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Mechanical Characterization of PLA Used in Manufacturing of 3D Printed Medical Equipment for COVID-19 Pandemic

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Abstract—**The 3D printing technology allows to overcome the lack of medical equipment during the Covid19 pandemic around the world. The PLA is widely used to produce medical devices and personal protective equipment. The aim of this paper is to determine the mechanical behavior of PLA-parts fabricated using Open-Source 3D printer based on FDM process. The mechanical behavior is characterized by two proprieties which are flexural strength and flexural modulus of elasticity. The mechanical properties are determined from the experimental results of three-point bending test according to the following process parameters: printing speed, deposition angle and extruder temperature. The results obtained show that the mechanical properties depend on the three process parameters. The response surface method and the variance analysis technique were used to establish an empirical model between process parameters and mechanical properties. The optimal printing parameters were determined using the desirability function. The Finite Element Analysis for Flexural Strength was performed to validate the experimental results.**

Keywords—3D printing, fused deposition modeling, mechanical behavior, three-point bending test, finite element method

I. INTRODUCTION

COVID-19 is an infectious disease caused by a virus belongs to the Coronaviruses family. It first appeared at the end of December 2019 in China [1]. It is classified as a pandemic on March 12, 2020 by the World Health Organization. During this pandemic, important stress has been placed on global healthcare systems due to lack of medical equipment. Currently, 3D printing is proving to be of crucial importance in the fight against COVID-19, it has emerged as the ultra-fast manufacturing solution to meet the needs of healthcare professionals. It is increasingly used to fabricate components of respiratory support and personal protective equipment [2].

3D printing is a new technology that allows fabricating solid pieces from a digital model made by Computer Aided Design (CAD) software [3]. The 3D printing machines use several manufacturing technologies such as Stereolithography (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Inkjet Printing (IP) [4]. Additionally, the most Open-Source 3D printers are based on FDM technology because of its ability to produce complex geometric objects, its accessibility to the general public and its low cost [5, 6]. This additive process consists in depositing a filament of thermoplastic material on the printing plate layer by layer. The PolyLactic Acid (PLA) is the most material of fabrication used in 3D printers based on FDM process [7]. The PLA has a relatively low melting temperature [8] which makes it require less heat energy to transform its physical state.

The material used in the FDM process has an effect on the mechanical properties of printed objects [9]. Furthermore, the quality of this objects depend also on the different printing parameters [10-12]. However, many studies focused on characterizing and optimizing FDM process parameters of PLA parts for flexural response [13, 14], tensile response [15-17], and compressive response of PLA-built parts [18, 19].

To make the printed objects stronger and useful in specific applications, we propose to study new strategies for depositing PLA material. This article consists in determining the optimal FDM process parameters offering the best mechanical behavior of PLA parts manufactured using a RepRap 3D printer. Three point bending test are carried out to determine the mechanical response such as flexural strength and flexural modulus of elasticity. Three process parameters were taken into account are printing speed, deposition angle and extruder temperature.

II. THE METHODOLOGY OF MECHANICAL TEST

A. Parts Fabrication

The WANHAO Duplicator 4S printer based on FDM process with a nozzle diameter of 0.4mm is used to fabricate the samples. The PLA filament used has a density of 1.25g/cm^3 and a diameter of 1.75mm.

The samples were manufactured with a geometry conforming to the standard EN ISO 178: 2010 [20]. Therefore, the samples have a parallelepiped shape of dimensions 80×10×4mm (see Fig. 1). The following parameters were modified during the fabrication of each sample: printing Speed (S), deposition Angle (A) and extruder Temperature (T). Three levels of printing speed were considered which are 30mm/s, 50mm/s and 70mm/s. As shown in Fig. 2, the deposition angle is taken equal to 0º, 30º and 60º. Three values

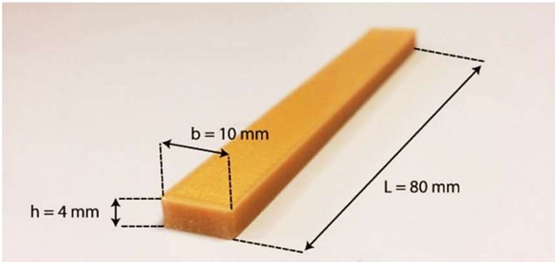


Fig. 1. Three-point bending test sample.

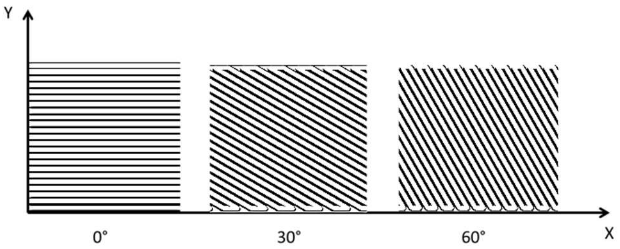


Fig. 2. Filament deposition angles.

of extruder temperature were studied: 190ºC, 200ºC and 210ºC. The other process settings were held constant.

B. *Mechanical Test*

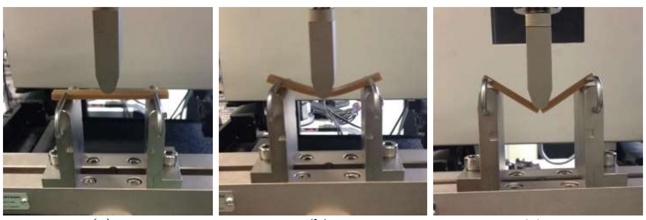
The three-point bending test of the PLA samples was performed according to the standard EN ISO 178: 2010 using Instron 5569 machine. Each sample has been deposited on the supports of the test machine, and the flexion force has been exerted on the center by a movable load punch which is moved with a speed of 2mm/min. The sample was deformed until the external facet failed. The samples were tested for each combination of process parameters. The different stages of the test are shown in Fig. 3.

To reduce the total time required and the number of test pieces needed, the mechanical tests was performed according to the Face Centered Central Composite Design (FCCCD) [21]. This plan is composed by a half-factorial plan consisting of 8 experimental tests, 6 axial points and a central part formed by 5 experiments. The central part provides a reasonable estimate of experimental error. The three process parameters represent the input factors of the design, while the response of the test performed is the flexural strength and flexural modulus of elasticity. Each factor value is coded in a level according to the experience plan technique. Table I shows the factor values and its levels.

III. Results and Duscussion

A. *Test Results*

Table II shows the values of flexural strength and flexural modulus of elasticity obtained from the experiment. The results show that the three process parameters considered (A,



(a) (b) (c)

Fig. 3. Mechanical test stages: (a) Initial state, (b) During bending, (c) Rupture of the part.

TABLE I. Factors Values and Their Levels

Factor	S	A	T
Unit	mm/s	degree	ºC
level (-1)	30	0	190
level (0)	50	30	200
level (+1)	70	60	210

T and S) have an effect on the mechanical properties of printed parts.

B. *Scanning Electron Microscopy Micrograph*

The Scanning Electron Microscope (SEM) was used to show the details of fractured surfaces at a microscopic scale. Fig. 4 shows the fracture surfaces. The SEM micrograph of the upper, lower, and central zone of the fracture surface during the test are illustrated in Fig. 5.

The observation of fracture facets under SEM shows the ductile behavior of different test parts. After a progressive damage of specimens presented by a propagation of cracks, rapid rupture is produced. The lower zone of test parts is smooth compared to the upper zone which is relatively rigorous.

TABLE II. Experimental Responses Obtained

Test Order	Factor Level			Flexural Strength (MPa)	Flexural Modulus (MPa)
	S	*A*	*T*		
1	-1	-1	-1	92.807	3386.613
2	-1	1	-1	86.379	3286.87
3	-1	-1	1	83.364	3285.7
4	-1	1	1	84.536	3225.15
5	1	-1	-1	86.783	3436.682
6	1	1	-1	86.908	3432.628
7	1	-1	1	85.656	3308.626
8	1	1	1	91.75	3298.076
9	1	0	0	86.663	3263.181
10	-1	0	0	83.096	3253.557
11	0	0	1	88.767	3362.883
12	0	0	-1	87.149	3289.171
13	0	1	0	85.171	3194.37
14	0	-1	0	85.597	3227.016
15	0	0	0	83.47	3272.587
16	0	0	0	88.005	3277.789
17	0	0	0	87.051	3257.938
18	0	0	0	87.155	3309.915
19	0	0	0	86.421	3279.51

Fig. 4. Fracture surfaces of test parts.


(a) (b) (c)

Fig. 5. SEM micrograph of the fracture surface of PLA part: (a) Upper zone, (b) Central zone, (c) Lower zone.

C. Stress-Strain Curve

Fig. 6 illustrates the evolution of the flexural stress according to the resulting deformation. The stress-strain curve during the bending test is characterized by two domains, an elastic domain and a plastic domain. The slope of the curve stress-strain in the elastic domain is the flexural modulus of elasticity. The flexural strength represents the highest point of the curve.

D. Test results analysis

The response surface method (RSM) and the Analysis of Variance (ANOVA) technique were performed using statistical software to investigate the experimental results and to develop an empirical model linking the three quantitative factors (A, T and S) and the mechanical response [22]. The full quadratic response surface model of response variable Y and three factors is written in the following polynomial form:

$$Y = \alpha_0 + \sum_{i=1}^{3} \alpha_i X_i + \sum_{i=1}^{3} \alpha_{ii} X_{ii}^2 + \sum_{i<j} \sum \alpha_{ij} X_i X_j \tag{1}$$

X_i is a quantitative factor. The coefficient α_0, α_i, α_{ii} and α_{ij} of the model must be calculated from the test results.

For confidence interval of 95%, the significance check based on ANOVA indicates that all the terms (linear, square and interaction terms) are significant for flexural strength σ_{fm} and flexural modulus of elasticity E_f. The final response surface equations in terms of coded units are determined using the t-test and are given respectively by (2) and (3). The coefficient of determination R^2 was 80.9% and 73.9% for flexural strength and flexural modulus of elasticity, respectively. Furthermore, average relative error of 1% and 0.75% are found between the predicted values obtained by the model and experimental results. These values prove that the model fits the data adequately.

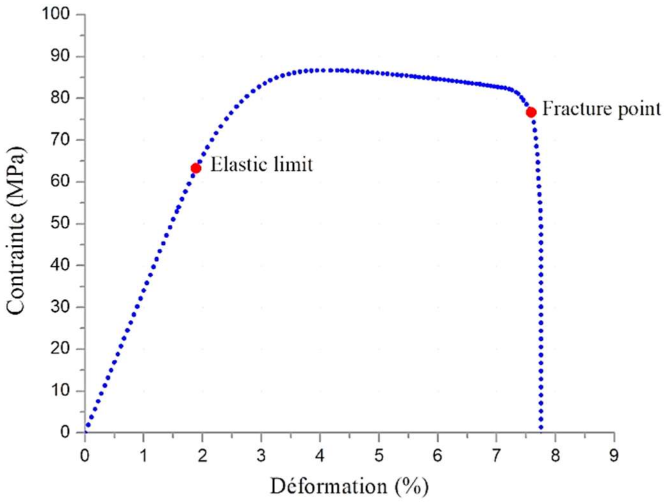


Fig. 6. Experimental stress-strain curve of three-point bending test for PLA part.

$$\sigma_{fm} = 86.108 + 0.758\,S + 0.054\,A - 0.595\,T - 0.839\,S^2 - 0.334\,A^2 + 2.24\,T^2 + 1.434\,S{\cdot}A + 1.875\,S{\cdot}T + 1.696\,A{\cdot}T \tag{2}$$

$$E_f = 3263.6 + 30.1\,S - 20.8\,A - 35.2\,T + 14.7\,S^2 - 33\,A^2 + 82.3\,T^2 + 18.2\,S{\cdot}A - 12.5\,S{\cdot}T + 4.1\,A{\cdot}T \tag{3}$$

The ANOVA assumptions were verified using the normality test, its diagrams are shown in Fig. 7 and Fig. 8 for flexural strength and flexural modulus of elasticity, respectively. The normality test results show that residuals follow normal distribution.

E. Optimization of FDM process parameters

The optimal process parameters that allow us to maximize the response and built stronger parts are determined using the individual desirability function (D). The desirability versus factor curves were plotted and given in Table III and Table IV for the two responses. The individual optimization results for flexural strength and flexural modulus of elasticity independently are summarized in the same Tables.

The composite desirability function was used to determine optimum factor levels for flexural strength and flexural modulus of elasticity simultaneously. The results of composite optimization show that the level (−1) for the factors S, A and T was the optimal choice to maximize the responses with composite desirability of 0.7976. Hence, the combination: printing speed 30mm/s, deposition angle 0º and extruder temperature 190ºC represents the optimal settings. The predicted value of flexural strength and flexural modulus of elasticity was 91.96 MPa and 3363.14 MPa respectively.

IV. Numerical simulations

The three point bending test was simulated using ANSYS Mechanical APDL 14.5 software and finite element method [23]. The geometry of PLA beam was modelled conforming

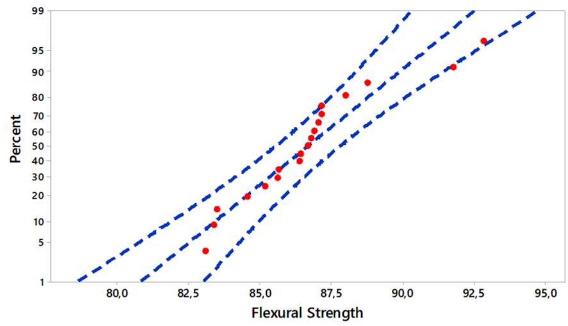


Fig. 7. Normal probability plot of flexural strength at 95% of confidence interval.

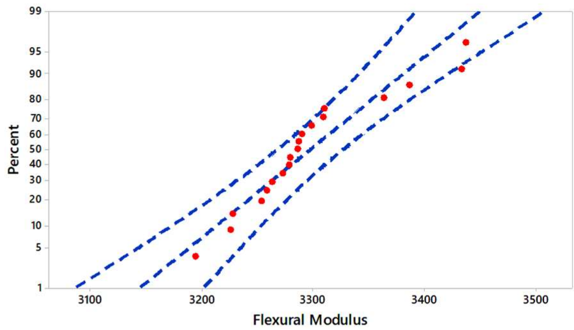


Fig. 8. Normal probability plot of flexural modulus of elasticity at 95% of confidence interval.

TABLE III. OPTIMIZATION RESULTS FOR FLEXURAL STRENGTH

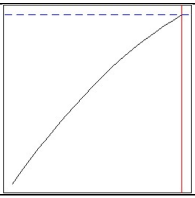
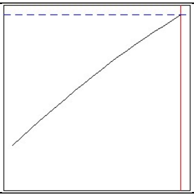
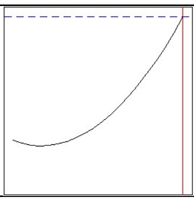
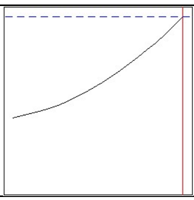
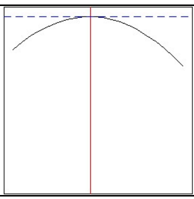
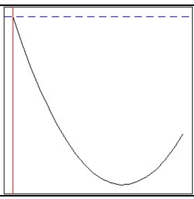
Printing Speed (S)		
	High	1
	Optimal	1
	Low	-1
Deposition Angle (A)		
	High	1
	Optimal	1
	Low	-1
Extruder Temperature (T)		
	High	1
	Optimal	1
	Low	-1
Desirability	0.9578	
Predicted response (MPa)	92.4	

TABLE IV. OPTIMIZATION RESULTS FOR FEXURAL MODULUS OF ELASTICITY

Printing Speed (S)		
	High	1
	Optimal	1
	Low	-1
Deposition Angle (A)		
	High	1
	Optimal	-0.091
	Low	-1
Extruder Temperature (T)		
	High	1
	Optimal	-1
	Low	-1
Desirability	1	
Predicted response (MPa)	3438.7	

to the optimal process parameters. The element type 2-node BEAM188 with six DOF per node, three translational DOF in nodal directions and three rotational DOF around the nodal axes was used to meshed the beam. The boundary conditions and loads applied were performing according to the experimental procedure. The nodal results obtained from the simulation of three point bending test using ANSYS Mechanical APDL software for bending stress in optimal conditions are presented in Fig. 9. The flexural strength obtained from the finite element analysis results was 91.27 MPa.

Fig. 10 shows the comparison between experimental value obtained from the mechanical test, predicted value calculated by the empirical model and numerical value obtained from FEA simulation of flexural strength for the optimal conditions. The relative error between experimental and predicted value and on the other hand between experimental and numerical value of flexural strength was 1% and 1.7%, respectively. The low relative errors proved a good agreement between the various results.

V. CONCLUSION

In this paper the effect of three FDM process parameters on the mechanical proprieties of PLA-parts manufactured with RepRap 3D printer was investigated. An empiric model between 3D printing process parameters and mechanical responses was developed. The optimal settings were determined which are 30mm/s, 0 degree and 190ºC for printing speed , deposition angle and extruder temperature respectively. The Flexural behavior was simulated using ANSYS Mechanical APDL software. The FEA results confirm the experimental results with relative error obtained less than 5%.

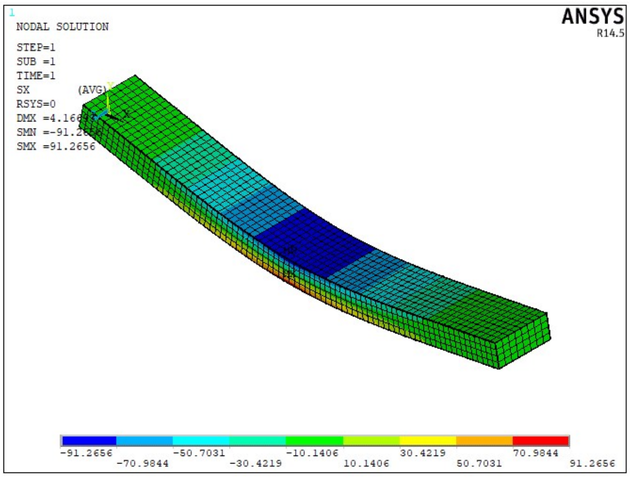


Fig. 9. Nodal solution for flexural stress.

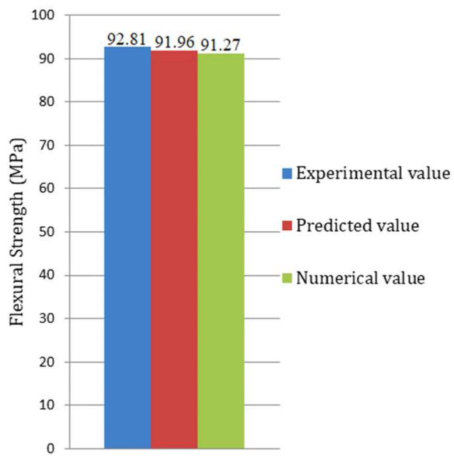


Fig. 10. Experimental, predicted and numerical value of flexural strength.

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