International Journal of
Science and Engineering Investigations
vol. 10, issue 109, February 2021
Received on February 22, 2021
ISSN: 2251-8843

Effect of Process Parameters on Tensile Property of 3D Printed PLA and PLA Composites Using FDM

A. Abu-El-Fadl[1], T. S. Mahmoud[2], M. Gouda[3]
[1,3]Higher Technological Institute, 10th of Ramadan City, Egypt
[2]Mechanical Engineering Department, Shoubra Faculty of Engineering, Benha University, Cairo, Egypt
([1]fadl_1000@yahoomail.com)

Abstract-Additive manufacturing technologies have been effectively useful in a wide range of applications. A popularly known manufacturing technology preferred widely for industries for creating complex structures at low prices is Fused deposition modeling (FDM). In the present investigation, studying the influence of process parameters (layer thickness and printing orientations) and filament materials parameter on the tensile property of 3D-Printed PLA PLUS, wood, and carbon fiber-based PLA composites, were printed using Fused Deposition Modelling (FDM). Samples with three different layer thicknesses (0.1, 0.2, 0.3 mm) and three printing orientations (Flat, On-edge, and Upright) were fabricated using four materials (PLA, PLA PLUS, wood, and carbon fiber-based PLA composites) and their tensile strengths were tested. Moreover, the analysis of variance (ANOVA) statistical approach was carried out to clarify the level of significance of the factors and their optimum combination. The results revealed that the printing orientations have the greatest influence on the tensile strength of FDM samples. Samples printed using the on-edge orientation exhibited a higher tensile strength of samples than those printed with flat and upright orientation. Increasing the layer thickness reduces the tensile strength of samples. The optimum tensile property of samples was found at an on-edge orientation with a layer thickness of 0.1 mm printed from virgin PLA material.

Keywords*- Additive Manufacturing, Fused Deposition Modeling (FDM), 3D-Printed, PLA*

I. INTRODUCTION

In the past five decades, industries pulled up their standards and limits in the way of manufacturing (objects/workpieces/materials/composites) from the level of manual controlling of machines to computerized controlling, and Additive Manufacturing (AM) or Rapid prototyping is one among those advanced manufacturing ways [1]. The improved quality and precision of the (RP) manufactured parts are the consequences of adequate material modification and process parameter optimization of RP techniques [2–3].3D printing is a special, novel, and creative additive manufacturing technology that creates objects through digitized model without traditional expensive cutting machines or casting machines [4–5]. It also has absolute predominance in producing components with complex shapes and multi-materials components compared to any other methods [6–8]. Meanwhile, a lot of raw materials can be saved during the printing process. Now, 3D printing components often appear in various fields, such as biomedicine [9–11], aerospace [9,12], automotive engineering [13].

One of the most widespread AM techniques is fused filament fabrication (FFF, also called fused deposition modeling, FDM) presents several advantages like widespread use, easy usability, and reduced cost compared to other AM techniques [14]. The FDM, developed by Stratasys. FDM has become one of the most famous 3D printing techniques throughout the world. In the FDM process, objects are built layer by layer, leading to their anisotropic mechanical properties. Firstly, the raw material is extruded into the nozzle and transformed to a semi-liquid state from the original filament state. After that, the semi-liquid material is deposited onto the previous layer and cools, solidifies, and integrates with the surrounding materials. When the whole layer is deposited, the platform supporting the object moves down by the height of one layer and the next layer will be printed [15]. Mohan N et al. [16] reviewed the materials and process parameters optimization of the FDM process. Thermoplastic materials such as PLA, ABS, metal matrix composites, ceramic composites, and natural fiber-reinforced composites are widely adopted in FDM printers.

Different material of thermoplastic polymers have been employed in FDM, including PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), nylon (a kind of polyamide), PETG (polyethylene terephthalate glycol-modified), PEI (polyethyleneimine) and PEEK (polyether ether ketone), to reach the desired performance of 3D printed components [17]. One of these materials, PLA, as a biodegradable green material has received considerable attention in biopolymer research owing to its excellent biocompatibility and sustainability [18].

The main goal of the paper is to understand the tensile behaviors of FDM-printed wood, and carbon fiber-based PLA composite and PLA Plus samples. In addition to the type of PLA composites, the effects of two important process parameters (printing variables) in FDM, i.e. layer thickness and building orientations on tensile properties are comprehensively investigated and analyzed. Finally, the above analysis is further verified by the observations of images from fracture surfaces of the tensile test.

II. EXPERIMENTAL PROCEDURES

A. *3D Printer and Materials*

The 3D printer of type FDM (Model: Dreamer NX, Flash forge Co., Ltd., China) was used in this research. The print resolution of the printer is about ± 0.2 mm. Figure1 shows a schematic view of the fused deposition modeling method where filament heated by the extruder and finally passes through the brass nozzle to print cad model according to programming code.

The filament material chosen for this study is Virgin Polylactic acid (PLA) and PLA PLUS which purchased from (esun company) and PLA with additive powder wood and carbon fiber with the diameter of 1.75 mm were purchased from SGS ROHS company) with a diameter of 1.75 mm were used as printing materials. The blend ratio of PLA and each additive was chosen as approximately 3:2 in this research, which is believed to have the effectively modified tensile property compared to the virgin PLA.

TABLE I. KEY PRINTING PARAMETERS USED IN THIS WORK

Materials	Virgin PLA, PLA PLUS, wood, and carbon fiber-based PLA
Nozzle Temperature	210˚
Printing speed	60mm/min
Nozzle diameter	0.4mm
Object Infill density	100%
Raster angle	45˚/-45˚
Layer height	0.1,0.2,0.3 mm
Infill Pattern	Linear

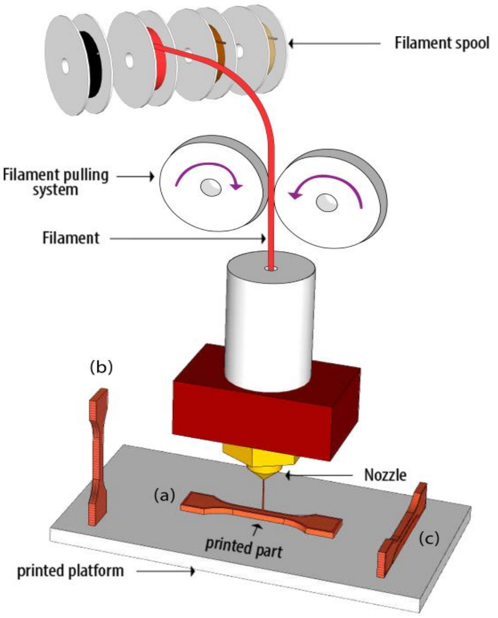

Figure 1. Schematic view of fused deposition modeling method: a) Flat, b) On-edge, c) Upright.

B. *Design of experiment*

Full factorial design of experiment which is used to investigate the effects of each of control factors on the tensile property of FDM samples, illustrated in Table 2, with three control factors (parameters) considering two process parameters are layer thickness and printing orientations, the last parameter is the type of material filament. Layer thickness that can be achieved by the 3D printer is defining the dimension between every two consecutive layers of printed material with three levels (0.1, 0.2, and 0.3 mm), printing orientation is the angle at which the infill is extruded (it can change from 0˚ and 180˚) with three levels (Flat, on edge, upright) and the material parameter which is the polymer material of extruded filament with four levels (Virgin, plus, wood and carbon fiber-based PLA composites). According to Taguchi s approach based on the selected parameters (Factors), the appropriate orthogonal array is L36 using software Minitab program for the investigation.

TABLE II. CONTROL FACTORS AND THEIR LEVELS FOR EXPERIMENTAL DESIGN

S.No.	Control Factors	Levels			
		1	2	3	4
1	Layer thickness	0.1	0.2	0.3	
2	Orientations	Flat	On-edge	Upright	
3	Filament Material	Virgin	PLUS	Wood	Carbon

C. *Fabrication of samples:*

With the selected control factors, samples with dog-bone shaped printed by FDM printer according to ASTM D638-14 standard for the investigation are prepared in the four steps. In the first step, a model of three-dimensional (3D) ASTM standard is prepared, using the commercial computer. aided design (CAD) software (SOLIDWORKS) and saved as a stereolithography (.stl) file, then the second step start by exported the (.stl) file into an operation software package (Simplify 3d), and customized groups are created. At this stage, the part is sliced at a given layer thickness: (0.1, 0.2 and 0.3 mm). After that, the third step is producing the dog-bone sample after adjusting the machine setup, which printing was done one sample at a time, centered on the building plate to avoid possible printing problems. Layers were printed perpendicular to each other (Figure 2).

For each printing orientation (Flat, On-edge, and Upright) printed with the same printing path (45/-45). The first layer at a raster angle of 45° along the sample length and the next layer at a raster angle of -45° (crisscross), where, for instance, 45◦ means the axial direction along the sample length in the corresponding printing orientation, and -45◦ is the transverse direction and so on, up to the final layer by used nozzle diameter (0.1, 0.2 and 0.3mm) respectively. Finally, the dog-bone sample is taking away from the 3d printer, and the support material is cleaned.

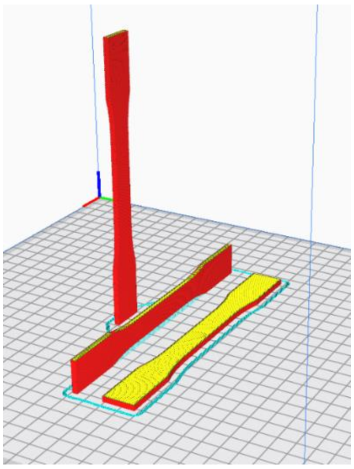

Figure 2. Tensile sample in the simplify program 3d printing FDM software.

D. *Mechanical Testing*

For the tensile test, after producing the 3D printed specimens, tensile tests were carried out with the aid of a tensile apparatus. The experiments were performed according to the ASTM D638, and five same samples were prepared to make sure the obtained values of tensile strength reliable. Tensile properties were tested in a universal testing machine (Model: HLC-150, manufactured by Jinan Testing Equipment Co., Ltd., China) with a load of 100 KN. The samples were loaded up to material failure at a displacement rate of 5 mm/min for the tensile test.

III. RESULTS AND ANALYSIS

A. *Formability*

In this part, To evaluate printing formability of virgin PLA, PLA PLUS, wood, and carbon fiber PLA composite parts in terms of printing with a layer thickness (0.1, 0.2, and 0.3 mm) as well as different orientations (Flat, On-edge, and Upright). For example, successful FDM-printed samples of different PLA composites are presented in Figure3.

Figure 3. FDM samples of different materials with three-angle orientations: a) Flat, b)On-edge,c) Upright.

Figure 4 shows that FDM-printed samples of virgin PLA in flat, on-edge, and upright orientations with three different values of layer thickness. The most difficult orientation is upright. Moreover, printing in upright orientation was performed without any printing of support structure.

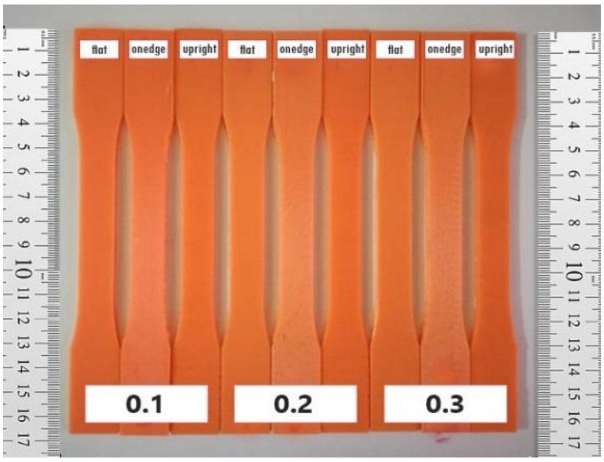

Figure 4. 3D printed samples of virgin PLA in flat, on-edge, and upright orientations with layer thickness0.1,0.2, and 0.3mm).

B. *Influence of Control Factors on tensile strength:*

Figure 5 show the variation of the tensile strength of all FDM 36 samples with three control factors with different levels, two of these control factors are the process parameter which is the layer thickness parameter with three levels (0.1,0.2 and 0.3 mm) and printing orientations parameter with three levels also (flat, on-edge and upright). The last control factor is the filament materials parameter which has four levels (PLA, PLA PLUS, wood, and carbon fiber PLA composites). It has been found that the tensile strength varies between 54 and 18 Mpa. FDM samples printed with Virgin PLA filament material exhibited higher tensile strength when compared with those printed with another filament material which contains filler or fiber PLA. For example, samples printed with virgin PLA, PLA Plus, wood, and carbon fiber PLA composites at layer thickness 0.3 mm with upright build orientation, exhibited tensile strength and 22,17,15, and 18Mpa, respectively. It is clear from Figure 5 that increasing the layer thickness slightly decreases the tensile strength of the FDM samples. For example, for samples printed in flat orientation with virgin PLA, PLA Plus, wood, and carbon fiber PLA composites materials at 0.1mm layer thickness, exhibited tensile strength 49, 45, 38, and 44 Mpa, respectively, and for 0.3 mm layer thickness exhibited tensile strength 39, 33, 29 and 34 Mpa, respectively.

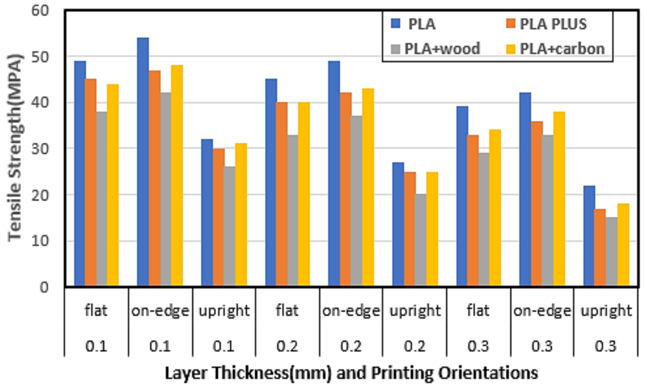

Figure 5. Variation of the tensile strength of different filament materials FDM samples printed with various layer thickness and printing orientations.

From Figure 5, all FDM samples printed in on-edge orientation with different filament materials and layer thickness have high tensile strength than FDM samples printed at flat and upright orientation. For example, FDM samples of different filament materials with 0.1 mm layer thickness printed at on-edge orientation, exhibited tensile strength with 54, 47, 42, and 48 Mpa compared to 49,45,38, and 44 Mpa for samples printed in flat orientation and 33,30,26 and 31 Mpa for samples printed in an upright orientation.

According to the results, it can be concluded that increasing the layer thickness of different filament materials decreasing the tensile strength. For PLA and its composites, the best tensile properties could be obtained when external loading direction is parallel to the build orientations of printed filaments are oriented longitudinally (e.g., the cases in flat and on-edge orientations). On the contrary, the worse tensile properties could be obtained when the tested specimen is loaded along with the build orientation (e.g., the cases in upright orientations) due to weak interlayer bonding. Results have demonstrated that tensile properties are very sensitive to filler materials. As for wood and chopped carbon fiber-based PLA samples, the tensile strength is decreased to some extent under different printing orientations and layer thickness.

C. *ANOVA Results*

Table 3 lists the ANOVA results for the tensile strength of FDM samples. The last columns in the tables show the percentage of contribution (P_c) of each factor on the total variation indicating the influence of the factors on the results. The higher the value of the P_c, the more statistical and physical significant the factor is. From the analysis of Table 3, it can be observed that printing orientations, layer thickness, and filament materials significantly affect the tensile strength of FDM samples. The printing orientations exhibited the highest statistical and physical significance on the tensile strength of FDM samples. The layer thickness and filament material exhibited much lower statistical and physical significance when compared with the printing orientations. The printing orientations exhibited P_c values of 67% for the tensile strength of FDM samples. While the layer thickness and filament material exhibited (P_c) values of 20.18% and 11.82% for tensile strength of FDM samples. From Tables 3, the residuals are less than 2%, which indicates that there are no interactions between angle orientation, layer thickness, and filament material.

TABLE III. THE ANOVA RESULTS FOR TENSILE STRENGTH OF FDM SAMPLES.

Source of variation	DF	Adj SS	Adj MS	F-Value	P-Value	P_c
Layer thickness	2	705.56	352.78	267.37	0.000	20.1807
Printing Orientations	2	2340.39	1170.19	886.88	0.000	66.9406
Filament Material	3	413.33	137.78	10.4.42	0.000	11.8222
Residual	28	36.94	1.32			100.00
Total		3496.22				
$R^2 = 98.94\%$						

DF, degrees of freedom; SS, sum of squares; MS, mean square; F, F-test, P, Statistical significance, P_c; percentage of contribution.

Figure 6 shows that the main effect plot for tensile strength will be generated between layer thickness(L), printing orientations(O), and filament material(M), and the resulted plot is shown below. At lesser thicknesses of the layer, the tensile strength of the material was low. With change orientation of FDM samples from (On-edge to Flat and then to Upright) respectively, higher tensile strength for FDM samples printed in on-edge orientation. Later, with adding filler or fibers to virgin filament material, there is a sharp decrease in tensile strength of the material.

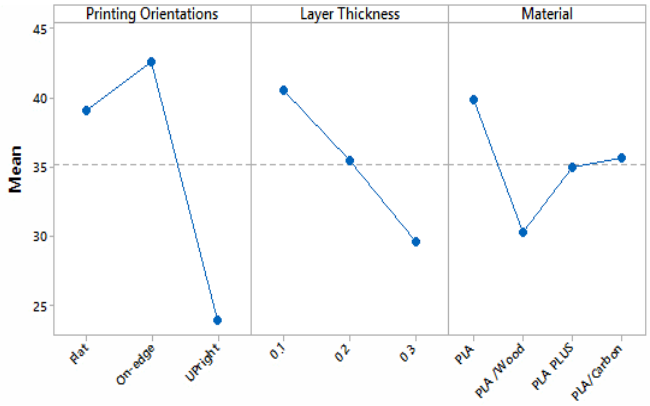

Figure 6. Main Effects plot for tensile strength

Below equation is the regression equation for tensile strength and it generates predicted values for the specimen material at considered control factors:

$$\text{Tensile Strength} = 35.222 + 5.278\ L_1 + 0.278 L_2 - 5.556\ L_3 + 3.861\ O_1 + 7.361\ O_2 - 11.222\ O_3 + 4.667\ M_1 - 0.222\ M_2 - 4.889\ M_3 + 0.444\ M_4. \qquad (1)$$

1) Analysis of experimented and predicted values of tensile:

All the test specimens (36) printed by FDM printer for evaluating the strengths of tensile has been undergone for test and the values obtained were listed in the below Table 4. Predicted values for these tensile strengths were obtained from the equations generated during the ANOVA analysis. And to know the accuracy of the experimentation conducted, there a finding of Error percentage helps in determining the deviation between the obtained and predicted values. The mathematical equation representation was written below here.

Percentage of Error =

$$\left|(\text{Experimented-Predicted})\right| / (\text{Experimented}) \qquad (2)$$

Error percentage has been calculated and it ranges differently for tensile strength. Coming to tensile strength, error reaches up to 9.633%. By averaging all these percentages of error, the results were as, for tensile it was 2.78% i.e., mean error. All the values were mentioned in the following Table 4. The following bar graphs were drawn by the values taken from Table 4. All the values were mentioned in the following Table 5, where: A, B, C, D, and E refer to Layer thickness, printing orientation, experimented, Predicted, and % Error, respectively. Graphs were generated between experimented and predicted values of the specimens for tensile strengths. Figure 7 was for comparison between Experimented and Predicted Tensile strength.

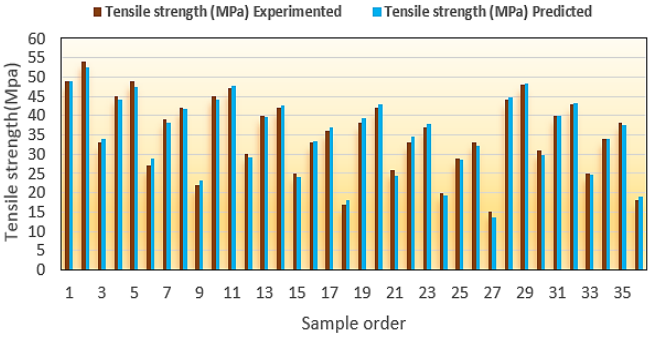

Figure 7. Comparison between experimented tensile strength & predicted tensile strength.

I. CONCLUSIONS

Based on the results presented, the following conclusions can be drawn that the FDM tensile samples printed in on-edge orientation exhibited higher tensile strength than FDM samples printed in the flat or upright orientation. While all the samples printed along upright orientation have the weakest tensile strength due to weak interlayer bonding. The increasing layer thickness of FDM samples decreasing the tensile strength of samples. Furthermore, the optimum layer thickness was 0.1 mm.For filament materials, Virgin PLA filament material of 3D printing FDM tensile samples exhibited better tensile property than those printed with PLA composites filament materials. Filament material exhibited the least statistical and physical significance effect on FDM samples. Adding wood and chopped carbon fiber into virgin PLA significantly lowers the tensile property of FDM samples due to defects such as high porosity, poor compaction, and adhesion between filament layers, compared to virgin PLA. Tensile FDM sample showed that the highest value records at layer thickness 0.1mm printed in on-edge orientation with virgin PLA material.

TABLE IV. TENSILE STRENGTH VALUES AT MAXIMUM POINT OF EXPERIMENTED AND PREDICTED.

Specimen No.	Material	Process Parameters		Tensile strength (MPa)		
		A	B	C	D	E
1	Virgin PLA	0.1	Flat	49	49.028	0.057
2		0.1	On-edge	54	52.528	2.726
3		0.1	Upright	33	33.945	2.864
4		0.2	Flat	45	44.028	2.160
5		0.2	On-edge	49	47.528	3.004
6		0.2	Upright	27	28.945	7.204
7		0.3	Flat	39	38.194	2.067
8		0.3	On-edge	42	41.694	0.729
9		0.3	Upright	22	23.111	5.050
10	PLA PLUS	0.1	Flat	45	44.139	1.913
11		0.1	On-edge	47	47.639	1.360
12		0.1	Upright	30	29.056	3.147
13		0.2	Flat	40	39.739	0.653
14		0.2	On-edge	42	42.639	1.521
15		0.2	Upright	25	24.056	3.776
16		0.3	Flat	33	33.305	0.924
17		0.3	On-edge	36	36.805	2.236
18		0.3	Upright	17	18.222	7.188
19	PLA/Wood	0.1	Flat	38	39.472	3.874
20		0.1	On-edge	42	42.972	2.314
21		0.1	Upright	26	24.389	6.196
22		0.2	Flat	33	34.472	4.461
23		0.2	On-edge	37	37.972	2.627
24		0.2	Upright	20	19.389	3.055
25		0.3	Flat	29	28.638	1.248
26		0.3	On-edge	33	32.138	2.612
27		0.3	Upright	15	13.555	9.633
28	PLA/carbon	0.1	Flat	44	44.805	1.830
29		0.1	On-edge	48	48.305	0.635
30		0.1	Upright	31	29.722	4.123
31		0.2	Flat	40	39.805	0.488
32		0.2	On-edge	43	43.305	0.709
33		0.2	Upright	25	24.722	1.112
34		0.3	Flat	34	33.971	0.085
35		0.3	On-edge	38	37.471	1.392
36		0.3	Upright	18	18.888	4.933
				Error%	2.775%	

ACKNOWLEDGMENTS

The authors are thankful to Higher Technological Institute, 10th of Ramadan City, Egypt for providing financial support and facilities for carrying out this work.

REFERENCES

[1] K.Durgashyam, M. Indra Reddy, A. Balakrishna, K. Satyanarayana.2019."Experimental investigation on mechanical properties of PETG material processed by fused deposition modeling method". Department of Mechanical Engineering, SRKR Engineering College, Bhimavaram, A.P 534204, India

[2] J. Nagendra et al. 2019. "Nylon-aramid polymer composite as sliding liner for lube-less sliding bearing by fused deposition modeling". AIP Conf. Proc.

[3] M.W.M. Cunico. 2011. "Development of new rapid prototyping process". Rapid Prototyp. J. 17, 138-147.

[4] Wang X, Jiang M, Zhou Z, Gou J, Hui D.2016. "3D printing of polymer matrix composites: a review and perspective". Compos.B.Eng ;110:442-58.

[5] Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D.2018. "Additive manufacturing (3D printing): a

[6] review of materials, methods, applications, and challenges". Compos B Eng:13.

[7] Ferreira RTL, Amatte IC, Dutra TA, Bürger D.2017. "Experimental characterization and micrography of 3D printed PLA and PLA reinforced with short carbon fibers". Compos B Eng;124:88-100.

[8] Justo J, Távara L, García-Guzmán L, París F .2018. "Characterization of 3D printed long fibre reinforced composites". Compo,Struct:185.

[9] Hou Z, Tian X, Zhang J, Li D. 2018. "D printed continuous fiber-reinforced composite corrugated structure". Compos Struct:184.

[10] Murr LE. 2016. " Frontiers of 3D printing/additive manufacturing: from human organs to aircraft fabrication". J Mater Sci Technol;32(10):987-95.

[11] Knowlton S, Yenilmez B, .2016. " Tasoglu S. Towards single-step biofabrication of organs on a chip via 3D printing". TrendsBiotechnol;34(9):685-8.

[12] Ji S, Guvendiren M. 2017. "Recent advances in bioink design for 3D bioprinting of tissues and organs". Front Bioeng Biotechnol;5(23).

[13] Kobryn PA, Ontko NR, PL P, TJ S.2006. "Additive manufacturing of aerospace alloys for aircraft structures". Additive manufacturing of aerospace alloys for aircraft structures.

[14] Talagani MR, Dormohammadi S, Dutton R, Godines C, Baid H, Abdi F, et al. 2015. " Numerical simulation of big area additive manufacturing (3D Printing (of a full-size car". SAMPLE J;51(4):27;43(1):114-23.

[15] A.S. de León, A. Domínguez-Calvo, S.I. Molina Dpto. 2019. "Materials with enhanced adhesive properties based on acrylonitrile-butadiene-styrene (ABS)/thermoplastic polyurethane (TPU) blends for fused filament fabrication (FFF)". Ciencia de los Materiales, I. M. y Q. I., IMEYMAT , s/n, 11510 Puerto Real, Cádiz, Spain.

[16] Tianyun Yao, Zichen Deng, Kai Zhang .2019. "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations". Shiman Li School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an, 710072, PR China

[17] Mohan N, Senthil P, Vinodh S, Jayanth N. 2017. "A review on composite materials and process parameters optimization for the fused deposition modeling process". Virtual Phys Prototyp;12(1):47-59.

[18] Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Allison MB, et al.,.2017. "Materials for additive manufacturing". CIRP Ann-ManufTechnol;66:659-81.

[19] Eynde MVD, Puyvelde PV. 3D printing of polylactic acid.2017. In: Advances in polymer science. Berlin, Heidelberg: Springer;http://dx.doi.org/10.1007/12.

How to Cite this Article:

Abu-El-Fadl, A., Mahmoud, T. S. & Gouda, M. (2021). Effect of Process Parameters on Tensile Property of 3D Printed PLA and PLA Composites Using FDM. International Journal of Science and Engineering Investigations (IJSEI), 10(109), 47-52. http://www.ijsei.com/papers/ijsei-1010921-06.pdf