

Computational Investigation of The Influence of Process Parameters of 3D Printed PLA Material

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Abstract

This study uses numerical simulation to examine the relationship between critical process parameters say, feed rate, layer height, and raster angle, on residual stresses and distortions and on the achievable density of FFF prints to identify the optimal input parameter combinations for ISO 527-2 type 1A. Methods of additive manufacturing that are utilised widely used to manufacture thermoplastic parts is fused filament fabrication. High residual stresses are one of the intrinsic phenomena that limit the widespread use of FFF in industry, despite the fact that it is now a well-established additive manufacturing process. Not all of the consequences, such as residual stresses, warping, and thermal cracking, are addressed by postprocessing. The analysis of interdependencies among various process outcomes reveals crucial insights. It is observed that high feed rates and larger layer heights are correlated with an increase in residual stresses, dimensional distortions in the final printed components, and increased porosity. The most favourable results are obtained when a raster angle of 45 degrees is employed. These findings highlight the significance of careful parameter selection and process optimisation in FFF to mitigate inherent challenges and enhance printed component reliability as well as quality.

Keywords: Fused filament fabrication (FFF), raster angle, feed rate, layer hight, residual stress, porosity, warpage, polylactic acid

INTRODUCTION

Additive manufacturing (AM) has become a game-changing technology with profound implications across many industries. This innovative manufacturing approach starkly contrasts traditional subtractive methods, as it enables the creation of complex, customised, and intricate structures layer by layer [1]. Over the past few decades, AM has redefined the boundaries of conventional manufacturing and spurred innovation in design, materials science, and engineering. The fundamental principle of AM involves the successive addition of layers material to build up a three-dimensional object from a digital model. These include reduced material waste, increased design freedom, faster prototyping, and the ability to

create previously unattainable geometries. Consequently, AM has found applications in diverse sectors, such as automotive, healthcare, and consumer goods, to name just a few [2].

AM has seen a proliferation of techniques, each offering unique advantages and trade-offs. These techniques range from VAT photopolymerisation and selective laser sintering to binder jetting and FFF. [3] VAT photopolymerisation methods exhibit high accuracy and resolution due to the fine laser or light-based curing process. Generally considered less accurate, FFF can achieve satisfactory resolution with precise parameter

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tuning and high-quality filaments. SLS and FFF offer a broader selection of materials compared to VAT photopolymerisation methods.

FFF can accommodate many thermoplastic materials, which have composites and speciality filaments. Binder jetting and FFF have good speed and scalability, with FFF preferred for rapid prototyping. VAT photopolymerisation does slower print speeds, making itself unsuitable for large-scale production. VAT photopolymerisation methods need post-processing steps, which leads to complexity and time in the manufacturing process [4]. Moreover, FFF's simplicity of use, minimal post-processing requirements, and ease of parameter optimisation enhance its appeal, allowing a broader user base to harness its potential [5]. While some AM techniques excel in precision or speed, FFF's capacity for rapid prototyping and suitability for short production runs position it as a versatile and practical tool for product development and smallscale manufacturing, solidifying its status as a prominent player in the field of AM.

As AM technology continues to evolve, various studies explore novel materials, optimise processes, and develop sophisticated post-processing techniques to enhance AM-produced components' reliability, precision, and scalability. Owing to the intricate microstructures and inherent anisotropic mechanical characteristics exhibited by components produced through Fused Filament Fabrication (FFF), coupled with the multitude of process variables involved, the application of computational simulation, specifically finite element analysis, has proven to be invaluable for assessing structural performance [6].

Within the context of 3D-printed FFF parts characterized by cellular lattice structures, finite element (FE) models have been employed to investigate the influence of various infill patterns and densities [7–8] on the mechanical properties of components. This approach aids in interpreting the occurrence of anisotropic damage under severe compression loading conditions [9], predicting the anisotropy introduced by the 3D printing process [10], and assessing the impact of porosity by analysing stress-strain distributions for various build angles [11].

Yan et al [12]. conducted an examination of residual stresses and microstructure in H13 tool steel. The as-built specimens displayed notable compressive stresses ranging from 940 to 1420 MPa. Similar results have also been reported by Vrancken et al. [13]. While residual stresses have been extensively explored, a fuller comprehension of the complex interaction between input parameters and residual stresses is still required. Previous research suggests that the most influential parameters encompass laser power, thickness, nozzle temperature, and print speed [14].

Hanzl et al [15]. concluded that laser power and scanning speed exert a significant impact on the mechanical attributes of AM-manufactured parts. Numerous studies have investigated the ramifications of processing parameters, including those conducted by Gu et al. [16], Delgado et al. [17], Thijs et al. [18], and Campanelli et al. [19]. Vigneshwaran et al. [20] embarked on an inquiry into the effect of FFF printing parameters on the fatigue strength of PLA under diverse printing configurations. Through meticulous analysis, the key determinants affecting the fatigue life of PLA materials in 3D printing were identified as fill density, nozzle diameter, and layer height [21].

Nonetheless, within the existing body of research investigating the impacts of specific process parameters—specifically, layer height, raster angle, and feed rate on porosity, distortions, and residual stresses, there exists a notable absence of comprehensive simultaneous examinations. Previous literature has proposed that the presence of pores exerts a mitigating influence on residual stresses [22]–[24]. As a result, in the context of process planning, gaining a full comprehension of the intricate relationships between these process outcomes is critical. Consequently, it is crucial to clarify the interdependencies between residual stresses, distortions, and porosity and to conduct a thorough examination of the effects of process parameters on these process outcomes in this research work.

MATERIALS AND METHODS

In this study, Digimat has been utilised for numerical simulation. The geometry of the FE model of the specimen has been discretised into 35,890 voxels. The model has been studied using mesh convergence, and a mesh size of .71 mm was chosen, Figure 1.

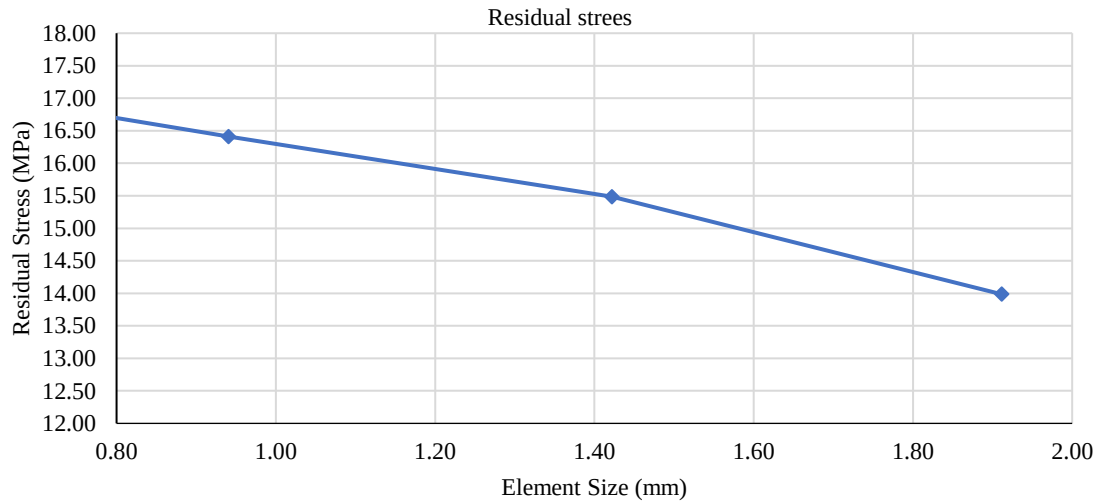


Figure 1. Mesh Convergence Study

The first step in the FFF is to create or obtain a 3D computer model. Using slicing software, the 3D model is subsequently split into a series of 2D layers in the following stage, which generates a G-code file containing instructions for the 3D printer. Layer height, raster angle, and feed rate have been varied in the G-Code instruction. The real printing process starts when the 3D printer receives the G-code. The printer's heated nozzle, i.e., 210 degrees Celsius in this case, melts a filament material and deposits it layer by layer according to the G-code instructions, gradually building the physical object. In this simulation, PLA has been used as thermoplastic, Table 1. Each layer cools and solidifies rapidly upon deposition, adhering to the previous layers to create a cohesive structure. Once the printer completes all the layers, the finished object can be carefully removed from the print bed.

Table 1. PLA Specifications

Material	Diameter	Young's modulus	Flexural strength
Polylactic Acid (PLA)	1.75mm	5–10 GPa	<140 MPa

The investigation was conducted using a standard ISO 527-2 Type 1A specimen. As illustrated in figure 2, the specimen exhibited a maximum length of 170mm, with corresponding maximum dimensions of 20mm in width and 5mm in thickness.

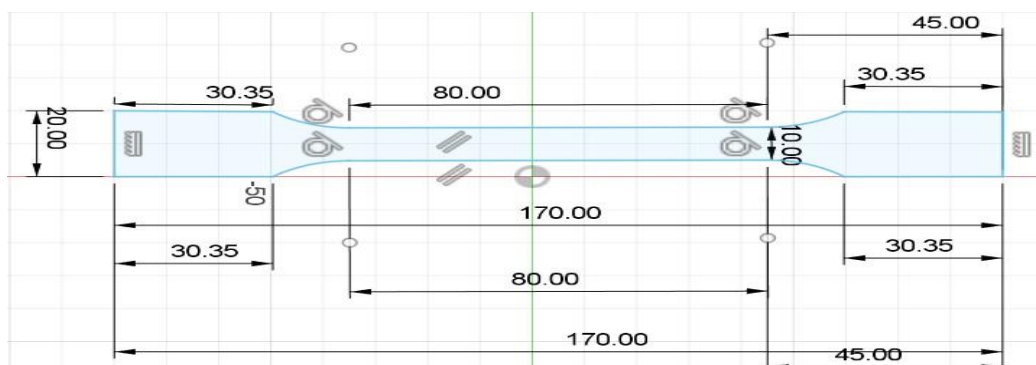


Figure 2. Dimensions ISO 527-2 Type 1A

A thorough examination of the literature cited within this study revealed that several process parameters significantly influenced the overall strength characteristics of the specimens. To establish a comprehensive foundation for this investigation, a total of 27 specimens were generated, encompassing various permutations of these three influential factors, as detailed in

Table 2. Investigative Parameters [25].

Levels	Factors		
	Layer Thickness (mm)	Feed Rate (mm/s)	Raster Angle
1	0.1	20	0°
2	.15	40	45°
3	0.4	60	90°

Table 2 provides an overview of the selected testing parameters. Specifically, Layer Thickness was finetuned incrementally by 0.05mm to 0.25mm, spanning the range from 0.1mm to 0.4mm. Conversely, the Feed Rate underwent adjustments, spanning from 20mm/s to 80mm/s. Simultaneously, the Raster Angle was incrementally rotated by 45°, reaching a full 90° rotation. These variations created 27 unique combinations of these parameters, forming the fundamental framework for the simulation design. It is important to note that other significant parameters remained constant across all specimens, as detailed in Table 3.

Table 3. Constant Simulation Parameters [25]

Parameters	Infill Pattern	Infill Density	Nozzle Temperature	Bed Temperature
Values/Type	Lines	80%	210°C	60°C

RESULTS AND DISCUSSION

Porosity, residual stress, and warpage are key aspects that can significantly influence the quality, performance, and structural integrity of 3D-printed components. Understanding how these parameters affect these factors is essential for optimising AM processes, minimising defects, and ensuring the reliability of printed parts. Through a systematic investigation, the further section sheds light on the intricate relationship between process parameters and the quality of the Print.

Effect of Process Parameters on Porosity

Porosity is critical in additive manufacturing as it directly impacts the quality and functionality of 3Dprinted parts. When porosity increases, there is a notable reduction in the overall strength of the component, making it more susceptible to failure under mechanical stress. Parts with reduced porosity tend to have smoother and more aesthetically pleasing surfaces, which is especially crucial for components with stringent cosmetic requirements. Furthermore, lower porosity can be essential for parts requiring airtight seals, fluid containment, or effective heat insulation. Porosity can be decreased by looking at the effects of various process factors in more detail.

Layer Height

The variation in layer height within the specified range from .1 mm to .4 mm directly influences the specimens' porosity. Lower layer heights reduce porosity due to improved inter-layer bonding, while excessively high layer heights increase porosity due to inadequate material fusion. In this simulation, the raster angle was kept constant at 45 degrees and speed at 20mm/min.

Porosity at .1 mm shows the lowest porosity, and .4 mm shows the highest. The variation is little when moving from .1 mm layer height to .2 mm than .2 mm to .4 mm. Figure 3 shows little variation at lower layer height; as the layer height increases, the change in porosity is more drastic.

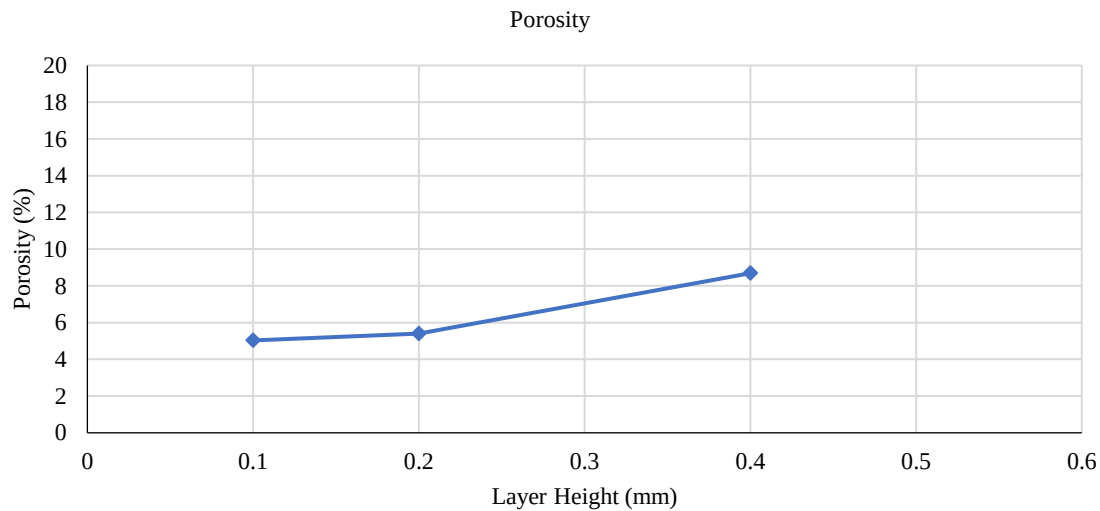


Figure 3. Layer Height vs Porosity

Feed Rate

Feed rate has a significant impact on porosity. A higher feed rate causes incomplete material deposition, leading to voids and higher porosity, whereas a lower feed rate enhances material fusion, resulting in reduced porosity. This study kept the raster angle constant at 45 degrees and layer height at .1mm.

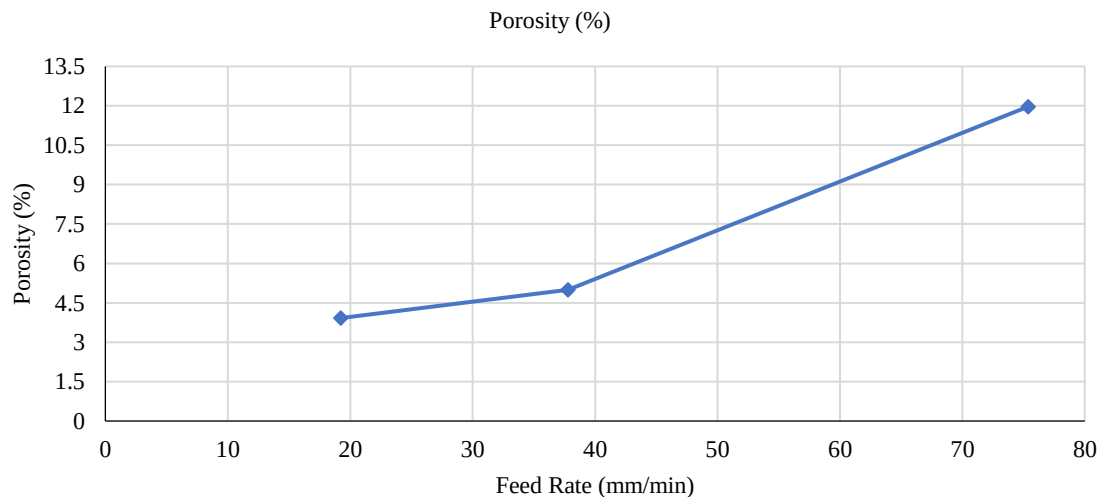


Figure 4. Feed Rate vs Porosity

According to figure 4, Porosity is lowest at 20 mm/min, and at 80 mm is the highest. Transitioning from 20 mm/min to 40 mm/min exhibits less variation than 40 mm/min to 80 mm/min. The Porosity varies more drastically at higher speeds.

Raster Angle

The orientation of raster angles affects porosity due to differences in material deposition patterns. In this investigation, the feed rate was fixed at 20 mm/min, and the layer height was consistently maintained at 0.1mm. From figure 5, specimens with varying raster angles from 0 degrees to 90 degrees exhibit variations in porosity, with 45 degrees showing best inter-layer adhesion and lower porosity, while 90 degrees and 0 degrees show comparable porosity, with 0 degrees showing a bit better result.

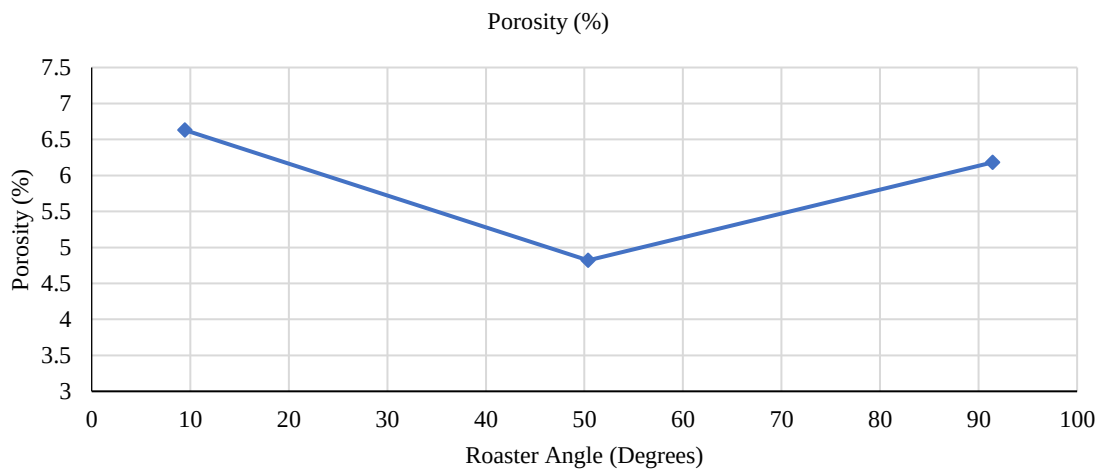


Figure 5. Raster Angle vs Porosity

A raster angle of 45 degrees shows the best result as it has the best overlapping patterns than other angles, as it covers most areas efficiently.

Effect of Process Parameters on Residual Stress

Because residual stress has a substantial effect on the functionality and quality of printed components, it is an important consideration. Residual stresses can arise during the printing process due to uneven cooling and solidification of material layers. Different process parameters influence the cooling and solidification of prints. Excessive residual stress compromises the integrity of printed components, while its reduction contributes to the overall reliability and performance of AM-produced parts. The subsequent section examines how various process factors affect residual stresses.

Layer Height

The layer height influences residual stress within the printed specimens. Changes in layer height can affect thermal gradients and, subsequently, the development of residual stresses. Lower layer heights reduce thermal stress due to smaller temperature differentials between layers. A consistent raster angle of 45 degrees and a constant speed of 20 mm/min were maintained throughout this simulation.

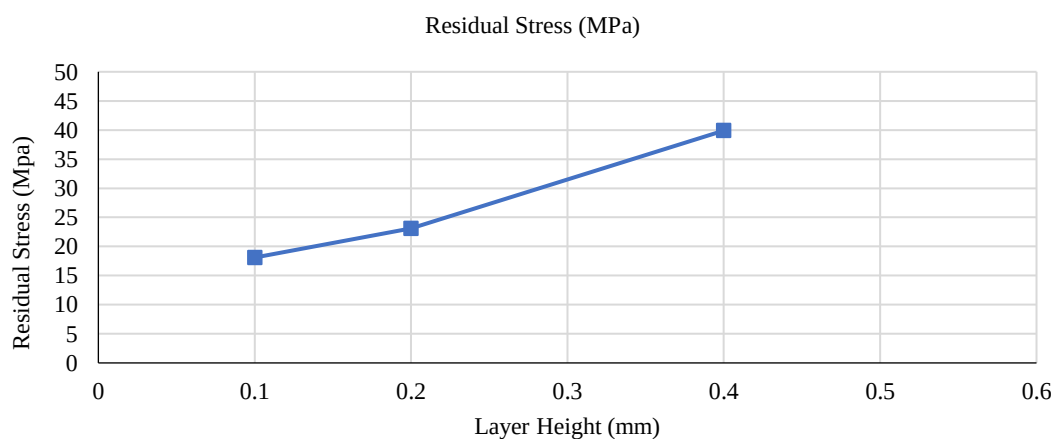


Figure 6. Layer Height vs Residual Stress

The residual stress is at its minimum when the layer height is set at 0.1 mm, whereas it reaches its maximum at 0.4 mm. The change in residual stress is relatively minor when transitioning from a 0.1 mm layer height to a 0.2 mm layer height, as compared to the more significant stress variation observed

when progressing from a 0.2 mm layer height to a 0.4 mm layer height. Figure 6 shows this trend by showing minimal fluctuations in residual stress at lower layer heights, with a noticeable increase in residual stress changes as the layer height is raised.

Feed Rate

Feed rate alterations influence the cooling rate, which impacts the magnitude of residual stresses. Slower feed rates allow for more controlled cooling, reducing residual stress levels. In this investigation, the raster angle remained consistently set at 45 degrees, while the layer height was maintained at 0.1mm throughout the study.

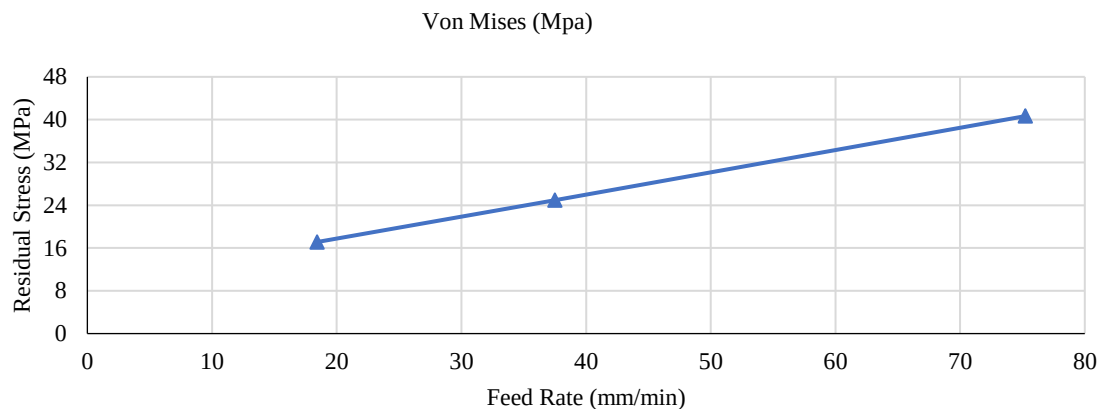


Figure 7. Feed Rate vs Residual Stress

Based on the figure 7, it can be observed that the minimum residual stress is recorded at a speed of 20 mm/min, while the maximum residual stress is observed at 80 mm/min. The change in residual stress is similar when transitioning from a speed of 20 mm/min to 40 mm/min compared to the transition from 40 mm/min to 80 mm/min. Notably, there is a linear variation in residual stress at higher machining speeds.

Raster Angle

Raster angle variations affect the distribution of residual stresses within the specimens. Specimens with different raster angles from 0 degrees to 90 degrees exhibit distinct stress patterns, influencing overall mechanical behaviour. In this study, the speed was set at a constant value of 20 mm/min, and the layer thickness was consistently maintained at 0.1 mm.

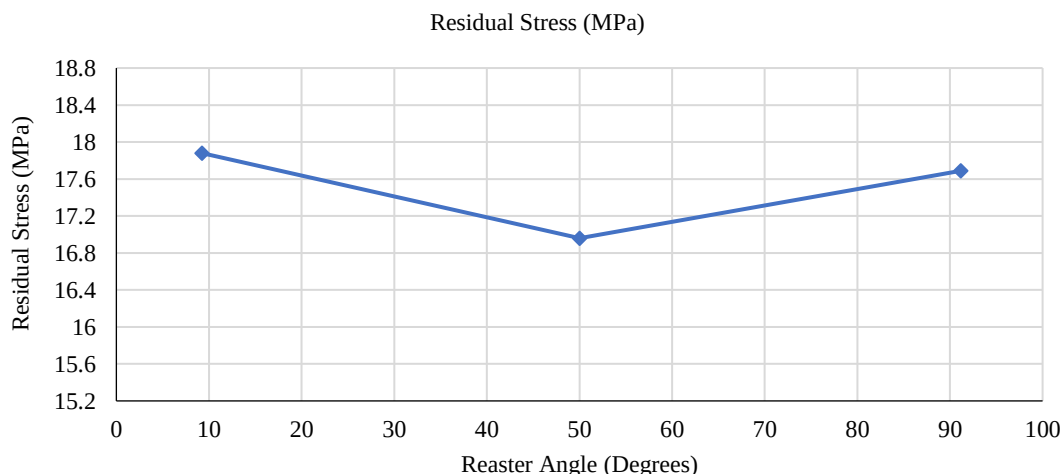


Figure 8. Raster angle vs residual stress

Based on the figure 8, it is evident that specimens featuring different raster angles ranging from 0 degrees to 90 degrees manifest distinct patterns of residual stress. A raster angle of 45 degrees stands out, showing superior inter-layer adhesion and reduced residual stress compared to the specimens set at 90 degrees and 0 degrees. Specifically, the 0-degree raster angle showcases slightly better outcomes in terms of residual stress when compared to the 90-degree angle.

Influence of Process Parameters on Warpage

Warpage significantly impacts the quality and functionality of printed parts as it increases. It results in dimensional inaccuracies, deformation, and even the complete failure of the printed component. Reducing warpages is a priority to produce parts that meet design specifications, minimize waste, and improve overall product quality. The further section explores various process parameters to mitigate warpage and optimize the reliability of AM-produced components.

Layer Height

Changes in layer height affect warpage tendencies. Higher layer heights lead to increased warpage due to differential cooling rates and thermal contraction. Throughout this simulation, the raster angle remained consistently fixed at 45 degrees while the speed was maintained at 20 mm/min.

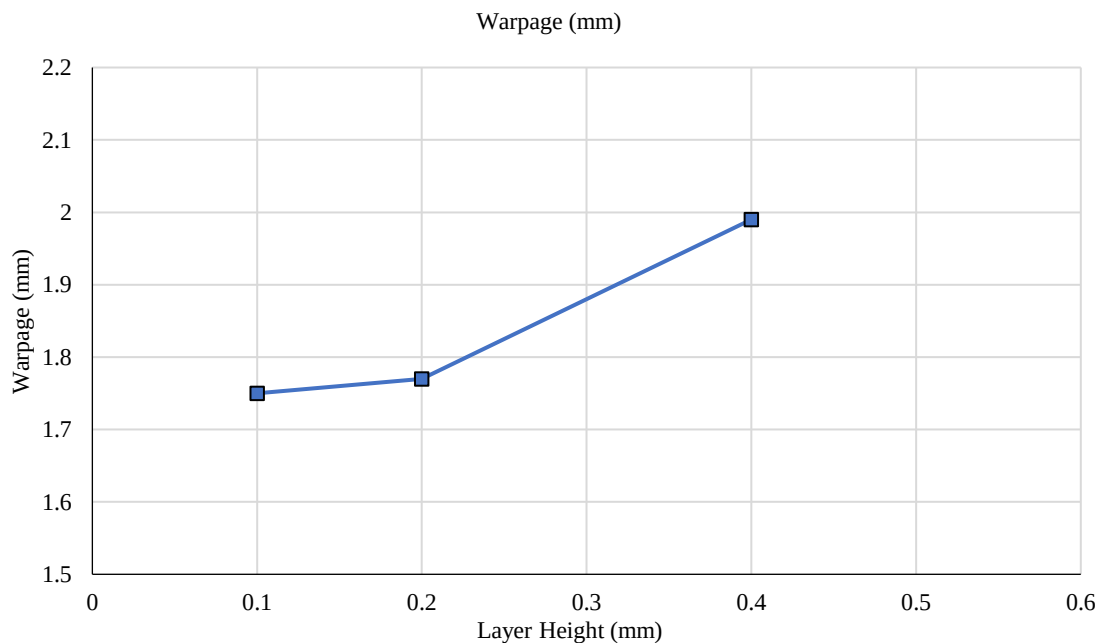


Figure 9. Layer Height vs Warpage

The lowest level of warpage is observed at a layer height of 0.1 mm, while the highest level of warpage is observed at 0.4 mm. Notably, the degree of variation in warpage exhibits a relatively minor change when transitioning from a 0.1 mm layer height to a 0.2 mm layer height, in contrast to the more pronounced shift observed when moving from a 0.2 mm layer height to a 0.4 mm layer height. The figure 9 provides a visual representation of these trends, highlighting the limited fluctuations in warpage at lower layer heights and the progressively more substantial changes as layer height increases.

Feed Rate

Feed rate adjustments impact warpage by influencing the speed of material deposition and, consequently, the distribution of thermal stresses within the specimens. In this investigation, the raster angle remained fixed at 45 degrees, and the layer height was consistently maintained at 0.1mm.

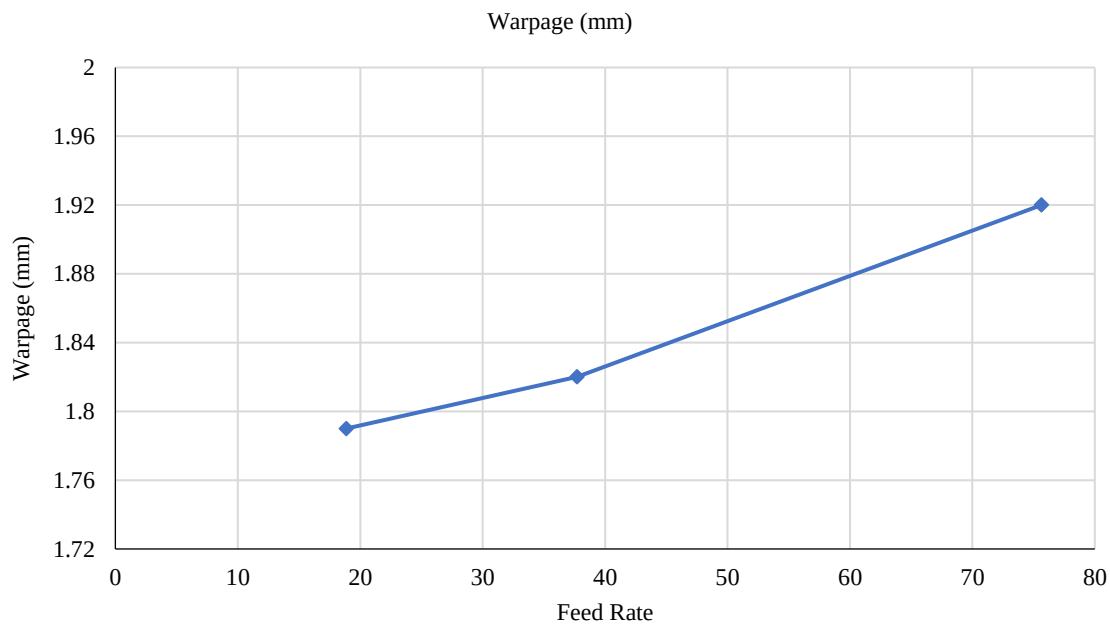


Figure 10. Feed Rate vs Warpage

As depicted in figure 10, the lowest levels of warpage are observed when the traverse speed is set at 20 mm/min, whereas the highest levels are evident at 80 mm/min. Notably, the transition from 20 mm/min to 40 mm/min exhibits a relatively modest variation in residual stress compared to the more pronounced variation experienced when increasing the traverse speed from 40 mm/min to 80 mm/min. It is noteworthy that higher traverse speeds correspond to more substantial fluctuations in warpage.

Raster Angle

Raster angle variations may warpage tendencies by altering the direction of material deposition and, subsequently, the thermal contraction and stress distribution within the specimens. The feed rate remained constant during this study at 20 mm/min, and the layer height was consistently kept at 0.1mm.

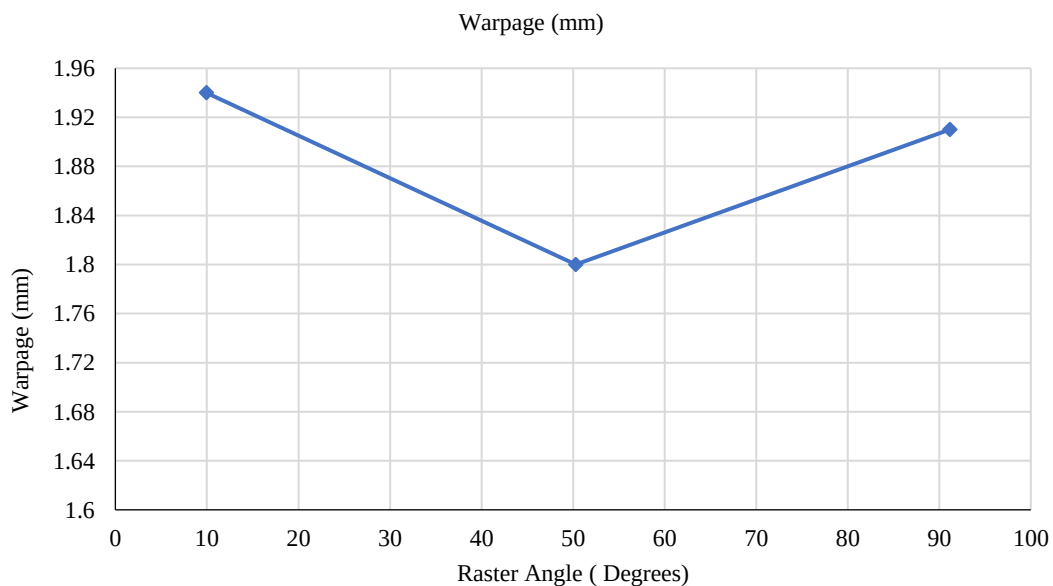


Figure 11. Raster Angle vs Warpage

According to the figure 11, specimens characterised by various raster angles spanning from 0 degrees to 90 degrees exhibit discernible variations in warpage patterns. Remarkably, a raster angle of 45 degrees emerges as the most prominent, displaying enhanced inter-layer adhesion and reduced warpage when contrasted with specimens configured at 90 degrees and 0 degrees. Furthermore, the 0-degree raster angle exhibits marginally improved outcomes in terms of residual stress as compared to the 90-degree angle.

CONCLUSION

The study demonstrates how process parameters affect porosity, distortion, and residual stresses and their effect on FFF (Fused Filament Fabrication) performance in the context of an ISO 527-2 Type 1A specimen. The investigation into feed rate, layer height, and raster angle has shed light on the complex interplay between these variables and their impact on porosity, residual stresses, and distortions in FFF prints. The findings of this study show the importance of parameter selection and process optimization. The high feed rates and larger layer heights tend to increase residual stresses, dimensional distortions, and porosity in the final printed components. However, in contrast, the utilization of a 45-degree raster angle emerges as a favourable choice, contributing to improved print quality and reliability.

REFERENCES

1. ISO/ASTM International, "ISO/ASTM 52900: Additive manufacturing - General principles and Terminology," Int. Stand., vol. 5, no. 978-84-9042-335-6, pp. 1-26, 2015.
2. I. Gibson, D. Rosen, and B. Stucker, 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. 2015. [Online]. Available: <http://link.springer.com/10.1007/978-1-4939-2113-3>
3. Hai, T., Ali, M. A., Dhahad, H. A., Alizadeh, A. A., Sharma, A., Almojil, S. F., ... & Wang, D. (2023). Optimal design and transient simulation next to environmental consideration of net-zero energy buildings with green hydrogen production and energy storage system. *Fuel*, 336, 127126.
4. M. Ahmadifar, K. Benfriha, M. Shirinbayan, and A. Tcharkhtchi, "Additive Manufacturing of Polymer-Based Composites Using Fused Filament Fabrication (FFF): a Review," *Appl. Compos. Mater.*, vol. 28, no. 5, pp. 1335-1380, 2021, <https://doi.org/10.1007/s10443-021-09933-8>
5. G. D. Goh, Y. L. Yap, H. K. J. Tan, S. L. Sing, G. L. Goh, and W. Y. Yeong, "Process-Structure-Properties in Polymer Additive Manufacturing via Material Extrusion: A Review," *Crit. Rev. Solid State Mater. Sci.*, vol. 45, no. 2, pp. 113-133, Mar. 2020, <https://doi.org/10.1080/10408436.2018.1549977>
6. Sharma, A., Sharma, K., Islam, A., & Roy, D. (2020). Effect of welding parameters on automated robotic arc welding process. *Materials Today: Proceedings*, 26, 2363-2367.
7. M. Kuciewicz, P. Baranowski, J. Malachowski, A. Poplawski, and P. Platek, "Modelling, and characterization of 3D printed cellular structures," *Mater. Des.*, vol. 142, pp. 177-189, Mar. 2018, <https://doi.org/10.1016/j.matdes.2018.01.028>
8. P. Platek et al., Mechanical response of additive manufactured regular cellular structures in quasi-static loading conditions-part ii: numerical investigations. 2017.
9. Sharma, A., Chaturvedi, R., Sharma, K., & Saraswat, M. (2022). Force evaluation and machining parameter optimization in milling of aluminium burr composite based on response surface method. *Advances in Materials and Processing Technologies*, 8(4), 4073-4094.
10. S. Guessasma, S. Belhabib, and H. Nouri, "Significance of pore percolation to drive anisotropic effects of 3D printed polymers revealed with X-ray -tomography and finite element computation," *Polymer (Guildf)*, vol. 81, Oct. 2015, <https://doi.org/10.1016/j.polymer.2015.10.041>
11. H. Nouri, S. Guessasma, and S. Belhabib, "Structural imperfections in additive manufacturing perceived from the X-ray micro-tomography perspective," *J. Mater. Process. Technol.*, vol. 234, pp. 113-124, 2016, <https://doi.org/10.1016/j.jmatprotec.2016.03.019>
12. Chaturvedi, R., Sharma, A., Sharma, K., & Saraswat, M. (2022). Tribological behaviour of multi-walled carbon nanotubes reinforced AA 7075 nano-composites. *Advances in Materials and Processing Technologies*, 8(4), 4743-4755.

13. B. Vrancken, R. Wauthle, J.-P. Kruth, and J. Humbeeck, "Study of the influence of material properties on residual stress in selective laser melting," 24th Int. SFF Symp. - An Addit. Manuf. Conf. SFF 2013, pp. 393–407, Jan. 2013.
14. I. Yadroitsev, I. Yadroitsava, P. Bertrand, and I. Smurov, "Factor analysis of selective laser melting process parameters and geometrical characteristics of synthesized single tracks," Rapid Prototyp. J., vol. 18, pp. 201–208, Apr. 2012, <https://doi.org/10.1108/13552541211218117>
15. Liu, Z., Zhanguo, S. U., Abed, A. M., Chaturvedi, R., Feyzbaxsh, M., & Salavat, A. K. (2022). A comparative thermodynamic and exergoeconomic scrutiny of four geothermal systems with various configurations of TEG and HDH unit implementations. Applied Thermal Engineering, 216, 119094.
16. B. Vrancken, R. Wauthle, J.-P. Kruth, and J. Humbeeck, "Study of the influence of material properties on residual stress in selective laser melting," 24th Int. SFF Symp. - An Addit. Manuf. Conf. SFF 2013, pp. 393–407, Jan. 2013.
17. Kumar, R., Pandey, A. K., Samykano, M., Mishra, Y. N., Mohan, R. V., Sharma, K., & Tyagi, V. V. (2022). Effect of surfactant on functionalized multi-walled carbon nano tubes enhanced salt hydrate phase change material. Journal of Energy Storage, 55, 105654.
18. L. Thijs, F. Verhaeghe, T. Craeghs, J. Van Humbeeck, and J.-P. Kruth, "A study of the microstructural evolution during selective laser melting of Ti–6Al–4V," Acta Mater., vol. 58, no. 9, pp. 3303–3312, 2010, <https://doi.org/10.1016/j.actamat.2010.02.004>.
19. S. L. Campanelli, N. Contuzzi, A. Angelastro, and A. D. Ludovico, "Capabilities and Performances of the Selective Laser Melting Process," M. J. Er, Ed. Rijeka: Intech Open, 2010, p. Ch. 13. <https://doi.org/10.5772/10432>.
20. Cao, Y., Dhahad, H. A., Sharma, K., ABo-Khalil, A. G., El-Shafay, A. S., & Ibrahim, B. F. (2022). Comparative thermoeconomic and thermodynamic analyses and optimization of an innovative solar-driven trigeneration system with carbon dioxide and nitrous oxide working fluids. Journal of Building Engineering, 45, 103486.
21. J. A. Travieso-Rodriguez, R. Jerez-Mesa, J. Llumà, O. Traver-Ramos, G. Gomez-Gras, and J. J. R. Rovira, "Mechanical properties of 3D-printing polylactic acid parts subjected to bending stress and fatigue testing," Materials (Basel), vol. 12, no. 23, 2019, <https://doi.org/10.3390/ma122333859>.
22. A. Wicaksana and T. Rachman, "Analysis of Factors Affecting Rubber Production at PT. Lonsum, Bulukumpa District, Bulukumba Regency," Angew. Chemie Int. Ed. 6(11), 951–952., vol. 3, no. 1, pp. 10–27, 2018, [Online]. Available: https://digilibadmin.unismuh.ac.id/upload/13589-Full_Text.pdf
23. A. S. Wu, D. W. Brown, M. Kumar, G. F. Gallegos, and W. E. King, "An Experimental Investigation into Additive Manufacturing-Induced Residual Stresses in 316L Stainless Steel," Metall. Mater. Trans. A, vol. 45, no. 13, pp. 6260–6270, 2014, <https://doi.org/10.1007/s11661-014-2549-x>.
24. Al-Muntaser, A. A., Pashameah, R. A., Sharma, K., Alzahrani, E., & Tarabiah, A. E. (2022). Reinforcement of structural, optical, electrical, and dielectric characteristics of CMC/PVA based on GNP/ZnO hybrid nanofiller: nanocomposites materials for energy-storage applications. International Journal of Energy Research, 46(15), 23984-23995.
25. Pachauri S, Gupta NK, Gupta A. Influence of 3D printing process parameters on the mechanical properties of polylactic acid (PLA) printed with fused filament fabrication: experimental and statistical analysis. International Journal on Interactive Design and Manufacturing (IJIDeM). 2023 Aug 14;1-9, <https://doi.org/10.1007/s12008-023-01424-3>.