en düşük delaminasyon ise I-WP (0.5426) numunesinde gözlemlenmiştir.

1. Introduction

PLA is a thermoplastic raw material with biodegradable and environmentally friendly properties (Tümer & Erbil, 2021). PLA is widely used in orthopedic implants, tissue engineering, textiles, automotive (Üner & Koçak, 2012; Yelten et al., 2022). In particular, PLA produces 3D models using the fused deposition modeling (FDM) additive manufacturing technique (Baraheni et al., 2021). However, additional joining processes, such as hole drilling and riveting, are required in PLA production. Depending on the machining parameters in drilling, the cutting forces negatively affect the surface and hole quality. Especially in the hole drilling process, delamination is one of the frequently encountered problems. The resulting delamination affects the tolerance in the joints after the drilling process (Domingo et al., 2015). In addition, due to the low thermal conductivity of PLA, which has a relatively low melting temperature, the heat generated during drilling remains on the surface and these areas melt and deform easily under heat (Boy, 2022). Decreased hole quality and clogging of the drill helix channels can result from the use of PLA, which is a brittle material that tends to crack during the drilling process. To avoid potential issues, it is imperative to optimize machining parameters such as cutting speed, speed, and feed rate. Studies have been carried out to optimize the drilling process of PLA and similar thermoplastic materials, as evidenced by the literature. Table 1 displays the studies on delamination and hole quality during the drilling of different polymer-based materials.

Table 1. Literature studies

Material	**Machining type**	**Machining parameters**		**Result**	**Reference**
polypropylene	Drilling	n (r/min) 4750 5562.5 6375 7187.5 8000	f (mm/min) 2500 3125 3750 4375 5000	A higher spindle and increased feed rate lead to higher roughness.	(Dhokia et al., 2008)
polyethylene	Drilling	Vc (m/min) 30 40 50	f (mm/rev) 0.006 0.0125 0.025	Less deformation and fewer burrs occur at high feed rate and low cutting speed.	(Altan & Altan, 2014)
polyamide polyether ether ketone polytetrafluoroethylene	Drilling	n (rpm) 6000 7000 8000	f (mm/min) 300 400 500	Maximum delamination factor occurred at 7000 rpm and 400 mm/min feed rate; minimum delamination occurred at 6000 rpm and 300 mm/min feed rate.	(Domingo et al., 2015)
carbon/polyimide carbon/polyether ether ketone	Drilling	Vc (m/min) 15 35 55 75	f (mm/rev) 0.02 0.04 0.06 0.08	Higher drilling forces resulted in more significant delamination and excessive tool wear.	(Xu et al., 2020)

Table 1. Literature studies (continued)

Material	Machining type	Machining parameters		Result	Reference
		Vc (mm/min)	f (mm/min)		
PLA	Drilling	165	1000	The best hole quality occurred at a feed rate of 1200 mm/min and a spindle speed of 600 rpm.	(Dezaki et al., 2020)
		Vc (m/min)	f (mm/rev)		
polyether ether ketone	Drilling	40 80 120	0.1 0.15 0.2	The lowest delamination was observed at a cutting speed of 120 m/min and a feed rate of 0.1 mm/rev. The highest delamination occurred at a cutting speed of 40 m/min and a feed rate of 0.2 mm/rev.	(Boy, 2022)

When the literature was examined, it was seen that there are a limited number of studies on drilling on PLA. The majority of studies have focused on the impact of feed rate and rotational speed parameters when drilling PLA plates. However, there is a gap in the literature regarding the drilling of lattice-structured specimens. Unlike the literature, the delamination that occurs when drilling different lattice structures produced with the additive manufacturing (AM) technique instead of flat PLA plates was examined. Lattice structures produced by AM are gaining popularity in various industrial fields, including biomedical, aviation, space, and defense industries. As the usage of lattice structures increases, post-production assembly operations require final machining. The most commonly used process for creating holes is hole drilling. However, during drilling operations, delamination can occur, which negatively affects the quality and durability of the assembly. Therefore, it is necessary to investigate the formation of delamination during the hole drilling process after producing lattice structures. In this study, PLA samples with four different lattice structures were produced using a 3D printer, and a drilling process was applied. Delamination, burrs, and circularity deviations were measured by taking images from the entrance and exit of the holes. The obtained results are discussed.

2. Material and Methods

2.1. Material

In this study, PLA was used as the production material. PLA was preferred because it has the characteristics of being easy to print and durable, which are widely used in 3D printers. The thermal and mechanical properties of PLA material are given in Table 2.

Table 2. Thermal and mechanical properties of PLA (Corneillie & Smet, 2015)

Properties	Value
Modulus of elasticity (MPa)	3500-4150
Tensile strength (MPa)	50-70
Elongation (%)	4-7
Melting point (°C)	150-170
Deformation temperature (°C)	55
Glass transition temperature (°C)	55-60

2.2. Design and production of lattice structures

Cylinder specimens with a height of 30 mm and a diameter of 20 mm were used in the experiments. The internal structure of the specimens was designed in four different lattice structures: gyroid, I-WP, nevoius and diamond. The lattice structures were designed using MSLattice software and CAD models were created (Figure 1). G codes of the designed models were created and production was carried out with the Ultimaker Extend 3 3D printer (Figure 2). Finally, drilling test specimens were obtained (Figure 3).

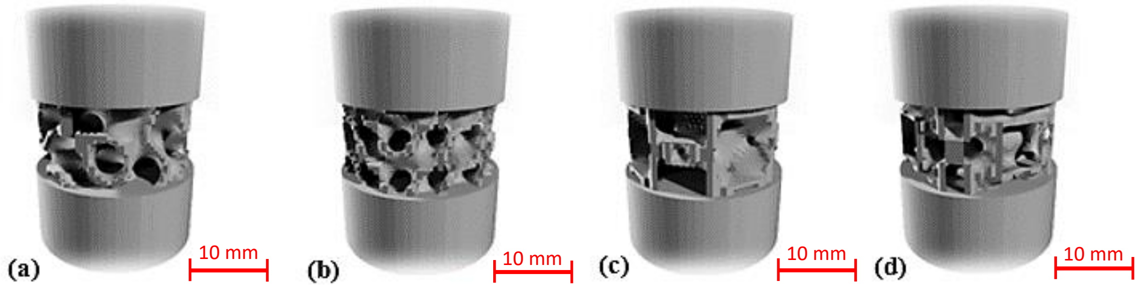

Figure 1. CAD models of lattice structures; (a) gyroid, (b) I-WP, (c) nevoius, (d) diamond.

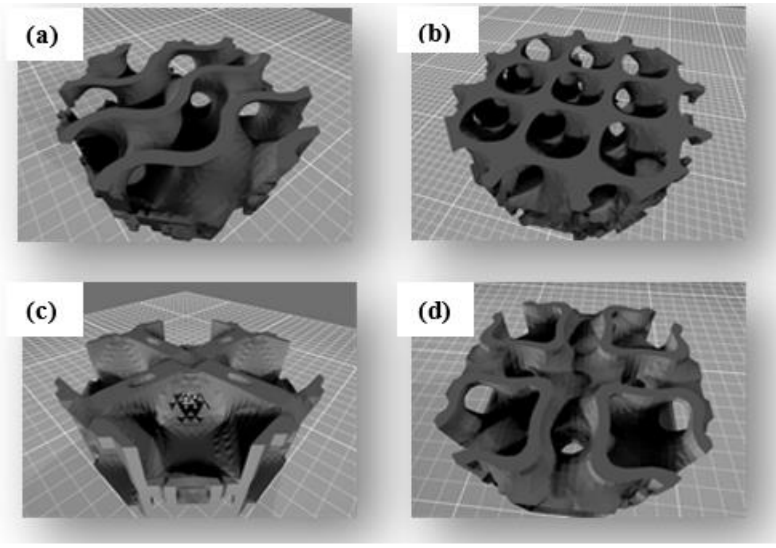

Figure 2. Lattice structure images of the samples; (a) gyroid, (b) I-WP, (c) nevoius, (d) diamond.

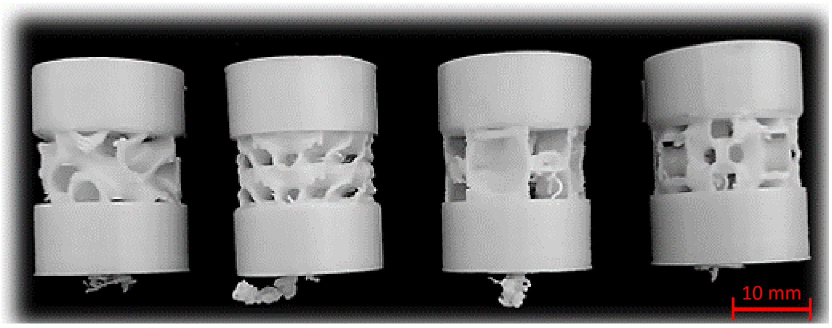

Figure 3. Drilling test specimens.

2.3. Drilling process

The drilling process was carried out using a 5 mm diameter HSS drill bit with a feed rate of 0.1 mm/rev and a speed of 4500 rpm. Drilling parameters were chosen similar to those in studies on drilling PLA materials in the literature. The drilling process was carried out in Brother Speedio S500X1 brand (Türkiye/Malatya) CNC vertical machining center. Microscope images were taken from the drilled specimens and the effect of the lattice structure design on the hole quality was analyzed. The schematic representation of the drilling process is given in Figure 4.

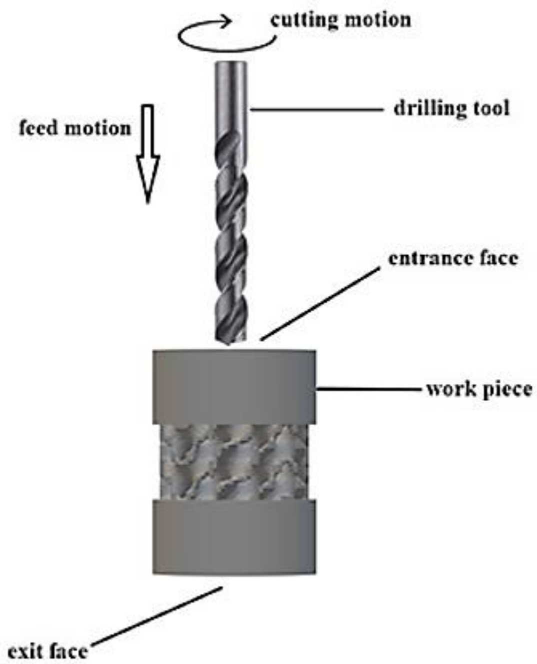

Figure 4. Schematic representation of the drilling process.

2.4. Calculation of the delamination factor

Delamination is calculated by the ratio of the rupture and deformation area the tool creates as it enters and exits the material. In this study, the delamination factor (F_d) was calculated by the ratio of (A_{del}) to the hole area (A_0) (Figure 5) (Equation 1) (Ozdemir et al., 2023). Hole images were taken with a Euromax Stereo Microscope.

$$F_d = \frac{A_{del}}{A_0} \tag{1}$$

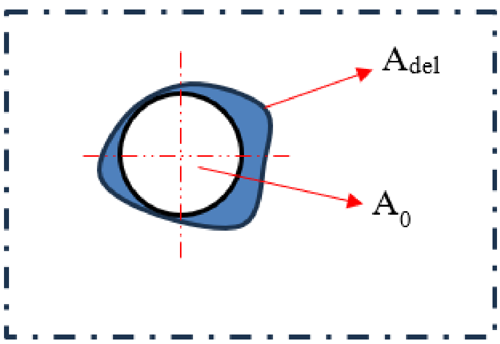

Figure 5. Delamination and hole area.

2.5. Calculation of the burr height measurement

The burr height resulting from the drilling process was measured using images taken from the Dino-Lite digital microscope. Measurements were taken at the entrance and exit of the hole and averaged over the profile images of the part from four directions (see Figure 6) (Bahçe & Özdemir, 2021).

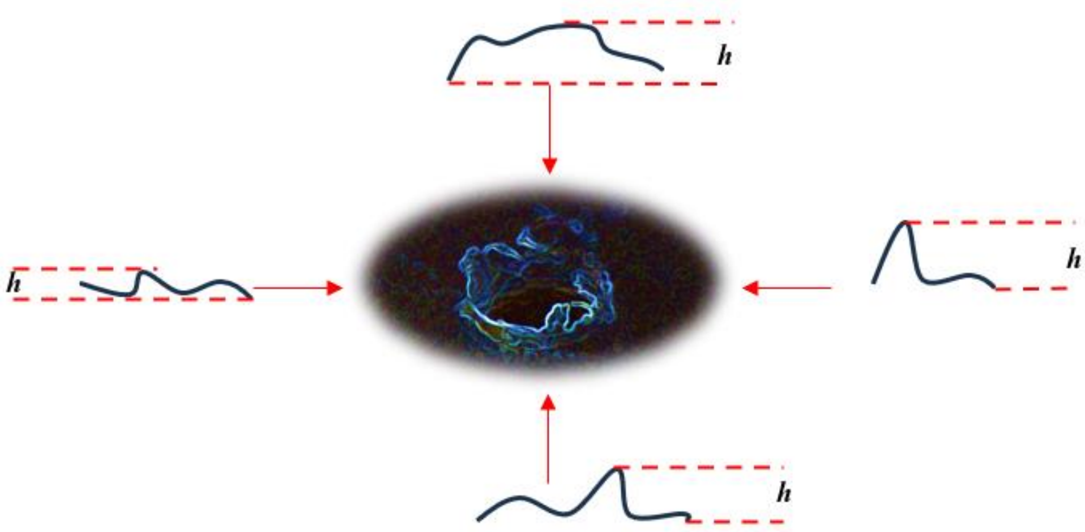

Figure 6. Burr height measurement.

2.6. Calculation of the hole circularity change

In the drilling process, heat is released due to the drill contacting the part at high speed. For this reason, parts made of PLA material may be subjected to distortion and melting due to excessive heat (Figure 7). This situation affects the circularity of the holes (Sato et al., 2017). Images were taken with a Dino-Lite digital microscope to measure the circularity at the entrance and exit of the holes. The transverse (D_w) and longitudinal (D_h) diameters of the holes were measured, and the sum of the ratio of the absolute difference between the required diameter (D_0) and the diameter was calculated as the circularity deviation (D_{def}) (Equation 2).

$$D_{def} = \frac{|D_w - D_0|}{D_0} + \frac{|D_h - D_0|}{D_0} \tag{2}$$

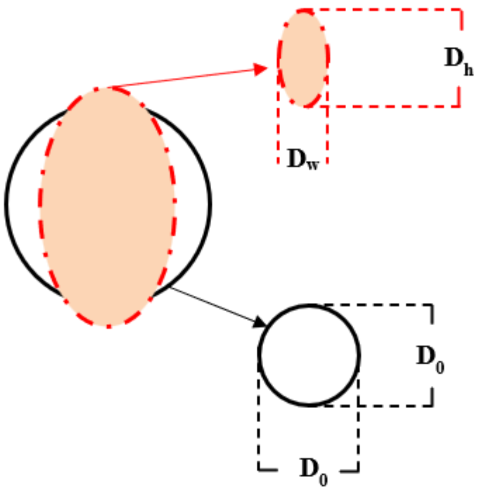

Figure 7. Hole circularity change.

3. Results and Discussion

The study analyzed the effects of lattice structure design on hole quality by performing drilling on specimens with four different designs: gyroid, I-WP, nevoius, and diamond. Delamination and burr heights around the hole were measured, and the circularity at the entrance and exit of the hole was calculated. The results are presented in Table 3.

Table 3. Experiment measurement results

	Delamination	
Lattice structure	**Entrance**	**Exit**
Gyroid	0.5423	0.6229
I-WP	0.5601	0.5426
Nevoius	0.5578	0.5453
Dimond	0.5433	0.5765
	Burr	
Lattice structure	**Entrance**	**Exit**
Gyroid	0	2.934
I-WP	0	0.154
Nevoius	0	0
Dimond	0	1.821
	Circularity	
Lattice structure	**Entrance**	**Exit**
Gyroid	0.1923	0.1453
I-WP	0.2094	0.2521
Nevoius	0.1838	0.1068
Dimond	0.2051	0.2308

*Units mm.

3.1. Effect of lattice structure design on delamination

When the test specimens are analyzed, it is seen that the entrance and exit delamination values show different courses (Table 3). Entrance delamination was least in the Gyroid (0.5423) and most in the I-WP (0.5601) structure (Figure 8).

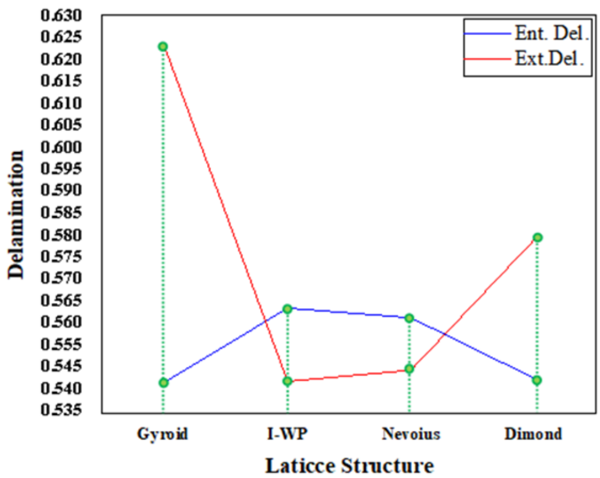

Figure 8. Hole entrance and exit delamination variation.

The Gyroid, nevoius, diamond lattice structures, and hole entrance exhibit slight delamination. In the I-WP lattice structure, the delamination area spreads over a wider region (see

Figure 9). The delamination at the hole entrance, caused by the initial impact of the drill against the part without cutting, is primarily due to the material absorbing the thrust force (Madhan Kumar & Jayakumar, 2022). Although all specimens were soft due to their plasticity, it can be concluded that the I-WP lattice structure behaves more rigidly and causes entry delamination. Deformations were independent of the central hole body, and burr extensions were not considered when calculating the delamination.

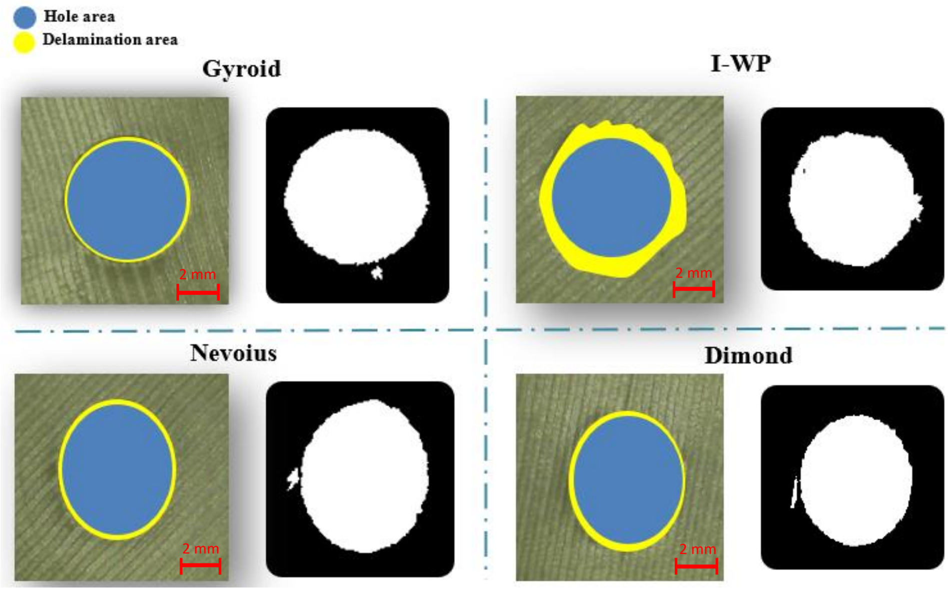

Figure 9. Hole entry delamination regions.

The delamination observed at the hole exit regions of the specimens is higher than at the entrance. The lattice structure with the highest delamination at the hole exit was Gyroid (0.6229), while the lowest was I-WP (0.5426). Figure 10 displays the delamination zones at the hole exit. Delamination at the hole exit is typically caused by chip accumulation, temperature, and sudden force changes that reduce the drill's cutting ability. Deformation occurs around the hole as a result of the drill breaking off the chip without cutting (Usta et al., 2022).

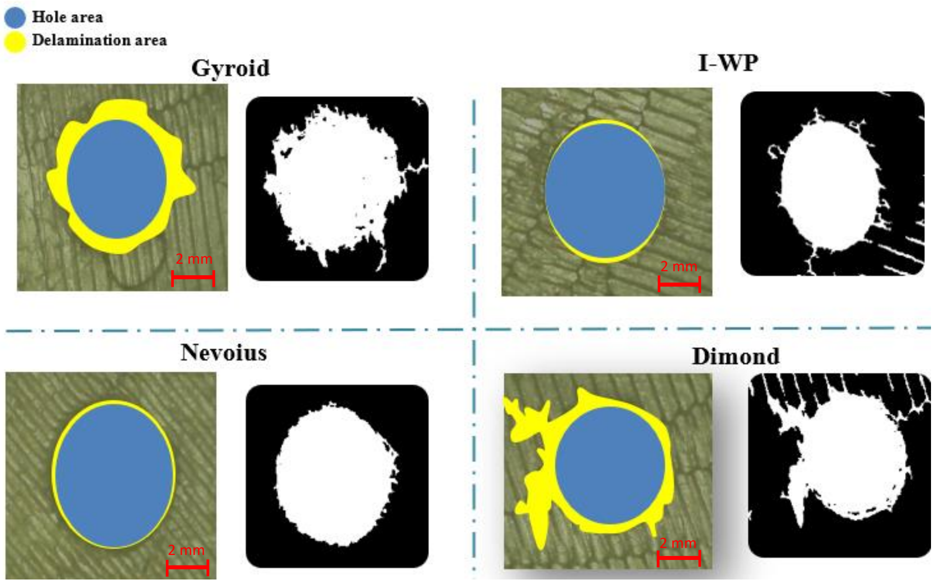

Figure 10. Hole exit delamination regions.

3.2. Effect of lattice structure design on burr size

The formation of burrs in the drilling process occurs as a result of the machining parameters (feed, speed) combined with the material properties of the workpiece and affecting the chip removal ability (Altan & Altan, 2014; Bahçe & Özdemir, 2019). In Figure 11, no burrs were observed at the entrance of the holes in all specimens. Additionally, the Nevoius lattice structure specimen showed no burrs at the exit of the holes. When considering the low delamination at the entrance and exit of this lattice structure, it is evident that the chip removal process is of higher quality than the other samples.

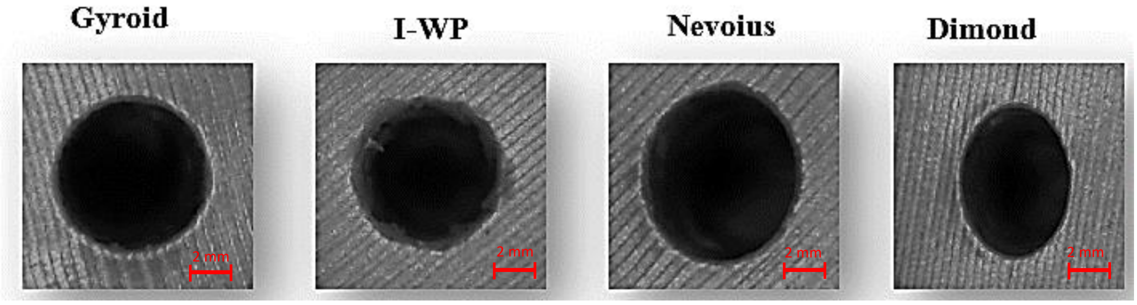

Figure 11. View of the hole entrance.

In the other samples, the exit burr height was 2.934, 1.821, and 0.154 mm for Gyroid, diamond, and I-WP, respectively. Transient burr formation is observed in a gyroid lattice structure, and uniform burr formation is observed in a diamond lattice structure (Figure 12) (Bahçe & Özdemir, 2021). In general, the highest delamination and burr formation is seen in the Gyroid sample, which shows that this material is more flexible than the others and the burr accumulation in front of the tool is higher.

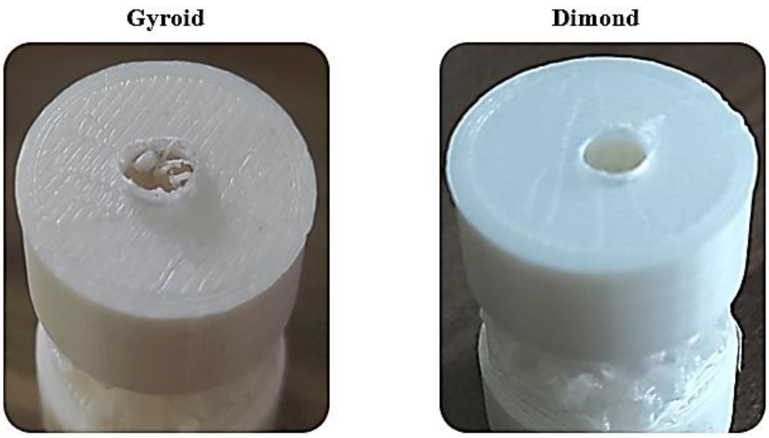

Figure 12. Images of burrs at the exit of the hole.

3.3. Effect of lattice structure design on circularity error

PLA-type elastic materials are prone to deformation under the influence of temperature and force (Anbuchezhiyan & Vignesh, 2023). For this reason, geometrical accuracy deteriorates according to the conditions of the machining processes. Especially at high temperatures, melting, shrinkage and distortion are frequently observed. This situation gave similar results in the experiments, and it is seen that the circularity is distorted both at the entrance and exit of all samples (Figure 13). The holes are flattened or expanded based on their diameter as well as their circularity value.

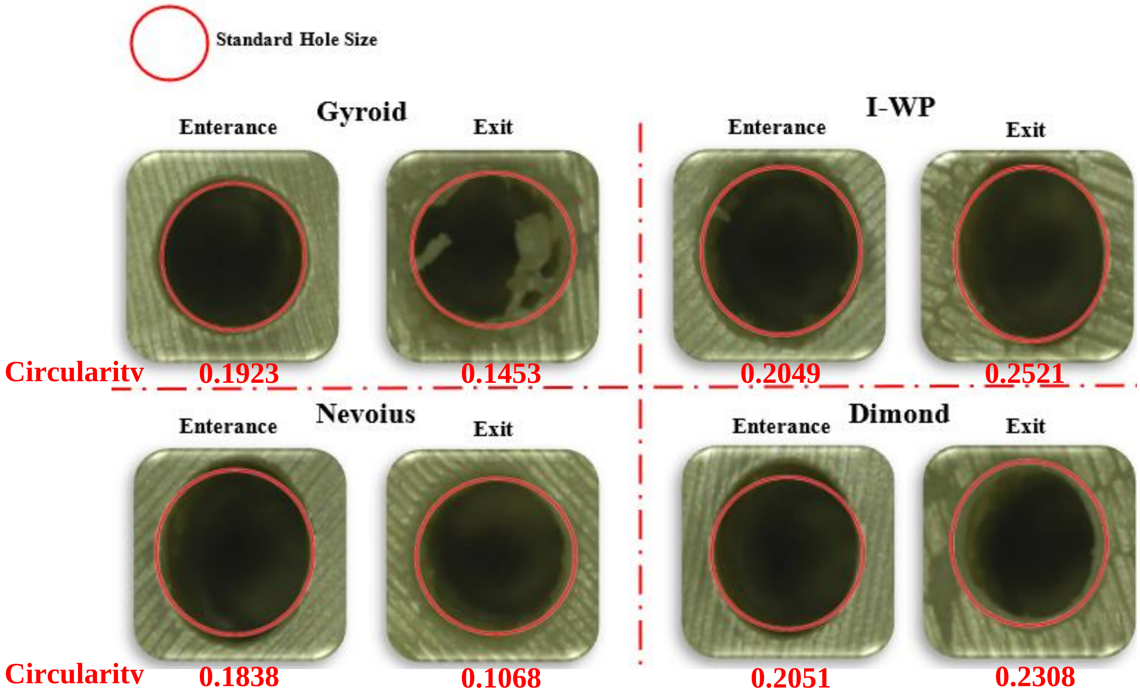

Figure 13. Difference between the standard hole and realized hole.

Figure 14 shows a higher circularity deviation in the entrance and exit holes of the I-WP lattice structure compared to other lattice structures. Particularly at the exit, the hole cross-section has narrowed transversely and lengthened longitudinally (see Figure 13). Secondly, it is seen that the circularity is high in the diamond lattice structure. Although the entrance hole is narrowed in width and elongated in length, the diameter of the exit hole is smaller than expected. The Nevoius lattice structure exhibits a slightly lower circularity deviation compared to the others. At the exit hole, the deviation occurred in the form of a length reduction.

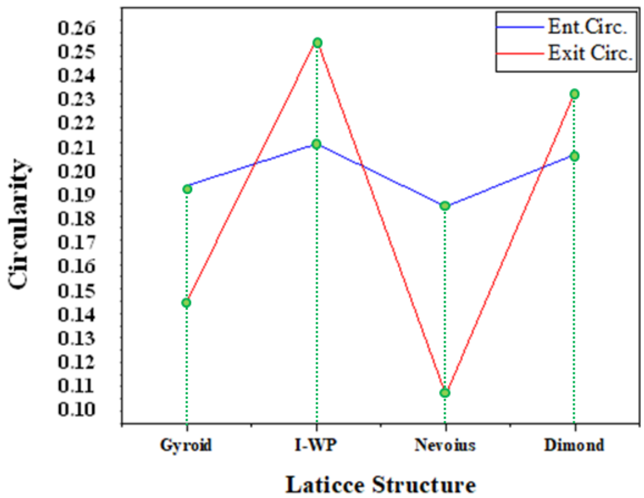

Figure 14. Hole entrance and exit circularity change.

4. Conclusion

PLA samples with four different lattice structures produced by additive manufacturing method were drilled using a 5 mm diameter HSS drill bit with 0.1 mm/rev feed rate and 4500 rpm.

Delamination, burr and circularity measurements were made from each sample. As a result of the analysis of the data obtained, the following results were obtained;

- At the entrance of the hole, the delamination was highest in I-WP (0.5601) and lowest in Gyroid (0.5423). At the hole exit, the Gyroid sample exhibited the highest delamination (0.6229), while the I-WP sample exhibited the lowest (0.5426).
- No burrs were observed at the entrance of any of the samples. Additionally, no burrs were observed at the exit of the hole in the Nevoius lattice structure. The exit burr height was 2.934 mm, 1.821 mm, and 0.154 mm in Gyroid, Diamond, and I-WP, respectively. Among the various lattice structures, the Gyroid lattice structure exhibits the highest values for both delamination and burr height.
- Circularity deviation was observed in all specimens. specimens, with the I-WP lattice structure showing the highest deviation at the entrance and exit of the hole.
- All factors considered, the holes drilled in the specimens using the Nevoius lattice structure are better quality than the others.

References

Altan, M., & Altan, E. (2014). Investigation of burr formation and surface roughness in drilling engineering plastics. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *36*(2), 347-354. https://doi.org/10.1007/s40430-013-0089-8

Anbuchezhiyan, G., & Vignesh, M. (2023). Implication of machining characteristics of pla/bronze ıntermixture synthesized by additive manufacturing. *Materials Letters*, *351*, 135065. https://doi.org/10.1016/j.matlet.2023.135065

Bahçe, E., & Özdemir, B. (2019). Investigation of the burr formation during the drilling of free-form surfaces in Al 7075 Alloy. *Journal of Materials Research and Technology*, *8*(5), 4198-4208. https://doi.org/10.1016/j.jmrt.2019.07.028

Bahçe, E., & Özdemir, B. (2021). Burr measurement method based on burr surface area. *International Journal of Precision Engineering and Manufacturing - Green Technology*, *8*(4), 1287-1296. https://doi.org/10.1007/s40684-020-00228-0

Baraheni, M., Shabgard, M. R., & Amini, S. (2021). Evaluating the hole quality produced by vibratory drilling: Additive manufactured PLA+. *The International Journal of Advanced Manufacturing Technology*, *117*(3-4), 785-794. https://doi.org/10.1007/s00170-021-07750-8

Boy, M. (2022). PEEK-CF30 termoplastik malzemenin delinmesinde delme parametrelerinin etkileri: İtme kuvveti, yüzey pürüzlülüğü ve delaminasyon. *Yüzüncü Yıl Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, *27*(3), 570-580. https://doi.org/10.53433/yyufbed.1104700

Corneillie, S., & Smet, M. (2015). PLA architectures: The role of branching. *Polymer Chemistry*, *6*(6), 850-867. https://doi.org/10.1039/C4PY01572J

Dezaki, M. L., Ariffin, M. K. a. M., & Ismail, M. I. S. (2020). Effects of CNC machining on surface roughness in fused deposition modelling (FDM) products. *Materials*, *13*(11), 2608. https://doi.org/10.3390/ma13112608

Dhokia, V. G., Kumar, S., Vichare, P., Newman, S. T., & Allen, R. D. (2008). Surface roughness prediction model for CNC machining of polypropylene. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *222*(2), 137-157. https://doi.org/10.1243/09544054JEM884

Domingo, R., Marín, M., de Agustina, B., & Calvo, R. (2015). Delamination analysis of polymeric materials during the drilling process. *Procedia Engineering*, *132*, 448-455. https://doi.org/10.1016/j.proeng.2015.12.518

Madhan Kumar, A., & Jayakumar, K. (2022). Mechanical and drilling characterization of biodegradable PLA particulate green composites. *Journal of the Chinese Institute of Engineers*, *45*(5), 437-452. https://doi.org/10.1080/02533839.2022.2061602

Özdemir, B., Kilickap, E., Bahçe, E., Yardimeden, A., & Emir, E. (2024). Optimization of parameters for drilling composite materials with freeform surfaces. *Materials and Manufacturing Processes*, *39*(1), 55-68. https://doi.org/10.1080/10426914.2023.2187826

Sato, M., Fukuma, A., Yamamoto, K., & Matsuno, T. (2017). Roundness in drilling of Low-Rigidity workpiece. *Key Engineering Materials*, *749*, 46-51. https://doi.org/10.4028/www.scientific.net/kem.749.46

Tümer, E. D., & Erbil, H. Y. (2021). Extrusion-based 3D printing applications of PLA composites: A review. *Coatings*, *11*(4), 390. https://doi.org/10.3390/coatings11040390

Usta, F., Türkmen, H. S., & Scarpa, F. (2022). High-velocity ımpact resistance of doubly curved sandwich panels with re-entrant honeycomb and foam core. *International Journal of Impact Engineering*, *165*, 104230. https://doi.org/10.1016/j.ijimpeng.2022.104230

Üner, I., & Koçak, E. D. (2013). Poli (laktik asit)'in kullanım alanları ve NANO lif üretimdeki uygulamaları. *İstanbul Ticaret Üniversitesi Fen Bilimleri Dergisi*, *11*(22), 79-88.

Xu, J., Huang, X., Davim, J. P., Ji, M., & Chen, M. (2020). On the machining behavior of carbon fiber reinforced polyimide and PEEK thermoplastic composites. *Polymer Composites*, *41*(9), 3649-3663. https://doi.org/10.1002/pc.25663

Yelten, A., Öztürk, M. H., & Yılmaz, S. (2022). 3-dimensional printing of PLA scaffolds for medical applications. *Turkish Journal of Engineering*, 6(4), 262-267. https://doi.org/10.31127/tuje.958192