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The Influence of the Layer Orientation on Ultimate Tensile Strength of 3D Printed Poly-lactic Acid

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Abstract

A significant increase in 3D printing technology has been done primarily in the twenty-first century, where there are many research works going on in different fields, such as aerospace, automotive, and medical sectors to improve the 3D printing technology. This paper investigates the effect of printing with four different methods on the tensile strength of the Fused Deposition Modeling printed Polylactic Acid parts. Experimental and statistical analysis found that there is no effect in horizontal printing in both ways, but there is a significant difference in other printing methods.

Keywords: 3D-printing, Polylactic Acid (PLA), Ultimate tensile strength, Fused deposition modelling (FDM), Hypothesis testing.

1. Introduction

Additive manufacturing (AM) has evolved tremendously since the patent filing of stereolithography technology (SLA) in the mid-80s [1] into a diverse array available in the market, and founded process categories for polymer processing, which are classified by ISO/ASTM 52900 such as powder bed fusion (PBF), vat photopolymerisation (VP), material extrusion (ME), and material jetting (MJ) [2]. The principle of AM to create final parts directly from CAD models now led to the notion of rapid manufacturing (RM) [1]. According to researchers, RM will significantly impact product development and manufacturing and aid a range of economic and societal effects, and it will be able to create environmentally beneficial designs. [3], [4]. In the coming decade, AM will significantly impact the economy and society [5].In comparison to other techniques, AM has a significant advantage in manufacturing complex-shaped components with multi-material. Moreover, throughout the printing process, a considerable amount of raw materials could be saved. 3D printing products are now widely used in a variety of sectors, such as food [6], aerospace [7], civil engineering [8], automobileindustry [9], [10], AM promotes the implementation of soft and hard tools to assist and reduce the manufacturing process time and enhance mass-replication operations, on the shop floor [11] and produce robust and lightweight parts [7] and spare parts supply chain [12]. The medical field also has a good portionof AM technology [13], [14]. As the Food and Drug Administration confirmed the first 3D printed drug in 2015, there has been an increasing interest in 3D printing of drugs [15].Fused deposition modelling (FDM), as well recognised as fused Filament Fabrication (FFF), is one of the most commonly used in Polymer additive manufacturing (AM)with outstanding mechanical, thermal, and chemical endurance [16], [17]. In comparison to other AM technologies, the FDM approach is significantly simple to set up and use. Several scientific researchers concur that FDM three-dimensional (3D) components are made through heating a fibre thermoplastic polymer filament to near the fusing temperature, then depositing it in an almost molten condition to form the required shape using a heated round spout. When the fibrethermoplastic polymer becomes cold, the material's mechanical properties, like tensile strength and strain, may change. FDM process parameters, such as printing speed, raster angle, layer height, and printing orientation have a significant impact on pattern qualities, and accurate level selection is also critical for component production. The effects of different parameters on responses were investigated in research to evaluate the characteristics of components. Experiments were carried out using a design of experiment (DOE) technique, and the results showed that process parameters, such as air gap, layer height, andraster angle have a significant impact on the responses of FDM-based ABS patterns [18], [19]. An experimental investigation studied the influence of build orientation on strength properties using three distinct AM technologies (3D printer, nano-composite deposition (NCDS), and FDM to produce cylindrical pieces [20]. By conducting various parameters of the FDM process, Anitha et al. used the Taguchi approach to examine the quality attributes of the prototypes [21]. Component orientation and support creation are two important challenges in layer manufacturing. The production of prototypes should be as

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rapidly as feasible. The most advantageous build orientation of components can shorten lead times and save overall prototype costs. Also, part orientation must be continuously maintained to such a degree that the least amount of support is required. Furthermore, the part must be firmly supported in such a way that the entire contact surface of the support is kept to a minimum during the prototyping process. As a result, the support structure has a limited impact on the prototype's surface properties [22]**.**The pause of printing is needed for some purposes, for example, changing the filament colour, adding an electronic device like sensor or transisitor, and adding a support material with different properties. This replacement takes time before resuming the printing, especially if there is just one extruder [23], [24]. This paper aims to investigate the Ultimate Tensile Strength (UTS) in different printing ways. The null hypothesis was that different printing methods and different printing orientations would have similar UTS. The rest of this article is set out as follows. The used materials, dimensions of the samples, testing machine, and statistical analysis are illustrated in section 2.The resultsof the experimental data and the discussion have also been analysed in section 3. The statistical analysis for the results and the suggested hypothesis is explained in details in section 4. The findings of this article have been explained in the last section.

2. Experiment details and methodology

2.1. printing machine and printing material

In this work, a FDM 3D printing machine was the Original Prusa i3 MK3S+ 3D, the USA was used (see Table 1 for basic technical details [25]). Parts are created with a Prusament polylactic acid (PLA) filament which is one of the environmentally-safe polymers and can be degradable [26] [27], which is green in colour, 1.75 mm in diameter, and has a tolerance of 0.05 mm, and the properties are shown in Table 2 [28], [29]. A total of twenty specimens were printed in four different ways, with five samples in each mode. The printing ways were continuous horizontal orientation, continuous vertical orientation, horizontal orientation with a pause, and vertical orientation with a pause. The pause was after 1 mm of printing (after printing the half of specimen), and the printing resumed after the specimen temperature reached room temperature. All samples were produced along the x-axis with a raster angle of +45°/-45° as shown in Figure 1 and the printed parameters were illustrated in Table 3. The experiment began with a 3D modelling design created with solid edge 3D modelling software. Solid Edge 3D is a widely used software in various sectors, such as architecture, electronic parts, manufacturing, and aviation. Solid Edge 3D software has very impressive characteristics, like the range of platforms in its mechanical engineering industry, which allows for creating one-of-a-kind design elements. A three-dimensional design (STL format file) was created according to the standard ISO 527 with 130 mm long, 20 mm in depth, and 2 mm in thickness, shown in Figure 2.

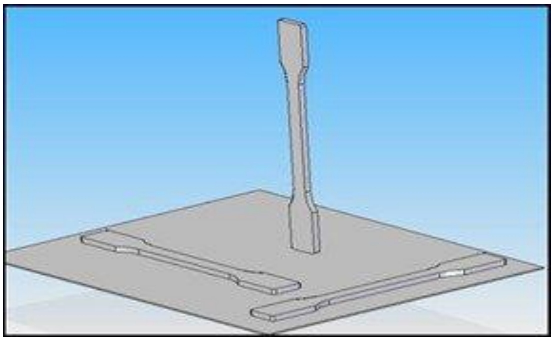

Figure 2. Printed Specimen

Table 1. Basic technical details for Prusa i3 [25].

Technical Parameters	Value	Unit
Build volume	25 x 21 x 21	mm
Layer height	0.05 – 0.35	mm
Maximum travel speed	200	mm/s
Maximum hotend/heatbed temperature	300 / 120	°C
Filament diameter	1.75	mm
Nozzle diameter	0.4	mm (default)

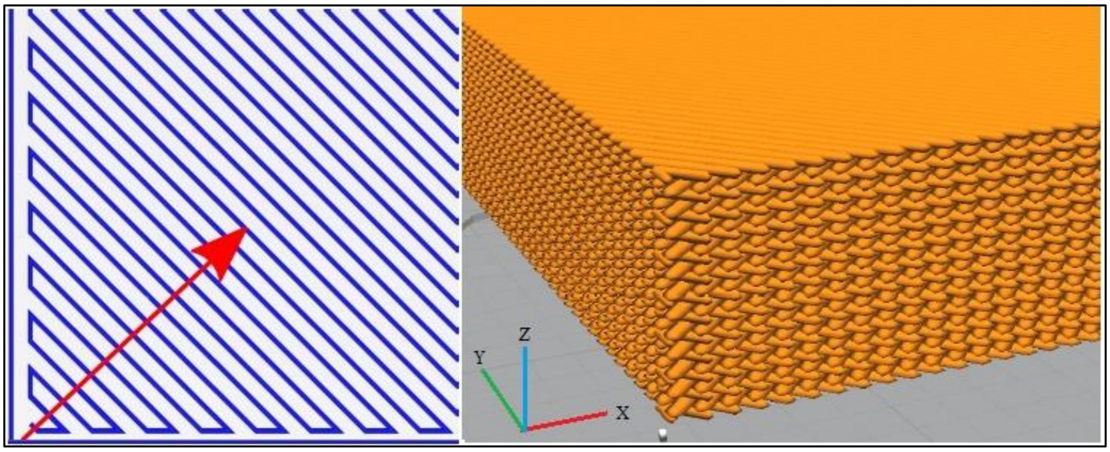

Figure 1. Raster angle+45°/-45°.

Table 2 .Property ranges for PLA materials produced using the FDM technique [28], [29].

Properties	PLA	Reference
Tensile strength (MPa)	15.5–72.2	[29]
Tensile modulus (GPa)	2.020–3.550	[29]
Elongation at break (%)	0.5–9.2	[29]
Flexural strength (MPa)	52–115.1	[29]
Flexural modulus (GPa)	2.392–4.930	[29]
Printing Temperature (˚C)	190–220	[28]
Printing Speed (mm/s)	40–90	[28]
Chemical composition	$(C_3H_4O_2)n$	[30]

Table 3. Printing parameters for all samples.

Printing parameter	Value	Unit
Nozzle temperature	215	°C
Bed temperature	30	°C
Printing speed	60	mm/s
Wall speed	50	mm/s
Wall thickness	0.4	mm
Layer height	0.2	mm
Infill density	100	%

The STL file model istransformed into a series of commands for printing layers in the FDM 3D printer, Ultimaker Cura. This software generates a G-Code (G-Programming Language) template providing the whole set of commands and directives to the desired 3D printer, such as printing orientation, speed, nozzle temperature, supports, wall thickness, infill density, and material. This file drives the circular nozzle of the FDM 3D printer and determines the particular routes and paths of printing. The FDM 3D printer uses the G-Code file commands to create the required solid part by extruding the heated PLA filament from the nozzle head and forming a sequence of thin slices upon each other on the bedplate. The circular nozzle moves horizontally along a linear route for each layer. After finishing printing, as shown in Figure , tensile tests are used in this paper to evaluate the mechanical characteristics of PLA materials produced using 3D printing technology. Figure shows how ZwickiLine was used for small test loads up to 5 kN. The tensile test speed is 5 mm/min, and the laboratory room temperature remains constant at 24 °C during the tensile process. As a result, it can be verified that the test conditions are ambient temperature and semi-equilibrium loading [31].

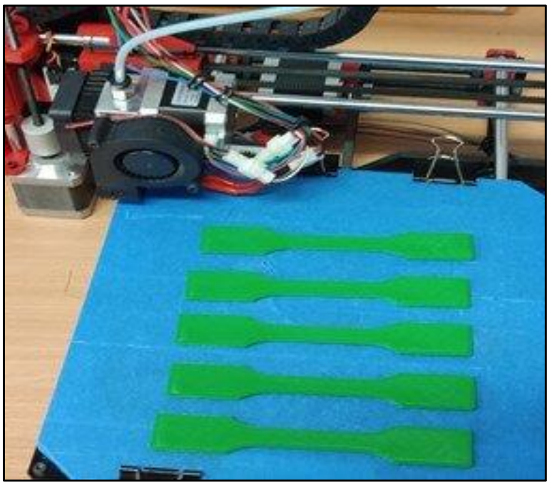

Figure 3. Printed specimens.

Figure 4. Tensile testing machine.

2.2. Statistical analysis

Many statistical tests are used to perform hypothesis testing for mean comparison like Tueky, Bonferroni, Dunn-Sidak, Scheffé, Fisher's Lsd, Holm-Sidak. This paper analysed the data using the Bonferroni method (ANOVA) to analyse the UTS results using OriginLab 2018 software.Before starting the hypothesis testing. Two parameters must be determined, the confidence level and the significant level (α). The confidence level denotes the chance that the estimation of a statistical parameter's location in a sample test is also true for the population.Before performing a test, confidence levels should be determined in advance since the error margin, and the test's required scope depends on the confidence level. From 90%-99%, confidence levels are commonly used in testing, and the confidence level =1 - α. The significance level (α) is the probability of rejecting the null hypothesis when it is true. Theconfidence level and the significant level for the statistical analysis in this paper are 95% and 0.05, respectively.

In statistical analysis, the Bonferroni test is a form of multiple comparison test named after Italian mathematician Carlo Emilio Bonferroni (1892–1960) [32]. When doing a hypothesis test with many comparisons, a result indicating statistical significance in the dependent variable may ultimately arise, even though there is none [33]. According to the Bonferroni test, each test's P-value must be equal to its alpha (α) divided by the number of tests executed. The significance level refers to the likelihood that the Bonferroni test would wrongly detect a variation in the sample that does not exist in the population (false positive) means. A 0.05 significance level is a widely used significance level. This study tested 6 comparisons (continuous horizontal vs horizontal with a pause, continuous horizontal vs continuous vertical, horizontal with a pause vs continuous vertical, continuous horizontal vs vertical with a pause, horizontal with a pause vs vertical with a pause, and continuous vertical vs vertical with a pause), there might be up to a 30% likelihood (0.05 + 0.05 + 0.05 + 0.05 + 0.05 + 0.05) that any one of them would demonstrate significant change by chance. By dividing the significance level by the number of tests, the Bonferroni adjustment corrects this. The significance level for a given comparison in this study would be 0.0083, with a chance of incorrectly detecting a difference of no more than 0.05.

3. Results and discussion

3.1. Experimental results

After printing the five specimens for every printing way, the average curve was drawn to find Young's modulus which represents the slope of the curve based on equation (1) as shown below [34]. The results of the tensile test shown in Table 2 and 5 illustrated that:

$$E = \frac{\sigma}{\varepsilon} \quad (1)$$

Table 2. UTS for all printed specimens.

Printing orientation	UTS	Average UTS	SD
Continuous horizontal	46.70	46.52	±0.27
	46.68		
	46.04		
	46.60		
	46.56		
Horizontal with a pause	47.54	47.55	±0.95
	47.54		
	48.45		
	48.22		
	46.01		
Continuous vertical	26.99	24.97	±3.70
	26.48		
	18.83		
	28.17		
	24.37		
Vertical with a pause	7.15	11.49	±4.50
	18.76		
	8.89		
	12.40		
	10.26		

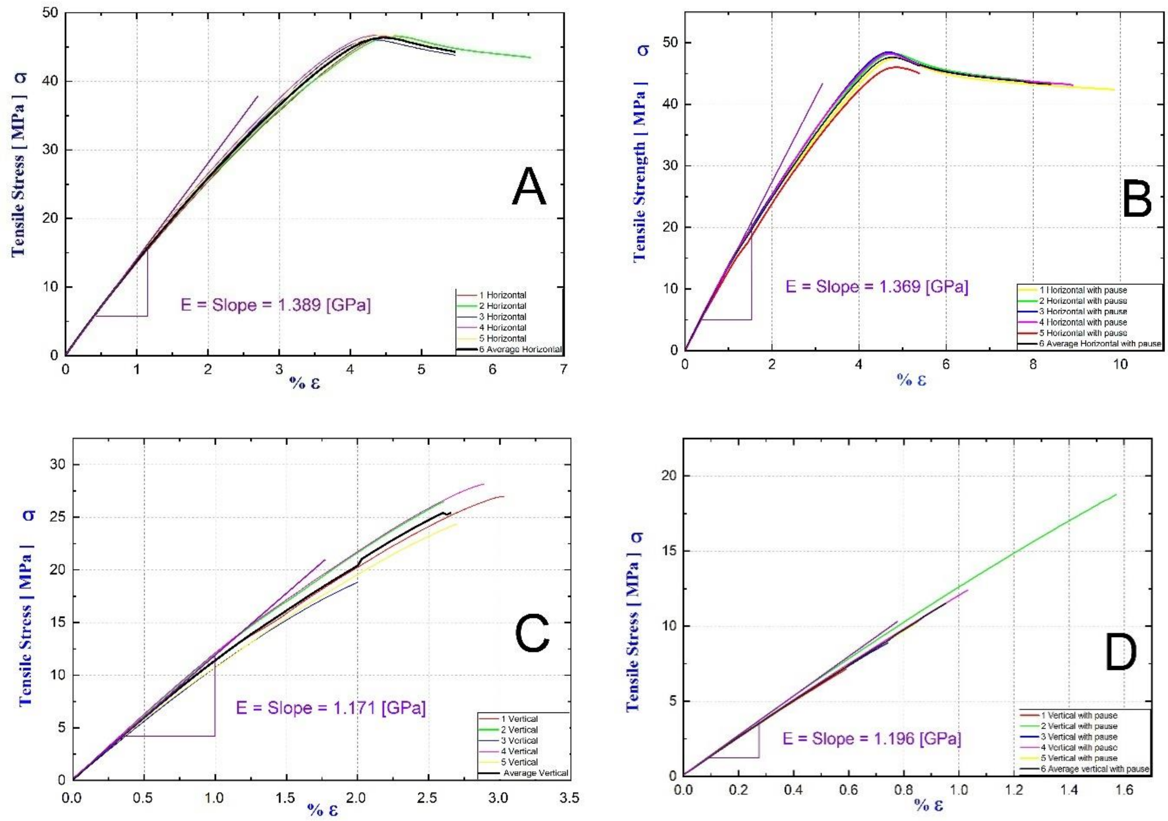

Figure 5. Average curves: continuous horizontal orientation (A), horizontal orientation with a pause (B), continuous vertical orientation (C), and vertical orientation with a pause (D).

The two-way horizontal printing showed a significant difference in the tensile strength than the two-way vertical printing. The UTS for continuous horizontal and horizontal witha pause printing was 46.52±0.27MPa and47.55±0.95MPa, respectively, while in the continuous vertical printing,the UTS was almost half of the continuous horizontal printing with UTS 24.97±3.7,and the vertical with a pauseUTS was the lowest with 11.49±4.5. The difference in the UTS between horizontal and vertical orientation is due to the direction of the test being perpendicular to the filament path.This means that in the horizontal orientation, the fracture happened in all layers while in the vertical orientation, the fracture happened just between two layers. Figure shows the box plot of the UTS of the four different ways of printing.

A material's Young's(Elastic) modulus is an essential, fundamental characteristic that defines how the material deforms when stressed [35]. It calculates the strain based on the size of the applied compressive or tensile stress. The greater Young's modulus, the less a material deforms in response to a given stress, making it stiffer. Figure illustratesYoung's modulus for the four printing ways.

3.2. Statistical analysis

T-value measures the size of the difference relative to the variation of the sample data. As the t-value increases, the evidence against the null hypothesis increases. The p-value describes how likely is the data randomly occurred by chance.The statistical analyses were done using the Bonferroni method, andTable 3 shows the results.

For horizontal with a pause – continuous horizontal, the t-value is 0.55, and the p-value is 1.0, and according to the Bonferroni test, we failed to reject the null hypothesis. For the rest of the printing methods, we rejected the null hypothesis. Significant equal one denotes that the variation of the means is significant at the 0.05 level and Significant equal zero denotes that the variation of the means is not significant at the 0.05 level.

4. Conclusion

The ultimate tensile strength of 3D printed PLA usingthe FDM method has been investigated.The experimental measurements were done, and the statistical analysis was applied to the results.The null hypothesis was thatdifferent printing methods and orientations might have similar UTS. We found that this hypothesis is true only in continuous horizontal printing and horizontal printing witha pause. The null hypothesis was rejected in continuous vertical printing and vertical printing witha pause. As a result, the pause in horizontal printing will not affect the UTS of the material while there is a significant difference in the UTS in the case of vertical printing.

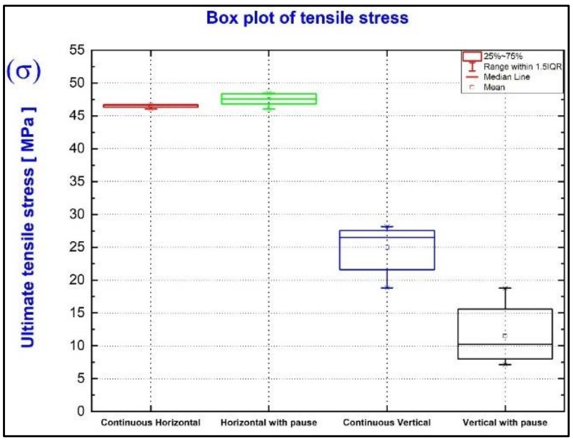

Figure 6. Tensile strength

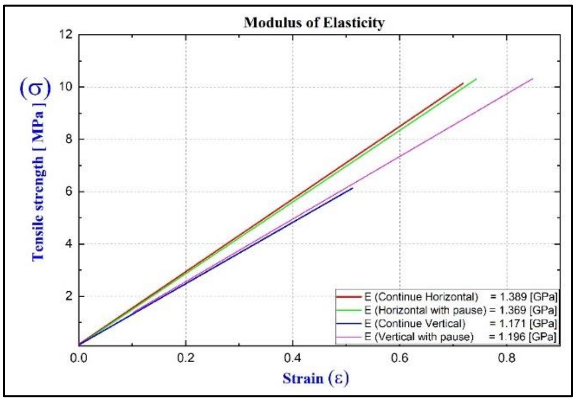

Figure 7. Young's modulus.

Table 3. Hypothesis test results.

Printing comparison	Mean difference	t-value	P-value	α	Significant
Horizontal with a pause – Continuous horizontal	1.04	0.55	1	0.05	0
Continuous vertical – Continuous horizontal	-21.55	-11.54	2.16×10-8	0.05	1
Continuous vertical - Horizontal with a pause	-22.58	-12.10	1.10×10-8	0.05	1
Vertical with a pause – Continuous horizontal	-35.02	-18.76	1.54×10-11	0.05	1
Vertical with a pause – Horizontal with a pause	-36.06	-19.32	9.81×10-12	0.05	1
Continuous vertical – Vertical with a pause	-13.47	-7.22	1.23×10-5	0.05	1

References

[1] M. Wiese, S. Thiede, and C. Herrmann, " Rapid manufacturing of automotive polymer series parts: A systematic review of processes, materials and challenges," Additive Manufacturing, vol. 36. Elsevier B.V., Dec. 01, 2020. doi: 10.1016/j.addma.2020.101582.

[2] DIN EN ISO/ASTM 52900. BeuthVerlag GmbH, Berlin, 2018.

[3] C. Tuck and R. Hague, "The pivotal role of rapid manufacturing in the production of cost-effective customised products," International Journal of Mass Customisation, vol. 1, no. 2/3, p. 360, 2006, doi: 10. 1504/ IJMASSC. 2006. 008630.

[4] T. A. Campbell and O. S. Ivanova, "Additive manufacturing as a disruptive technology: implications of three-dimensional printing, " Technology & Innovation, vol. 15, no. 1, pp. 67–79, Apr. 2013, doi: 10.3727/194982413X13608676060655.

[5] R. Jiang, R. Kleer, and F. T. Piller, "Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030," Technological Forecasting and Social Change, vol. 117, pp. 84–97, Apr. 2017, doi: 10.1016/J.TECHFORE.2017.01.006.

[6] J. I. Lipton, M. Cutler, F. Nigl, D. Cohen, and H. Lipson, "Additive manufacturing for the food industry," Trends in Food Science & Technology, vol. 43, no. 1, pp. 114–123, May 2015, doi: 10.1016/J.TIFS.2015.02.004.

[7] V. Mohanavel, K. S. Ashraff Ali, K. Ranganathan, J. Allen Jeffrey, M. M. Ravikumar, and S. Rajkumar, "The roles and applications of additive manufacturing in the aerospace and automobile sector," Materials Today: Proceedings, vol. 47, pp. 405–409, 2021, doi: 10.1016/j.matpr.2021.04.596.

[8] N. Labonnote, A. Rønnquist, B. Manum, and P. Rüther, "Additive construction: State-of-the-art, challenges and opportunities," Automation in Construction, vol. 72, pp. 347–366, Dec. 2016, doi: 10.1016/J.AUTCON.2016.08.026.

[9] G. N. H. and G. Dudas. Fedorko, "Design of allocation of new technological equipment within the frame of production process in company Getrag Ford Transmissions Slovakia, sro.," ActaMontanisticaSlovaca, vol. 15, pp. 14–22, 2010.

[10]M. R. Talaganiet al., "Numerical simulation of big area additive manufacturing (3D printing) of a full size car," SAMPE journal, vol. 51, no. 4, pp. 27–36, 2015.

[11]J. C. Vasco, "Additive manufacturing for the automotive industry," Additive Manufacturing, pp. 505–530, Jan. 2021, doi: 10.1016/B978-0-12-818411-0.00010-0.

[12]T. Eggenberger, K. Oettmeier, and E. Hofmann, "Additive Manufacturing in Automotive Spare Parts Supply Chains – A Conceptual Scenario Analysis of Possible Effects," in Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017, Springer International Publishing, 2018, pp. 223–237. doi: 10.1007/978-3-319-66866-6_22.

[13]S. Ji and M. Guvendiren, "Recent Advances in Bioink Design for 3D Bioprinting of Tissues and Organs," Frontiers in Bioengineering and Biotechnology, vol. 5, no. APR, Apr. 2017, doi: 10.3389/FBIOE.2017.00023/FULL.

[14]S. Knowlton, B. Yenilmez, and S. Tasoglu, "Towards Single-Step Biofabrication of Organs on a Chip via 3D Printing," Trends in Biotechnology, vol. 34, no. 9, pp. 685–688, Sep. 2016, doi: 10.1016/J.TIBTECH.2016.06.005.

[15]E. Lepowsky and S. Tasoglu, "3D printing for drug manufacturing: A perspective on the future of pharmaceuticals," International Journal of Bioprinting, vol. 4, no. 1, 2018, doi: 10.18063/IJB.V4I1.119.

[16]P. J. Nuñez, A. Rivas, E. García-Plaza, E. Beamud, and A. Sanz-Lobera, "Dimensional and Surface Texture Characterization in Fused Deposition Modelling (FDM) with ABS plus," in Procedia Engineering, 2015, vol. 132, pp. 856–863. doi: 10.1016/j.proeng.2015.12.570.

[17]I. Gibson, D. Rosen, and B. Stucker, "Additive Manufacturing Technologies 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing Second Edition."

[18]S. H. Ahn, M. Montero, D. Odell, S. Roundy, and P. K. Wright, "Anisotropic material properties of fused deposition modeling ABS," Rapid Prototyping Journal, vol. 8, no. 4, pp. 248–257, 2002, doi: 10.1108/ 13552540210441166/ FULL/ HTML.

[19]B. H. Lee, J. Abdullah, and Z. A. Khan, "Optimization of rapid prototyping parameters for production of flexible ABS object," Journal of Materials Processing Technology, vol. 169, no. 1, pp. 54–61, Oct. 2005, doi: 10.1016/ J.JMATPROTEC. 2005.02.259.

[20]C. S. Lee, S. G. Kim, H. J. Kim, and S. H. Ahn," Measurement of anisotropic compressive strength of rapid prototyping parts," Journal of Materials Processing Technology, vol. 187–188, pp. 627–630, Jun. 2007, doi: 10.1016/J.JMATPROTEC.2006.11.095.

[21]R. Anitha, S. Arunachalam, and P. Radhakrishnan, "Critical parameters influencing the quality of prototypes in fused deposition modelling," Journal of Materials Processing Technology, vol. 118, no. 1–3, pp. 385–388, Dec. 2001, doi: 10.1016/S0924-0136(01)00980-3.

[22]P. K. Venuvinod and W. Ma, Rapid Prototyping. Boston, MA: Springer US, 2004. doi: 10.1007/978-1-4757-6361-4.

[23]R. Singh, R. Kumar, I. Farina, F. Colangelo, L. Feo, and F. Fraternali, "Multi-Material Additive Manufacturing of Sustainable Innovative Materials and Structures," Polymers 2019, Vol. 11, Page 62, vol. 11, no. 1, p. 62, Jan. 2019, doi: 10.3390/POLYM11010062.

[24]H. Kim, E. Park, S. Kim, B. Park, N. Kim, and S. Lee, "Experimental Study on Mechanical Properties of Single- and Dual-material 3D Printed Products," Procedia Manufacturing, vol. 10, pp. 887–897, 2017, doi: 10.1016/J.PROMFG.2017.07.076.

[25]"Original Prusa i3 MK3S kit." https://shop.prusa3d.com/ en/3d-printers/180-original-prusa-i3-mk3s-kit.html?gclid= CjwKCAjwh5qLBhALEiwAioods7nYfRQNcI_r6IDMkGr9 RLWRZsfKAJkZqQBCYtOZcs-KvA8QZsViqBoCG3YQ AvD_BwE (accessed Oct. 13, 2021).

[26]A. Hadny, Q. Ayun, J. Triyono, and E. Pujiyanto, "Optimization of Injection Molding Simulation of Bioabsorbable Bone Screw Using Taguchi Method and Particle Swarm Optimization," Jordan Journal of Mechanical and Industrial Engineering, vol. 16, no. 2, pp. 319–325, 2022.

[27]S. G. Ghalme, "Improving Mechanical Properties of Rice Husk and Straw Fiber Reinforced Polymer Composite through Reinforcement Optimization," Jordan Journal of Mechanical and Industrial Engineering, vol. 15, no. 5, pp. 411–417, 2021.

[28]T. Yao, Z. Deng, K. Zhang, and S. Li, "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations," Composites Part B: Engineering, vol. 163, pp. 393–402, Apr. 2019, doi: 10.1016/J.COMPOSITESB.2019.01.025.

[29]A. Nugroho, R. Ardiansyah, L. Rusita, and I. L. Larasati, "Effect of layer thickness on flexural properties of PLA (PolyLactid Acid) by 3D printing," IOP Conf. Series: Journal of Physics: Conf. Series, vol. 1130, p. 12017, 2018, doi: 10.1088/1742-6596/1130/1/012017.

[30]O. Avinc and A. Khoddami, "Overview of Poly(Lactic Acid) (PLA) Fibre Part I: Production, Properties, Performance, Environmental Impact, and End-use Applications of Poly(lactic acid) Fibres," Fibre Chemistry, vol. 41, no. 6, 2009.

[31]G. Fedorko, V. Molnár, Ž. Ferková, P. Peterka, J. Krešák, and M. Tomašková, "Possibilities of failure analysis for steel

cord conveyor belts using knowledge obtained from non-destructive testing of steel ropes," Engineering Failure Analysis, vol. 67, pp. 33–45, Sep. 2016, doi: 10.1016/J.ENGFAILANAL.2016.05.026.

[32]R. Henry, "Etymologia: Bonferroni Correction - Volume 21, Number 2—February 2015 - Emerging Infectious Diseases journal - CDC," Emerging Infectious Diseases, vol. 21, no. 2, p. 289, 2015, doi: 10.3201/EID2102.ET2102.

[33]G. V. S. S. Sharma, P. S. Rao, and B. Surendra Babu, "Establishing Process Capability Indices in a Sugar Manufacturing Industry-an Industrial Engineering Perspective," Jordan Journal of Mechanical and Industrial Engineering, vol. 15, no. 4, pp. 319–328, 2021.

[34]V. Ivanco, S. Kmet, and G. Fedorko, "Finite element simulation of creep of spiral strands," Engineering Structures, vol. 117, pp. 220–238, Jun. 2016, doi: 10.1016/ J.ENGSTRUCT. 2016.02.053.

[35]A. A. Mousa, "The Effects of Content and Surface Modification of Filler on the Mechanical Properties of Selective Laser Sintered Polyamide12 Composites," Jordan Journal of Mechanical and Industrial Engineering, vol. 8, pp. 265–274, 2014.