Empirical study and Machine Learning Prediction of Tensile strength in 3D Printed Eco-friendly Polylactic Acid

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ABSTRACT

With Additive Manufacturing (AM) technology such as Fused Deposition Modeling (FDM) technique being used to produce functional components, it is necessary to understand the combined effect of significant printing process parameters over the mechanical properties of printed parts. The present work employed the full factorial technique to investigate the effect of printing process parameters such as infill density, infill pattern, layer height, and nozzle size over the tensile strength of the printed parts. Analysis of Variance (ANOVA) was conducted and it identified the nozzle size as the most significant factor influencing tensile strength, followed by infill density. Layer height and infill shape had a smaller individual impact on tensile strength. However, with specific combinations of nozzle size and infill densities, noticeable variations in tensile strength were observed. Increasing the infill density enhances tensile strength proportional to the rise in mass due to the additional material. Although infill patterns had minimal effect on tensile strength, the specific strength varied, with the triangle pattern showing the highest specific strength of 7.11 MPa/g, which is 5.20% and 21.65% higher than the rectilinear and wiggle patterns. The highest tensile strength of 43.63 MPa was achieved using the wiggle pattern at 80% infill which is due to print orientation of wiggle pattern with the tensile load. Further, increasing the layer height and nozzle size significantly improved specific strength because of higher print quality and reduced defects. The experimental investigation proved the optimal nozzle to layer height ratio (N/L) for to achieve greater strength is 1.66. With the extensive datasets obtained using experimental investigation, a machine learning model was trained for predicting the tensile strength for the given printing process parameters. Due to its adaptability, efficiency and robustness, the Gaussian Process Regression was proved to estimate the tensile strength of the Polylactic Acid (PLA) material

4. CONCLUSION

The tensile strength of 3D printed PLA was experimented with various printing process parameters such as infill density, infill pattern, layer height, and nozzle size. The ML based GPRM was developed to predict the tensile strength. The following are the significant findings of the present work.

- The effect of printing process parameters over the resulted tensile strength was analyzed using ANOVA and its individual influence is in the order as follows: Nozzle size (38.7%) > Infill density (27.7%) > Layer height (6.1%) > Infill pattern (5.2%).
- The tensile strength is most significantly impacted by the choice of nozzle size. The strength increases in direct proportion to the size of the nozzle since larger filaments result in fewer printing flaws. Inter-layer gaps and irregular filament extrusions were seen across the 0.3 mm nozzle prints.
- As the ratio of N/L is so vital in defining the strength outcome, layer height selection affects the tensile strength. The N/L ratio of 1.66 offers highest tensile strength. As the N/L ratio increases, the radical shift becomes less noticeable.
- When the infill density rises, more material becomes available for preventing failure. The specific strength virtually stays constant across all infill densities. It means that at the micro level, there aren't any substantial influences made by the change in densities.
- The specimens printed with triangle infills held up better than those with rectilinear and wiggle patterns in terms of mean strength and specific strength. However, the performance of the wiggle patterns was superior with higher infill densities (80%) since wiggle angle orient towards the direction of applied load.
- The tensile strength of a PLA material was estimated in this study using the ML model GPRM. Over the training and testing datasets, the GPRM's predictive performance and matching residuals produced an accuracy of 88.34%, MAE of 3.17, and MAPE of 11.66.

STATEMENTS AND DECLARATIONS

Ethics approval: We comply with ethical standards. We provide our consent to take part.

Consent to participate and publication: The authors provide consent to participate and publication.

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REFERENCES

[1] V. Mishra, S. Negi, S. Kar, A. K. Sharma, Y. N. K. Rajbahadur, and Avinash Kumar, "Recent advances in fused deposition modeling based additive manufacturing of thermoplastic composite structures: A review," *Journal of Thermoplastic Composite Materials*, vol. 36, pp. 3094-3132, 2023.

[2] A. Haidiezul, M. Dollah, A. Hakim, S. Shahrin, and N. Shuaib, "Feasibility study of FDM 3D printing fabrication process for customized automotive front grille," in *AIP Conference Proceedings*, vol. 2544, pp. 040009, 2023.

[3] B. Aráoz, G. Bellía-Munzón, J. I. Bousquet, and É. B. Hermida, "Advantages of FDM and gamma irradiation to manufacture personalized medical devices for airway obstructions," *Frontiers in Bioengineering and Biotechnology*, vol. 11, pp. 1148295, 2023.

[4] D. Jimenez-Ordonez, A. Martinez-Hernandez, G. Martinez-Barrera, and C. J. M. Velasco-Santos, "Design and 3D printing manufacturing of complex structures for airflow evaluation," *Materials and Manufacturing Processes*, vol. 38, pp. 980-988, 2023.

[5] S. Kamble, A. Belhadi, S. Gupta, N. Islam, V. K. Verma, and Ludovico Solima, "Analyzing the barriers to building a 3-D printing enabled local medical supply chain ecosystem," IEEE Transactions on Engineering Management, vol. 71, pp. 12974-12991, 2024.

[6] Vigneshwaran Shanmugam, Karthik Babu, Gokul Kannan, Rhoda Afriyie Mensah, Saroj Kumar Samantaray, and Oisik Das, "The thermal properties of FDM printed polymeric materials: A review," *Polymer Degradation and Stability*, vol. 228, pp. 110902, 2024.

[7] N. A. Fountas, S. Zaoutsos, D. Chaidas, J. D. Kechagias, and N. M. Vaxevanidis, "Statistical modelling and optimization of mechanical properties for PLA and PLA/Wood FDM materials," *Materials Today: Proceedings*, vol. 93, pp. 824-830, 2023.

[8] A. Patel and M. Taufik, "A study on design and development of prosthetics by fused deposition modelling," *AIP Conference Proceedings*, vol. 2800, pp. 020144, 2023.

[9] N. Ranjan, R. Singh, I. Ahuja, M. Rahman, and S. J. D. P. i. B. E. Ramakrishna, "PLA-HAp-CS-based biocompatible scaffolds prepared through micro-additive manufacturing: a review and future applications," 3D printing in Biomedical Engineering: Springer, pp. 209-229, 2020.

[10] G. Embia, B. R. Moharana, A. Mohamed, K. Muduli, and N. B. Muhammad, "3D printing pathways for sustainable manufacturing," *New horizons for industry 4.0 in modern business: Springer*, pp. 253-272, 2023.

[11] J. Antić, Ž. Mišković, R. Mitrović, Z. Stamenić, and J. Antelj, "The Risk assessment of 3D printing FDM technology," *Procedia Structural Integrity*, vol. 48, pp. 274-279, 2023.

[12] G. Rajeshkumar, S. Arvindh Seshadri, G.L. Devnani, M.R. Sanjay, Suchart Siengchin, J. Prakash Maran, Naif Abdullah Al-Dhabi, Ponmurugan Karuppiah, Valan Arasu Mariadhas, N. Sivarajasekar, and A. Ronaldo Anuf, "Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites–A comprehensive review," *Journal of Cleaner production*, vol. 310, pp. 127483, 2021.

[13] N. Ranjan, R. Singh, and I. J. M. T. P. Ahuja, "Investigations for mechanical properties of PLA-HAp-CS based functional prototypes," Materials Today: Proceedings, vol. 18, pp. 2329-2334, 2019.

[14] V. Ambade, S. Rajurkar, G. Awari, B. Yelamasetti, and S. Shelare, "Influence of FDM process parameters on tensile strength of parts printed by PLA material," *International Journal on Interactive Design and Manufacturing*, 2023, doi: 10.1007/s12008-023-01490-7.

[15] S. Hamat, M. R. Ishak, S. M. Sapuan, N. Yidris, M. S. Hussin, and M.S. Abd Manan, "Influence of filament fabrication parameter on tensile strength and filament size of 3D printing PLA-3D850," *Materials Today: Proceedings*, vol. 74, pp. 457-461, 2023.

[16] J. Nagarjun, J. Kanchana, G. Rajeshkumar, and A. Anto Dilip, "Enhanced mechanical characteristics of polylactic acid/tamarind kernel filler green composite filament for 3D printing," *Polymer Composites*, vol. 44, pp. 7925-7940, 2023.

[17] N. Jayakumar, H. Arumugam, and A. D. Albert Selvaraj, " Mechanical behaviour of the post processed 3D printed PLA parts using polar and non-polar solvents," *Polymer Bulletin*, vol. 81, pp. 4257-4274, 2024.

[18] H. Gonabadi, A. Yadav, and S. Bull, "The effect of processing parameters on the mechanical characteristics of PLA produced by a 3D FFF printer," *The International Journal of Advanced Manufacturing Technology*, vol. 111, pp. 695-709, 2020.

[19] N. Ranjan, R. Singh, and I. J. B. Ahuja, "Material processing of PLA-HAp-CS-based thermoplastic composite through fused deposition modeling for biomedical applications," Biomanufacturing: Springer, pp. 123-136, 2019.

[20] N. Lokesh, B. Praveena, J. S. Reddy, V. K. Vasu, and S. Vijaykumar, "Evaluation on effect of printing process parameter through Taguchi approach on mechanical properties of 3D printed PLA specimens using FDM at constant printing temperature," *Materials Today: Proceedings,* vol. 52, pp. 1288-1293, 2022.

[21] C. Tang, J. Liu, Y. Yang, Y. Liu, S. Jiang, and W. Hao, "Effect of process parameters on mechanical properties of 3D printed PLA lattice structures," *Composites Part C: Open Access,* vol. 3, pp. 100076, 2020.

[22] H. K. Dave, N. H. Patadiya, A. R. Prajapati, and S. R. Rajpurohit, "Effect of infill pattern and infill density at varying part orientation on tensile properties of fused deposition modeling-printed poly-lactic acid part," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol. 235, pp. 1811-1827, 2021.

[23] R. B. Kristiawan, F. Imaduddin, D. Ariawan, and Z. Arifin, "A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters," *Open Engineering,* vol. 11, pp. 639-649, 2021.

[24] B. A. Aloyaydi, S. Sivasankaran, and H. R. Ammar, "Influence of infill density on microstructure and flexural behavior of 3D printed PLA thermoplastic parts processed by fusion deposition modeling," *AIMS Mater.Sci,* vol. 6, pp. 1033-1048, 2019.

[25] A. Balasuadhakar, S. Thirumalai Kumaran, and M. Uthayakumar, "Machine learning models for enhanced cutting temperature prediction in hard milling process," *International Journal on Interactive Design and Manufacturing,* vol. 18, pp. 3935–3950, 2024.

[26] Jia Liu, Jiafeng Ye, Fahim Momin, Xinyu Zhang, and Anyi Li, "Nonparametric Bayesian framework for material and process optimization with nanocomposite fused filament fabrication," *Additive Manufacturing*, vol. 54, pp. 102765, 2022.

[27] Ammar Ali, Raja Dilawar Riaz, Umair Jalil Malik, Syed Baqar Abbas, Muhammad Usman, Mati Ullah Shah, In-Ho Kim, Asad Hanif, and Muhammad Faizan, "Machine Learning-based predictive model for tensile and flexural strength of 3D-Printed concrete," *Materials,* vol. 16, pp. 4149, 2023.

[28] Iván La Fé-Perdomo, Jorge A. Ramos-Grez, Ignacio Jeria, Carolina Guerra, and Germán Omar Barrionuevo, "Comparative analysis and experimental validation of statistical and machine learning-based regressors for modeling the surface roughness

and mechanical properties of 316L stainless steel specimens produced by selective laser melting," *Journal of Manufacturing Processes*, vol. 80, pp. 666-682, 2022.

[29] M. Q. Tanveer, G. Mishra, S. Mishra, and R. Sharma, "Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts-a current review," *Materials Today: Proceedings*, vol. 62, pp. 100-108, 2022.

[30] Doina Frunzaverde, Vasile Cojocaru, Nicoleta Bacescu, Costel-Relu Ciubotariu, Calin-Octavian Miclosina, Raul Rusalin Turiac, and Gabriela Marginean, "The influence of the layer height and the filament color on the dimensional accuracy and the tensile strength of FDM-printed PLA specimens," *Polymers*, vol. 15, pp. 2377, 2023.

[31] F. Kartal, and A. Kaptan, "Investigating the effect of nozzle diameter on tensile strength in 3D-Printed printed polylactic acid parts," *Black Sea Journal of Engineering and Science*, vol. 6, pp. 276-287, 2023.

[32] A. N. Dickson, J. N. Barry, K. A. McDonnell, and D. P. Dowling, "Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing," *Additive Manufacturing*, vol. 16, pp. 146-152, 2017.

[33] Andreas K. Lianos, Tianyang Zhou, Suzanne R. Peterson, Pavan V. Kolluru, Dimitris C. Lagoudas, and Satish T.S. Bukkapatnam, "Towards spatial property control of the glass transition temperature and microstructure of 3d printed shape memory polymers via set-point tuning of the extrusion temperature and extraction of the underlying physical model with gaussian process regression," *Journal of Manufacturing Processes*, vol. 119, pp. 1022-1032, 2024.

[34] N. Fountas, P. Kostazos, H. Pavlidis, V. Antoniou, D. Manolakos, and N. Vaxevanidis, "Experimental investigation and statistical modelling for assessing the tensile properties of FDM fabricated parts," *Procedia Structural Integrity*, vol. 26, pp. 139-146, 2020.

[35] J. Nagarjun, S. Manimaran, and M. Krishnaprakash, "Additive manufacturing of nylon parts and implication study on change in infill densities and structures," *Futuristic Trends in Intelligent Manufacturing: Springer*, pp. 245–260, 2021.