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The Effect of Fused Deposition Modeling Parameters (FDM) on the Mechanical Properties of Polylactic Acid (PLA) Printed Parts

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ABSTRACT

The most common method for additive manufacturing of thermoplastics is fused deposition modeling (FDM), which is becoming a growing trend in a variety of engineering applications since it can easily create intricate parts. The appropriate choice of process parameters has a significant impact on the mechanical qualities of 3D-printed parts. This study examined the effect of four crucial process variables on the tensile strength of polylactic acid (PLA) samples: infill density, printing speed, build orientation, and layer thickness. Samples were printed in accordance with ASTM D638 using an FDM 3D printer. The findings of this study show that the tensile strength of the PLA-printed samples is highly influenced by factors such as layer thickness, build orientation, and infill density. The PLA-printed samples' tensile strength and Young's modulus were significantly affected by the 90° orientations, hollow infill, 0.4 mm thickness, and 100 mm/s speed. Therefore, as the FDM 3D printer becomes progressively more significant for manufacturing engineering components, finding the parameter values that may lead to stronger mechanical and physical characteristics would definitely help designers and manufacturers globally.

1. Introduction

The aforementioned problems may be resolved by additive manufacturing (AM) technology, commonly referred to as three-dimensional (3D) printing, because of its adaptable design, ease of manufacture, reduced production costs, and less waste of raw materials [1-3]. A number of methods for AM are available for purchase on the market, including stereolithography, laminated object manufacturing, inkjet modeling, and fused deposition modeling (FDM). But unlike other AM methods that use various laser systems, resins and powders, FDM is a commonly used technology that includes extruding semi-solid thermoplastic material via a nozzle [4-6]. Processing times can be significantly

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shortened by employing lightweight materials to create complicated geometries with the use of FDM [7].

The most widely studied thermoplastic polymers used in the FDM technique are polylactic acid (PLA), acrylonitrile–butadiene styrene (ABS), polyethylene terephthalate (PET), polypropylene (PP), and high-density polyethylene (HDPE) [8–10]. One of these polymers, PLA, has drawn a lot of attention since it is bio-based and biodegradable and can effectively replace plastics made from petrochemicals [11]. PLA is extremely compatible with a broad spectrum of FDM equipment due to its low melting point and significantly reduced molecular weight [12]. Based on current research, a variety of printing parameters, including nozzle temperature, infill pattern, nozzle diameter, printing speed, build orientation, infill density, layer thickness, etc., can be altered to improve the mechanical performance of printed parts [13–15]. Therefore, in order to produce components with improved dimensional accuracy and improved mechanical functioning, it is imperative to manage and regulate all of these aspects effectively within the FDM manufacturing process [16].

The literature revealed that there had not been much research conducted regarding the effects of the configurations for the FDM 3D printer (UpPlus model) utilizing PLA filament. The majority of earlier studies look into how different parameter settings affect 3D printer models like the CubePro, FlashForge, and MakerBot. This study aims to evaluate the impacts of 3D printing parameters on the mechanical properties of PLA material manufactured by an FDM 3D printer, such as tensile strength, Young's modulus, elongation at break, and maximum load. Other researchers who work with PLA material could derive great insights from the study's results, which will be a useful dataset in the field of additive manufacturing.

2. Materials and Methods

The main objective of this study was to conduct research into how 3D printing settings affected the mechanical characteristics of PLA specimens. Figure 1 depicts the study's methodology used for the project. The initial stage involved planning and setting up the experiment, in which the 3D printing control configurations were carefully selected. Next, using CAD software, a 3D printer was used to create the model of the tensile specimen. After that, tensile tests were performed on each printed sample.

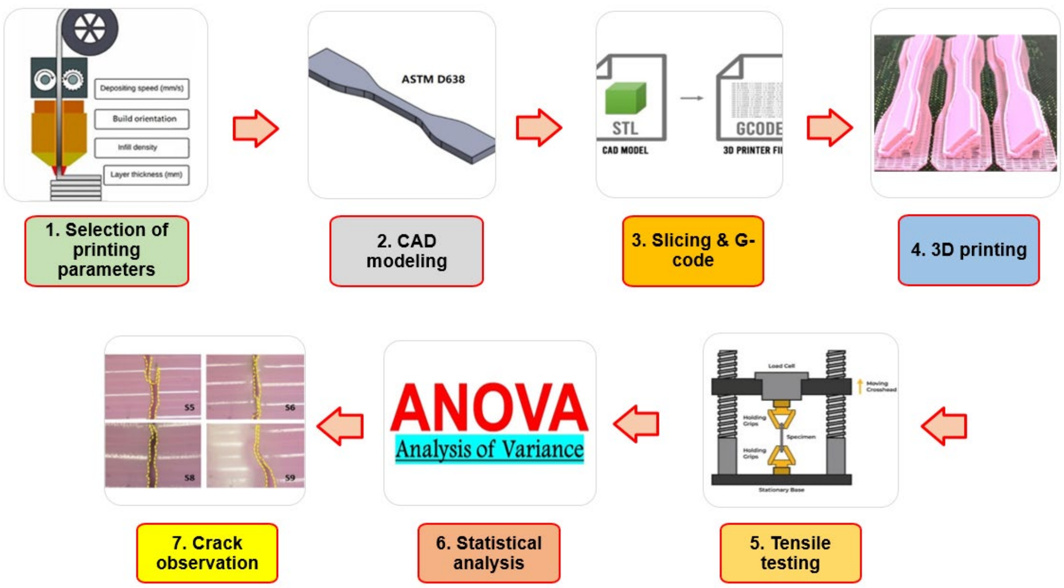

Fig. 1. Flow Diagram of Research Methodology

2.1 Materials

PLA's favourable printing attributes and simplicity of usage as a 3D printing filament make it one of the most widely utilized thermoplastics for FDM. Compared with conventional polymers, this biodegradable thermoplastic material comes from greener sources, has fewer potentially dangerous ingredients, and can be manufactured at lower temperatures, saving energy [17]. PLA filaments with a 1.75 mm diameter were purchased for this research from eSUN in Shenzhen, China. Before being used, filaments were kept out of the way by being kept in plastic desiccators with silica gel inside to prevent moisture adsorption.

2.2 Selection of Printing Parameters

Figure 2 shows the selected printing parameters; printing speed (10, 50 and 100 mm/s), orientation (0, 45 and 90°), infill (solid, loose and hollow) and layer thickness (0.2, 0.3 and 0.4 mm). The desire to preserve the mechanical performance and printing quality of 3D-printed parts encouraged the selection of the parameters. Tensile tests were performed in nine sets, with three replicates for each set. The experiment's response was determined by tensile strength (MPa), Young's modulus (GPa), maximum load (N), and elongation at break (mm).

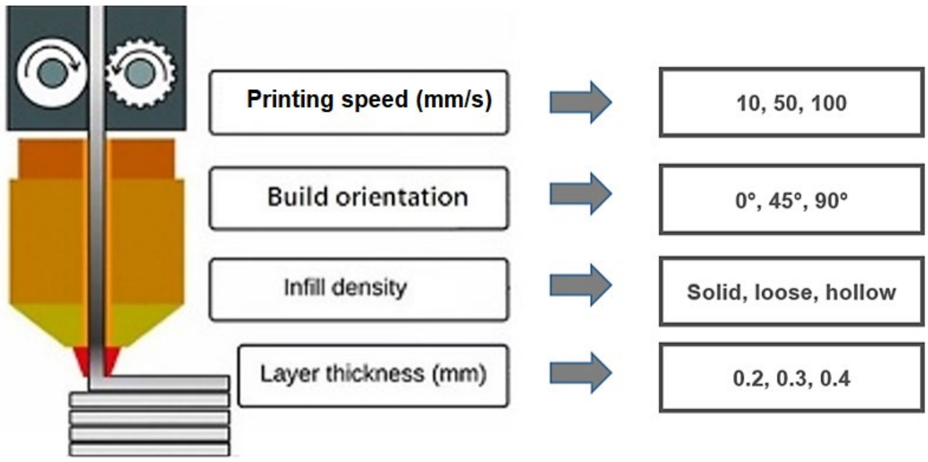

Fig. 2. Selected Printing Parameters

2.3 Printing Process

The specimens were printed using a 3D printer (UP Plus 2, Beijing, China) with a 0.4 mm nozzle diameter in accordance with the experiment's design table. The UP Studio 3 slicer software is utilized by this printer to slice the 3D model and adjust multiple variables of the 3D printing process, including layer thickness, printing speed, infill type, heated bed temperature, and fan speed. Standard tessellation language (STL) files were created from the models once the test pieces were designed by Catia V9 software. These files were used to position the model for the construction process and numerical slicing, enabling the FDM-3D printer to produce layers by layers. Next, using the USB or SD card connector on the FDM 3D printer, the G-code file was uploaded. To assure printing precision and accuracy, all samples were printed horizontally, with the print head axis aligned.

2.4 Tensile Testing

Tensile tests were carried out on dog-bone samples in accordance with ASTM-D638, type IV specifications, with dimensions of 115 mm (length) × 19 mm (width) × 3.2 mm (thickness). All the samples were performed using a universal testing machine (Instron 5969, MA, USA), equipped with a 50 kN load cell and a constant crosshead speed of 5 mm/min.

2.5 Statistical Analysis

The significant difference in the primary factors was ascertained by applying one-way ANOVA. According to Ahmad et al. [18], an ANOVA was also utilized to determine the significant factor influencing the experimental conditions**.**

2.6 Microscopic Analysis

The fractured or cracked samples were observed by an optical microscope (Nikon LV, Japan).

3. Results and Discussion

3.1 Mechanical Properties

Figure 3 shows the fractured tensile samples (after tensile testing) from a series of experiments, E1 to E9. All printed samples failed at the necking area, and the experiment's results were collected successfully. Figure 4 depicts the tensile strength, Young's modulus, maximum load, and elongation at break for E1-E9 samples. According to the results, the E9 samples exhibited the highest tensile strength and Young's modulus values of 42.7 MPa and 2.9 GPa, respectively, as shown in Figure 4(a). This also demonstrated the relationship between tensile strength and modulus, with increasing tensile strength leading to greater Young's modulus. However, E5 samples had the lowest tensile strength (30.5 MPa) and. In addition, the E1 and E7 samples had lower Young's modulus values than the rest. Figure 4(b) shows a graph of tensile strength vs maximum load for all samples. This graph pattern demonstrates how tensile strength increased as the maximum load ascended. However, the relationship between tensile strength and elongation at break differs, as seen in Figure 4(c).

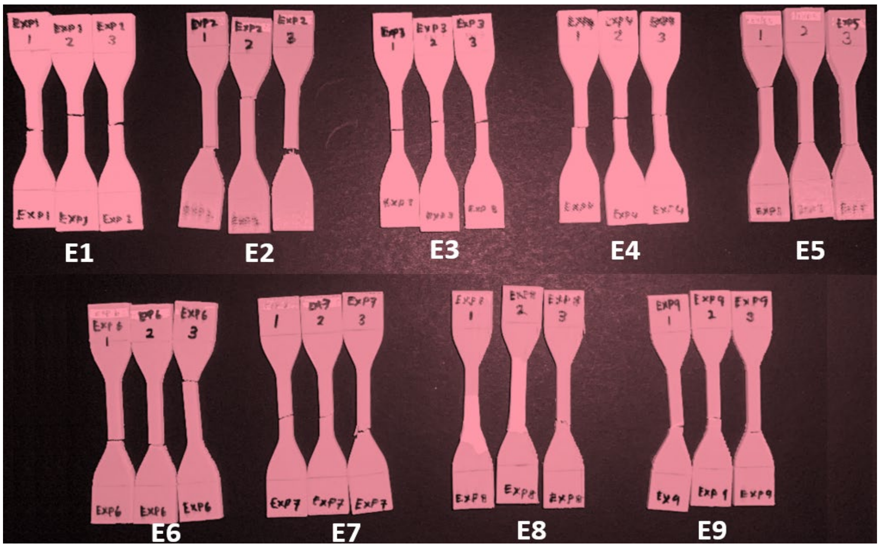

Fig. 3. Fractured Tensile Samples (E1 – E9)

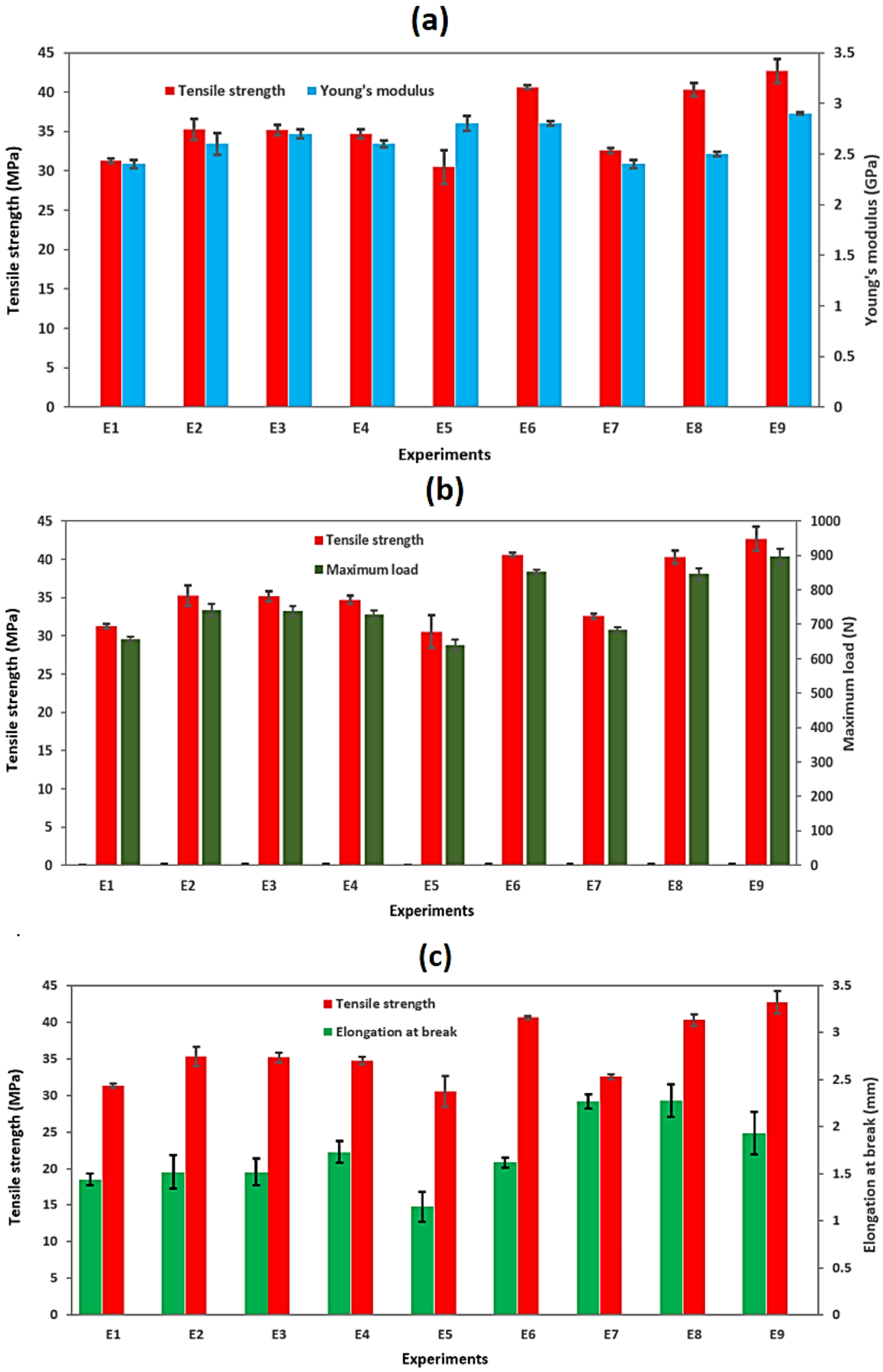

Fig. 4. Graphs of (a) tensile strength vs. Young's modulus (b) tensile strength vs. maximum load and (c) tensile strength vs. elongation at break

According to the results, the E9 sample exhibits significant mechanical properties. As a consequence, the parameters of 90° orientation, infill (hollow), 0.4 mm thickness, and 100 mm/s speed were found to have a substantial effect on the tensile strength and Young's modulus of PLA samples. Furthermore, the results showed that the samples' tensile strength rose as layer thickness grew. Previous research utilizing PLA filament reported the same pattern of increasing tensile strength [15,19]. Furthermore, an increase in the thickness of each layer allows the flow of the partially melted substance within the increased gaps between the printed paths, resulting in a significant improvement in its rigidity [20]. Table 1 shows the results of one-way ANOVA for tensile strength, maximum load, elongation at break and Young's modulus. One-way ANOVA with a confidence interval of 95% was used to examine the main effects of input parameters on each response. In regard to responses, the parameter is significant if the *P*-value is less than 0.05. The result indicates that the infill pattern had the significant impact on the value of tensile strength (*P*-value is 0.047) and elongation at break (*P*-value is 0.013). However, all printing parameters were not significantly different for Young's modulus and flexural strength, where the *P*-value was greater than 0.05.

Table 1
One-way ANOVA for all responses

Response	Source	DF	SS	SS err	MS	MS err	F-value	P-value
	Thickness	2	33.6	117.6	16.8	19.6	0.86	0.47
	Orientation	2	67.3	83.9	33.7	14	2.41	0.171
Tensile strength	Infill	2	61.8	89.4	30.9	14.9	12.07	0.047
	Speed	2	46.8	104.4	23.4	17.4	1.34	0.329
	Error	6	395.3			65.9		
	Total	8	604.8					
	Thickness	2	62689	202267	31344	33711	0.93	0.445
	Orientation	2	137689	127267	68844	21211	3.25	0.111
Young's modulus	Infill	2	13089	251867	6544	41978	0.16	0.859
	Speed	2	10689	254267	5344	42378	0.13	0.884
	Error	6	835668			139278		
	Total	8	1059824					
	Thickness	2	14784	52013	7392	8669	0.85	0.472
	Orientation	2	29692	37105	14846	6184	2.4	0.171
Maximum load	Infill	2	27239	39558	13619	6593	2.07	0.208
	Speed	2	20809	45988	10404	7665	1.36	0.326
	Error	6	174664			29111		
	Total	8	267188					
	Thickness	2	0.8801	0.2735	0.44	0.0456	9.65	0.013
	Orientation	2	0.043	1.11	0.022	0.185	0.12	0.891
Elongation at break	Infill	2	0.9763	0.1773	0.4881	0.0295	16.52	0.004
	Speed	2	0.124	1.029	0.062	0.172	0.36	0.711
	Error	6	2.5898			0.4321		
	Total	8	4.6132					

Note: P-value < 0.05 is significant; DF is degree of freedom; SS err is sum of square error; SS is sum of square; MS is mean square; MS err is mean of square error

3.1 Cracked Propagation

Figure 5 shows the fractured cross-section of nine specimens. The fracture surfaces of all specimens were perpendicular to the load direction which indicates a quasi-brittle behavior. Starting at the necking area, the cracks continued to grow in an uneven pattern. The result indicates that the type of crack for S2, S5, S6, S8 and S9 samples was horizontal type. Whereby, for S1, S3, S4 and S7 samples show the crack pattern was diagonal type. Theoretically, the samples with diagonal crack will result the less in mechanical properties. It is proved that the S1 and S7 samples had diagonal cracked showed the lower value in tensile and flexural strength.

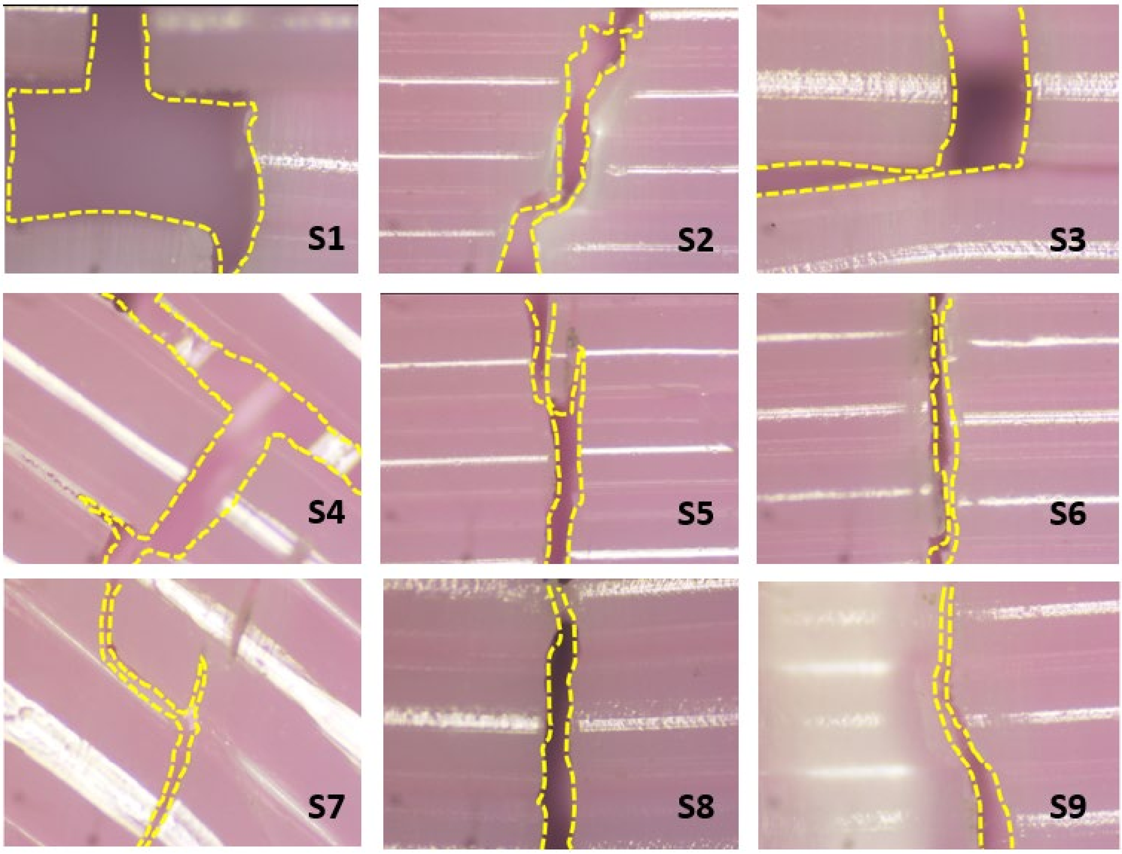

Fig. 5. Microscopic images on crack pattern of S1-S9 samples

4. Conclusions

In this study, the effect of printing parameters on the mechanical properties of PLA-printed samples utilizing FDM was investigated. The samples were evaluated by tensile testing (ASTM D638). The parameters of 90° orientation, 0.4 mm thickness, hollow infill, and 100 mm/s speed were found to have a substantial effect on the tensile strength and Young's modulus of PLA-printed samples. Based on experiments, the following factors influence mechanical performance in order of preference: layer thickness, orientation, printing speed, and infill. The results of the optical microscope observation show that the samples had cracks of the horizontal and diagonal types. This study provides adequate information on FDM-3D printing utilizing PLA filament in the polymer industries, automotive components, and consumer goods industries. Future recommendations include carrying out the process of printing in a vacuum chamber to improve the final print results. This is because the nozzle transfers less heat, resulting in a smooth and steady reduction in the polymer's temperature, which strengthens the bonds between the layers.

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References

[1] Jayawardane, Heshan, Ian J. Davies, J. R. Gamage, Michele John, and Wahidul K. Biswas. "Sustainability perspectives–a review of additive and subtractive manufacturing." *Sustainable Manufacturing and Service Economics* 2 (2023): 100015. https://doi.org/10.1016/j.smse.2023.100015

[2] Ahmad, Mohd Nazri, Mohamad Ridzwan Ishak, Mastura Mohammad Taha, Faizal Mustapha, and Zulkiflle Leman. "Finite element analysis of oil palm fiber reinforced thermoplastic composites for fused deposition modeling." *Materials Today: Proceedings* 74 (2023): 509-512. https://doi.org/10.1016/j.matpr.2022.12.052

[3] Ahmad, Mohd Nazri, Mohamad Ridzwan Ishak, Mastura Mohammad Taha, Faizal Mustapha, and Zulkiflle Leman. "Rheological properties of natural fiber reinforced thermoplastic composite for fused deposition modeling (FDM): a short review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 98, no. 2 (2022): 157-164. https://doi.org/10.37934/arfmts.98.2.157164

[4] Matsuzaki, Ryosuke, Masahito Ueda, Masaki Namiki, Tae-Kun Jeong, Hirosuke Asahara, Keisuke Horiguchi, Taishi Nakamura, Akira Todoroki, and Yoshiyasu Hirano. "Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation." *Scientific reports* 6, no. 1 (2016): 23058. https://doi.org/10.1038/srep23058

[5] Jayawardane, Heshan, Ian J. Davies, J. R. Gamage, Michele John, and Wahidul K. Biswas. "Investigating the 'techno-eco-efficiency'performance of pump impellers: metal 3D printing vs. CNC machining." *The International Journal of Advanced Manufacturing Technology* 121, no. 9 (2022): 6811-6836. https://doi.org/10.1007/s00170-022-09748-2

[6] Uddin, M. Sidek, M. F. R. Sidek, M. A. Faizal, Reza Ghomashchi, and Alokesh Pramanik. "Evaluating mechanical properties and failure mechanisms of fused deposition modeling acrylonitrile butadiene styrene parts." *Journal of Manufacturing Science and Engineering* 139, no. 8 (2017): 081018. https://doi.org/10.1115/1.4036713

[7] Maguluri, Nagarjuna, Gamini Suresh, and K. Venkata Rao. "Assessing the effect of FDM processing parameters on mechanical properties of PLA parts using Taguchi method." *Journal of Thermoplastic Composite Materials* 36, no. 4 (2023): 1472-1488. https://doi.org/10.1177/08927057211053036

[8] Badia, J. D., and A. Ribes-Greus. "Mechanical recycling of polylactide, upgrading trends and combination of valorization techniques." *European Polymer Journal* 84 (2016): 22-39. https://doi.org/10.1016/j.eurpolymj.2016.09.005

[9] Sabil, Mohammed, and D. A. P. Prabhakar. "Optimisation of extrusion temperature and infill density of PLA material by using L16 orthogonal array." *Australian Journal of Mechanical Engineering* 22, no. 2 (2024): 241-257. https://doi.org/10.1080/14484846.2022.2073022

[10] Hikmat, Mohammed, Sarkawt Rostam, and Yassin Mustafa Ahmed. "Investigation of tensile property-based Taguchi method of PLA parts fabricated by FDM 3D printing technology." *Results in Engineering* 11 (2021): 100264. https://doi.org/10.1016/j.rineng.2021.100264

[11] Jayawardane, Heshan, Ian J. Davies, J. R. Gamage, Michele John, and Wahidul K. Biswas. "Additive manufacturing of recycled plastics: a 'techno-eco-efficiency'assessment." *The International Journal of Advanced Manufacturing Technology* 126, no. 3 (2023): 1471-1496. https://doi.org/10.1007/s00170-023-11169-8

[12] Torres, Jonathan, Matthew Cole, Allen Owji, Zachary DeMastry, and Ali P. Gordon. "An approach for mechanical property optimization of fused deposition modeling with polylactic acid via design of experiments." *Rapid Prototyping Journal* 22, no. 2 (2016): 387-404. https://doi.org/10.1108/RPJ-07-2014-0083

[13] Pinho, Ana C., Ana M. Amaro, and Ana P. Piedade. "3D printing goes greener: Study of the properties of post-consumer recycled polymers for the manufacturing of engineering components." *Waste Management* 118 (2020): 426-434. https://doi.org/10.1016/j.wasman.2020.09.003

[14] Atakok, Gurcan, Menderes Kam, and Hanife Bukre Koc. "Tensile, three-point bending and impact strength of 3D printed parts using PLA and recycled PLA filaments: A statistical investigation." *Journal of Materials Research and Technology* 18 (2022): 1542-1554. https://doi.org/10.1016/j.jmrt.2022.03.013

[15] Tan, Wilson Sutanto, Yopi Yusuf Tanoto, Ninuk Jonoadji, and Albertus Andrie Christian. "The effect of cooling and temperature in 3D printing process with fused deposition modelling technology on the mechanical properties with polylactic acid recycled material." PhD diss., Petra Christian University, 2021. https://doi.org/10.15866/ireme.v15i12.21573

[16] Ahmad, Mohd Nazri, Mohamad Ridzwan Ishak, Mastura Mohammad Taha, Faizal Mustapha, Zulkiflle Leman, Debby Dyne Anak Lukista, Irianto, and Ihwan Ghazali. "Application of Taguchi method to optimize the parameter of fused deposition modeling (FDM) using oil palm fiber reinforced thermoplastic composites." *Polymers* 14, no. 11 (2022): 2140. https://doi.org/10.3390/polym14112140

[17] Farazin, Ashkan, and Mehdi Mohammadimehr. "Effect of different parameters on the tensile properties of printed Polylactic acid samples by FDM: experimental design tested with MDs simulation." *The International Journal of Advanced Manufacturing Technology* 118, no. 1 (2022): 103-118. https://doi.org/10.1007/s00170-021-07330-w

[18] Ahmad, Mohd Nazri, and Abdullah Yahya. "Effects of 3D printing parameters on mechanical properties of ABS samples." *Designs* 7, no. 6 (2023): 136. https://doi.org/10.3390/designs7060136
[19] Lanzotti, Antonio, Massimo Martorelli, Saverio Maietta, Salvatore Gerbino, Francesco Penta, and Antonio Gloria. "A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA." *Procedia Cirp* 79 (2019): 143-146. https://doi.org/10.1016/j.procir.2019.02.030
[20] Dave, Harshit K., Ashish R. Prajapati, Shilpesh R. Rajpurohit, Naushil H. Patadiya, and Harit K. Raval. "Open hole tensile testing of 3D printed parts using in-house fabricated PLA filament." *Rapid Prototyping Journal* 26, no. 1 (2020): 21-31. https://doi.org/10.1108/RPJ-01-2019-0003