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OPTIMISATION OF PROCESS PARAMETERS ON TENSILE STRENGTH OF 3D PRINTED POLYLACTIC ACID (PLA) PARTS: ASTM D638 TYPE – IV

Akpakpavi, M. K.[1], Sackey, S. M.[2], and Asante-Afrifa, M. K.[3]
[1] *Department of Mechanical Engineering, Accra Technical University, Accra, Ghana.*
[1, 2 & 3] *Department of Mechanical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.*
[1]*micakpakpavi@yahoo.com*

ABSTRACT

Purpose: The purpose of this study is to optimize the influence of 3D printing processing parameters on the ultimate tensile strength of 3D printed Polylactic Acid (PLA) parts. The objective is to develop predictive models to help predict and attain optimised mechanical strength integrity of 3D printed parts.

Design/Methodology/Approach: In the present study, 3D printed PLA samples were modelled and fabricated using carefully selected processing parameters-processing speed, processing temperature and nozzle diameter. Tensile tests were performed by ASTM D638 standard. Two characteristics response optimisation models based on Taguchi Technique and multi-linear regression models were developed to optimise the process parameters and the ultimate tensile strength of the 3D printed samples.

Findings: Results of this study reveal that ultimate tensile strength is significantly affected by the Nozzle diameter. The ultimate tensile strength of the 3D-printed PLA sample was found to be significantly higher than the strength of the original PLA filament printed.

Research Implications/Limitations: In this study, only three critical 3D printing processing parameters including, processing speed; processing temperature and nozzle diameter were implemented concurrently.

Practical implication: The optimisation of process parameters for enhancing the tensile strength of 3D-printed PLA parts holds significant practical consequences, including cost savings, improved performance, sustainability, and innovation. The aforementioned consequences render PLA a more feasible and appealing material option for a diverse array of applications and industries.

Social implication: Optimisation of PLA printing can promote community engagement by allowing individuals to bring their creative ideas to life, fostering a sense of community and innovation.

Originality / Value: The unique aspect of this research resides in its particular emphasis on PLA, the utilization of empirical and data-based techniques to optimise process parameters, and its potential to enhance the real-world implementation of 3D printing with PLA across diverse industries.

Keywords: *3D Printing. experimental. optimisation. polylactic acid. tensile strength.*

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1.0 INTRODUCTION

Additive manufacturing techniques vary in terms of materials utilized for production and the technology employed for patterning, specifically including the fusion of layers produced during the process. Nevertheless, contemporary industrial practices encounter challenges in attaining precise components using various additive manufacturing techniques, mostly due to the reliance on layer-by-layer fabrication methods (Kumbhar & Mulay, 2016).

3D printing, an example of rapid prototyping (RP) technology, and solid free-form (SF) technology, is a popular additive manufacturing (AM) technique for fabricating three-dimensional solid objects from a digital design file (Maisarah et al., 2019). The creation of a 3D-printed object is achieved using additive processes (Sumalatha et al., 2021). In an additive process, an object is created by laying down successive layers of material until the object is created. Each of these layers can therefore be seen as a thinly sliced cross-section of the object (Mohammed, 2019).

Numerous studies have been conducted to investigate the utilization of various materials in the Fused Deposition Modelling (FDM) process. These materials include ABS (Acrylonitrile butadiene styrene), PLA (Polylactic acid), PET (Polyethylene terephthalate), Nylon, TPE (thermoplastic elastomer), TPU (Thermoplastic polyurethane), PC (Polycarbonate), PP (Polypropylene), PE (Polyethylene), among others. These materials find applications in many fields including aerospace, architecture, automobile, medical industry, and others (Oppon, Hackney, Shyha, & Birkett, 2015).

More so, 3D printing as an additive manufacturing method, is becoming widely popular in a wide range of applications, and the modern manufacturing world is resolved to replace conventional techniques with this method of manufacturing, where appropriate and suitable (Gomez-G et al., 2018). This is mostly due to the number of possible advantages that 3D printing can offer compared to conventional energy-intensive techniques including the ability to fabricate complex geometries as a single unit/part with no joints, lower material and labour cost, lower energy single-step processing temperature, less process complexity (CAD model-print-install), quick production time, short lead time, the less overall cost compared to the conventional technologies, relatively less expensive moulds and tooling requirements, possibility to produce small batches or batches of one economically, enabling mass customization, and so forth (Mohammed et al., 2020). Also, provided the 3D printing process is controlled, parts with good surface finish and near-net shapes can be produced (Chamil et al., 2020).

Several key barriers still exist across many RP processes despite their huge advantages and potential as a modern manufacturing methods (Brischetto et al., 2020). For example, a new foundation for CAD systems is needed that overcomes the limitations of solid modelling in representing very complex geometries and multiple materials (Wohlers, 1992). There are significant variations in geometry and properties among 7 identical parts built on different machines. Availability of processable materials is also limited (Gibson et al., 2010). Again, the

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problem arises when the mechanical strength of a 3D printed part is compromised; it is a must for some 3D printed products to meet the specified quality of strength including tensile strength, and other mechanical and thermal properties (Lay et al., 2019).

The precision of FDM technology is influenced by various characteristics, including layer thickness, build orientation, bed/nozzle temperature, feed rate, and the stair-stepping effect. Variations in these parameters can result in imprecise three-dimensional objects and have an impact on surface roughness, wettability, dimensional accuracy, and other significant qualities.

These need to be controlled to make the 3D printing process on the whole more efficient, effective, reliable and economical by saving time, material and post-processing operations without sacrificing the quality of the product (Ventola, 2014). Using different materials and printers with different combinations of controlled inputs, it is possible to define the quality of surface, mechanical, thermal and other properties of a 3D printed machinery part/component on different slopes. Also, currently, in the literature, not enough and sufficient work or research has been done to find out or predict the mechanical properties, typically, tensile strength integrity of a 3D printed part using a combination of nozzle diameter, processing speed and temperature as combined processing parameters simultaneously and concurrently. Therefore, among other things, the overall purpose of this study is to evolve a methodology that can be used to vary the pertinent process parameters for the 3D-printing process to ensure optimized mechanical strength integrity. Ultimately, by performing this research, the quality of a 3D-printed PLA component or part can be predicted by establishing the relationship between the printing technique and the printing parameters which have a direct effect on the quality of printed products produced (Ramya, & Vanapalli, 2016).

2.0 THEORIES UNDERPINNING THE STUDY

3D printing is an additive or AM process whereby layers of material are built up to create a 3D part. This is the opposite of subtractive manufacturing processes, where a final design is cut from a larger block of material. As a result, 3D printing creates less material wastage (Bermudez, 2021).

Moreover, Accurate mechanical property measurements are required to select materials and design a structure for its intended application. Engineers utilize this knowledge to make material decisions in both safety-critical and non-safety designs. These properties are determined using accepted measurement standards, certified databases, or reference materials. Applicable test standards are determined based on the final usage of the material, inherent weakness in the design, durability requirements, and safety factors (Imran et al., 2020). The parameters that define a typical mechanical system are collected by engineers at the design phase. Parameters such as estimates of the loading, temperature, moisture, and environment of the application, and material information such as mechanical properties, long-term stability, susceptibility to damage, and manufacturing cost are often collected by engineers before designing a part. Nonetheless, in AM, this can be difficult because material property information is often controlled by manufacturers and dependent

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on the AM process being used. AM processes, therefore, require effort for coupon-level tests such as printing a single bead or samples of material to optimize extrusion parameters, moving to ASTM dog-bone geometries to identify optimal print layouts, and finally incorporating the AM part into the other elements and components for further testing.

Indeed, in today's modeling-intensive world, many of these concepts are validated via simulation. Therefore, science-based standardized testing is required for AM materials to support accurate simulations. This testing requires confidence in material mechanical properties and performance, which is an area AM is lacking presently (Imran et al., 2020; Boon et al., 2018).

With regards to the Mechanical Property Characterization challenges in AM, Many AM processes differ from traditional polymer processing in that not all the material is melted and homogenized. The AM process of depositing layers of polymeric material results in parts with anisotropic properties, and residual stress, and this is a challenge. It is therefore incumbent on Researchers and Original Equipment Manufacturers (OEMs) to establish standardized methods to determine material properties from AM processing rather than the mechanical properties of a particular design. Also, despite the importance of this problem for the success of AM as a critical manufacturing process, the available literature in this area, currently, is not significantly large (Pascucci et al., 2018).

3.0 MATERIALS AND METHODS

3.1. Printing Material, 3D Printer, and Specimen Modelling and Fabrication

In this work, pure Polylactic Acid Resins (PLA) of size 1.75 mm diameter, is used as the raw material for preparing the black samples for this work. The filament was purchased from Amazon and sold by 3D Bazaar. Also, the PLA filament material used, according to the manufacturer has the following physical and mechanical properties as depicted in Table 1.

Table 1: Physical and Mechanical properties of the PLA used for this work according to the manufacturer

Property	Testing Method	Typical Value/ Printing	Typical Value/Injection molding
1. Tensile strength (MPA)	ASTM D638 (ISO 527)	49.5 ± 1.3	69.5 ± 0.5
2. Elongation at break (%)	ASTM D638 (ISO 527)	3.0 ± 0.4	28 ± 0.3
3. Bending modulus (MPA)	ASTM D790 (ISO 178)	3200 ± 220	3326 ± 210
4. Bending strength (MPA)	ASTM D790 (ISO 178)	92.1 ± 2.2	108.0 ± 12
5. Impact strength (KJ/m^2)	ASTM D256 (ISO 179)	3.4 ±0.21	4.0 ± 0.25
6. Density (g/cm^3)	ASTM D792 (ISO 1183)	2.36	
7. Glass Transition temperature ℃	DSC.IO 'C/min	50-60	
8. Melting index (g/IO min)	I''C216 kg	5-7	
9. Color	-	Black, Red	

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3.1.1 3D Printer

Craftbot IDEX Cartesian 3D printer, as pictured in Figure 1, is used in this research for producing the tensile specimens for this work. This printer has the capacity to 3D print materials such as: Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyvinyl Alcohol (PVA), High-density polyethylene (HDPE) and similar materials. The printer is located in the laboratories of the Intermediate Technology Transfer Unit (ITTU), Suame Magazine, Kumasi, affiliated with KNUST.

Figure 1: CraftBot IDEX Cartesian 3D printer, at the Intermediate Technology Transfer Unit (ITTU), Suame Magazine, Kumasi, affiliated with KNUST

3.1.2 Tensile Specimen Modelling

The tensile test sample specimens used in this study are modelled based on ASTM D638 type - IV, which is the standard used for the determination of tensile properties of reinforced and non-reinforced plastics (ASTM International, 2014). Solidworks software is used for modelling the geometry of the tensile specimens as depicted in Figure 2, by the ASTM D638 standards. The models are then saved in .stl file format and then imported to the 3D printing software.

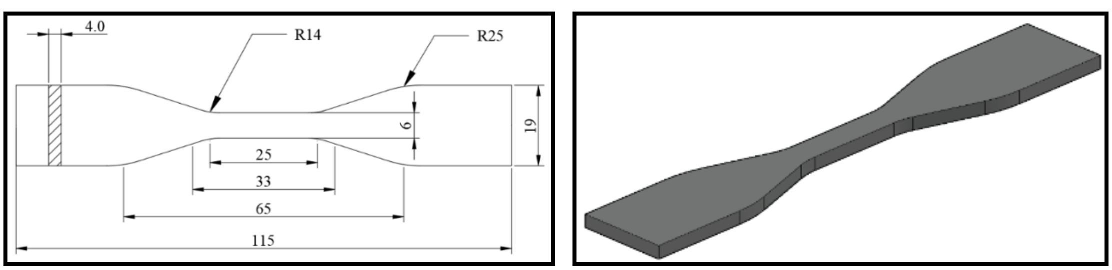

Figure 2: ASTM D638 Type IV and modelled tensile specimen

3.1.3 Specimen Fabrication

The tensile test specimens to be tested in this work, have the shape and geometrical dimensions as indicated in figure 2. Also, the 3D printer used to fabricate the tensile samples for this work is pictured in Figure 1 of this report. Among the tools used for the measurement of the prepared samples chiefly include, permanent marker, and digital calipers. The 3D printed PLA specimens

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were subsequently conditioned at a temperature of 23 ℃, and for forty (40) hours before proceeding with the tensile tests as per the ASTM standards (ASTM International, 2014).

3.2 Experimentation

3.2.1 Taguchi's Approach to Parameter Design

Taguchi's approach to parameter design enables engineers to systematically and efficiently optimize design parameters for performance and cost (Raviteja et al., 2020; Durakovic, 2017; Mohammed et al., 2019). The main steps in the Taguchi approach for parameter design include: (1) Determine the quality characteristics to be optimised; (2) Identify the Noise factors and test conditions; (3) Identify the control factors and their alternative levels; (4) Design the matrix experiment and define the data analysis procedure; (5) Conduct the matrix experiment; (6) Analyze the data and determine optimum level of control factors; (7) Predict the performance at these levels (Wille, 1990).

3.2.2 Optimum Levels Determination using the Taguchi Method

To analyze the results of experiments, and to obtain the optimal test parameter after investigations, the Taguchi method, which uses a statistical measure of performance called signal-to-noise (S/N) ratio borrowed from electrical control theory is used. The S/N ratio model developed by Dr. Taguchi is a performance measure to choose control levels that best cope with noise (Atefeh et al. 2021).

In this work, the tensile strengths of the 3D-printed PLA parts are required to be maximized and optimised, hence, the *Biggest-is-best characteristic* is the required ratio to be used for this work. Subsequently, equation 1, applies.

- *Biggest-is-best quality characteristic (strength, yield),*

$$S/N ratio\ (\eta) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \quad \textbf{(1)}$$

- *Smallest-is-best quality characteristic (contamination),*

$$S/N ratio\ (\eta) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}{y_i}^2\right) \quad \textbf{(2)}$$

- *Nominal-is-best quality characteristic (dimension).*

$$S/N ratio\ (\eta) = -10\log_{10}\left(\frac{\mu^2}{\sigma^2}\right) \quad \textbf{(3)}$$

3.2.3 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a hypothesis-testing method used to analyze the equality of two or more population (or treatment) means by examining the variances of samples which are taken. ANOVA permits us to determine whether the differences between the samples are only due to random error or if there are systematic treatment effects which make the mean in one group differ from the mean in another. Mainly, ANOVA is used to compare the parity of three or more means, but when the means from two samples are compared using ANOVA, it is similar to using a t-test to compare the means of independent samples (Krishnaiah et al., 2012).

3.2.4 Optimum Condition Predictions Using ANOVA Approach

In this work, the objective is to maximize the tensile strength and to predict the optimum tensile strength value as a response. For the factors involved in this work, i.e., the processing speed (S), the processing temperature (T) and the nozzle diameter (D), the predicted optimum response is obtained using equation (4) (Krishnaiah et al., 2012):

$$\mu_{predict} = \bar{Y} + (\bar{S}_1 - \bar{Y}) + (\bar{T}_1 - \bar{Y}) + (\bar{D}_1 - \bar{Y}) = (\bar{S}_1 + \bar{T}_1 + \bar{D}_1) - 2\bar{Y} \quad \textbf{(4)}$$

3.2.5 Optimum Condition Predictions Using Multi-Regression Analysis

In experiments, if the response (Y) is linearly related to more than one independent variable, the relationship is modelled as multiple linear regression. Suppose, we have X_1, X_2, X_3…. X_k independent variables (factors). A model that might describe the relationship is as presented in equation 5 (Krishnaiah et al., 2012):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_k X_k + e \quad \textbf{(5)}$$

3.2.6 Hypothesis Testing in Multi-linear Regression

The test for significance of regression is to determine whether there is a linear relationship between the response variable Y and the regression variables X_1, X_2, X_3 ….X_k.

$$H_0: \beta_1 = \beta_1 \ldots\ldots\ldots\ldots \beta_k = 0$$
$$H_1: \beta_j = \neq 0 \text{ for at least one j.} \quad (6)$$

Rejection of H_0 implies that at least one regression variable contributes to the model. The test procedure involves ANOVA and F-test (Krishnaiah et al., 2012).

3.3 Process Parameters Selection and Their Limits

In this work, a not much-studied process parameter, nozzle diameter, is used simultaneously with other process parameters including processing speed, and processing temperature to evaluate their concurrent and instantaneous effect on 3D printed PLA materials in terms of tensile strengths.
Three levels of parameters are considered for sample preparation in this work, and the parameters which are kept constant throughout this experimentation are shown in Tables 2 (a, b).

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Table 2a: Factors and their levels for this work

Factor	Symbol	Unit	Level		
			Low level (I) (-1)	Centre point (0)	High level (+1)
Processing speed	S	mm/s	70	80	90
Processing temperature	T	℃	215	220	230
Nozzle diameter	D	mm	0.40	0.60	0.80

Table 2b: List of fixed parameters used for this work

Parameter	Value
Filament diameter (mm)	1.75
Filament colour	Red
Hot plate temperature (℃)	60
Layer thickness (mm)	0.2
Wall thickness	2.0 mm
Infill density	100%
Infill geometry	Linear
Layer height	Compute as per the relation above
Number of layers	2
Raster angle (°)	0
Speed while travelling (mm/s)	120
Part orientation	Flat

3.3.1 Experimental Design Based on the Taguchi Method

To evaluate the effect of printing parameters of the FDM process on PLA printed parts, in terms of tensile strength, a Taguchi method is used to optimise the process. The Taguchi method has become a powerful tool for the systematic application of design and analysis of experiments to design and improve product quality. In this work, experimental designs are carried out using Taguchi's L_9 Orthogonal Array (OA) experimental design which consists of 9 combinations of processing speed, processing temperature and filament diameter. It considers three process parameters (without interaction) to be varied in three discrete levels. The experimental design is shown in the results in Table 3 of this report.

3.4 Tensile Test Experimental Procedure

In this work, the 3D-printed PLA specimens conditioned as per the ASTM D638 standards (ASTM International, 2014), are tested experimentally for tensile strength on a universal static material testing machine (UTM), located in the specimen preparation laboratory at Ghana Standards Authority, Legon, Accra. Tensile properties measurement is carried out on the Shimadzu Japan-made Auto-Graph AG 15 UTM machine, with a grip attachment distance of 33 mm. A load of 5.0 kN at a constant speed of 5 mm/min is applied. Specimens are placed in the UTM with the help of grippers, and a gradual load is applied on the specimens until failure, and the resultant loads are

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noted down for every single sample, thus obtaining the tensile loads for every specimen. The mechanical properties to be obtained from the tensile tests for this work are as illustrated in Equations (7-10).

$$\sigma_y = \frac{F_{max}}{A_O} \quad \textbf{(7)}$$

$$\sigma_u = \frac{F_{break}}{A_O} \quad \textbf{(8)}$$

$$\varepsilon_t = \frac{\Delta L}{L_O} \quad \textbf{(9)}$$

$$E_t = \frac{\sigma}{\varepsilon_t} \quad \textbf{(10)}$$

Where:

F_{max}: the maximum force sustained by the specimen,
F_{break}: the force sustained by the specimen at breakage,
L_o: original grip separation,
ΔL: extension (change in grip separation),
A_O: original cross-sectional area,
ε_t: normal strain at break.

Moreover, the cross-sectional area of the printed tensile samples is calculated as: [Width of narrow section (W) x Thickness (T)]. (That is, 6 x 4 =24 mm^2) as per Figure 2.

4.0 RESULTS AND DISCUSSION

The results of the tensile test are captured in the results table 3 of this report. The table shows the Taguchi L_9 orthogonal array. In all forty-five (45) black PLA samples were prepared and tested. As indicated in Table 3, there are nine experiment levels in all, hence, five representative samples were printed for each experimental level. Therefore, every experimental result value (that is, the ultimate tensile load (kN); ultimate tensile strength (N/mm^2), recorded in Table 3 for each of the nine experimental levels, is an average of five (5) tested samples to guarantee the reliability of test results. Figures 3 (a, b), illustrate a few of the tensile test samples before and after the tensile test procedures.

Figure 3: Prepared PLA tensile test samples (a) PLA test samples before testing and (b) broken PLA test samples after tensile testing

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4.1 Experimental Results and Taguchi Analysis

The results of the experiment are captured in Table 3 of this report. Subsequently, a table of signal-to-noise ratio (S/N) for ultimate tensile strength in this work is calculated for each experiment of L_9, essentially using equation 1 above. To calculate the S/N values for the tensile tests, the Taguchi Orthogonal Array is designed in Minitab18, using the tensile test results table presented in Table 3 of this report. It can be seen clearly from Table 3 that for the tensile output response factors, the largest resultant ultimate tensile strength value is (61.67 N/mm^2).

Subsequently, the resulting S/N table for the tensile test results is presented in Table 3. Also, for the S/N values presented in Table 3, graphs of (Main Effects Plot for S/N ratios for ultimate tensile strength, and Main Effects Plots for Means for the same ultimate tensile strength) were plotted to determine the effects of 3D printing parameters on the Ultimate Tensile Strength of 3D printed parts. The graphs plotted are as pictured in Figures 4 (a and b) respectively. Copiously, from the graphs, the optimal determined 3D printing parameter effects and their levels are *Nozzle Diameter (D) at level 3 (0.8 mm); Processing Speed (S) at level 3 (90 mm/s); and Processing Temperature at level 3 (230* ℃*)*.

4.1.2 Analysis of Variance (ANOVA)

Table 4 and Figure 5 show the percent effect of each parameter on the Ultimate Tensile Strength (UTS) of the 3D-printed samples. It can be seen that the Nozzle Diameter (D) has the most significant effect on the output response (UTS), and its contribution is 86.81%. After that, the second significant factor for the UTS is Processing Speed (S), and its contribution is about 11.61%, and the third significant factor for the UTS in this work is the Processing Temperature (T), with a contribution of about 0.48%.

4.1.3. Validation of Results

Validation of results is an important part of any experimental analysis and in project works like this. In this work, two Prediction Models, together with results confirmation experiments have been established to help analyze, predict, validate and above all, optimize the Ultimate Tensile Strength of 3D printed PLA parts. These predictive models include prediction by the *Taguchi Method and prediction by multi-linear regression Techniques*. These techniques are therefore explained in the subsequent sections of this report.

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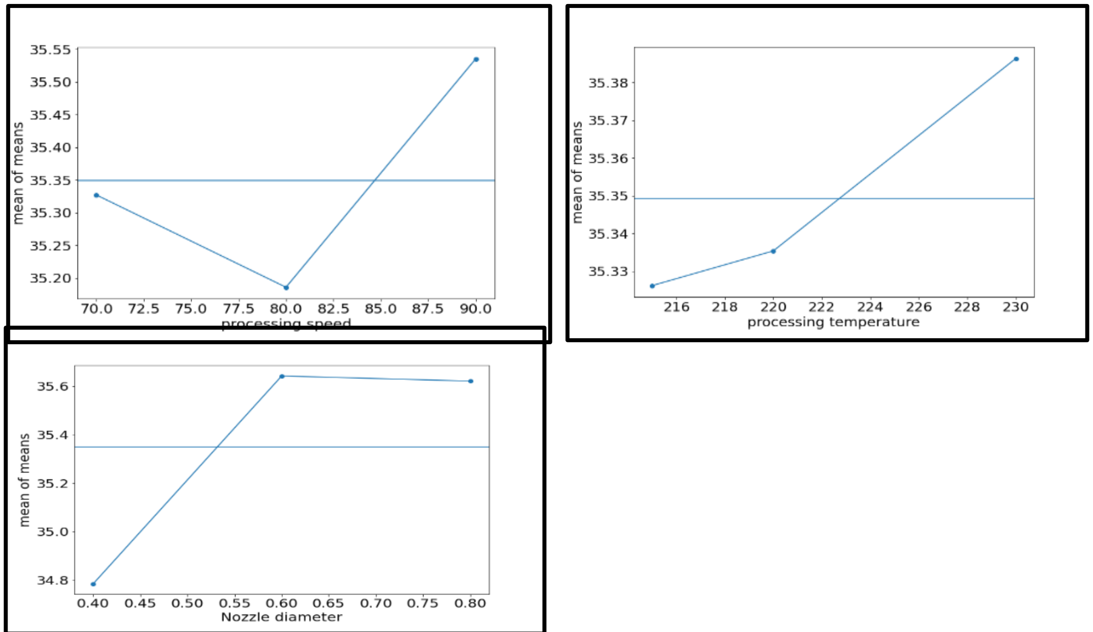

Figure 4a: Main effects plot for S/N ratios (UTS)

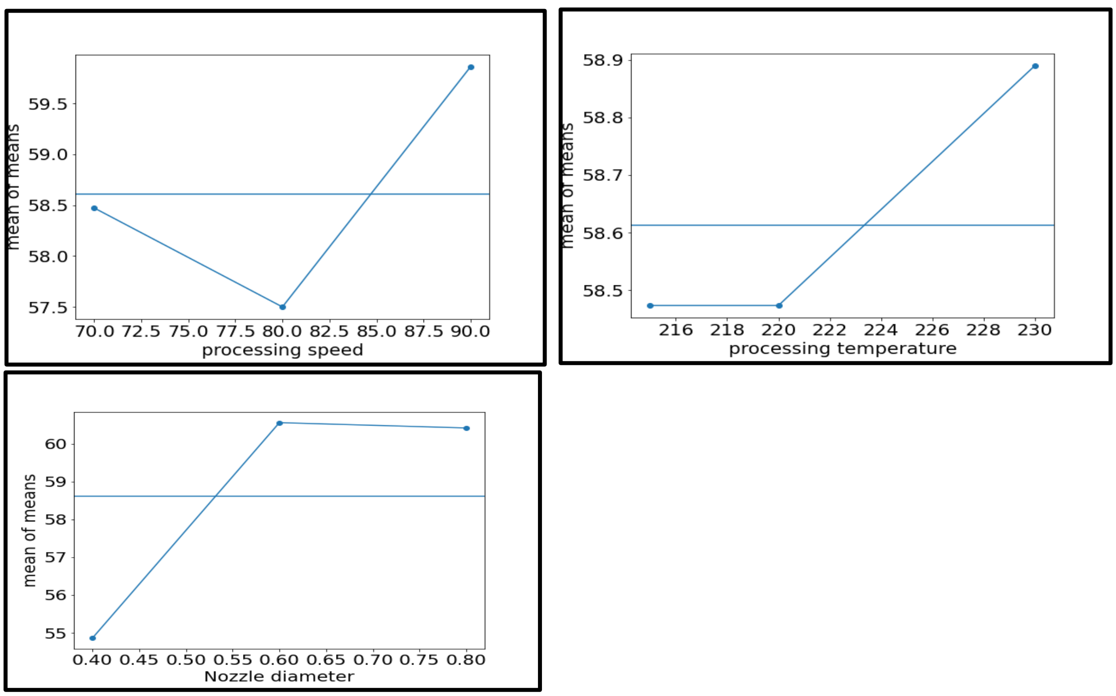

Figure 4b: Main effects plot for means (UTS)

ISSN: 2408-7920

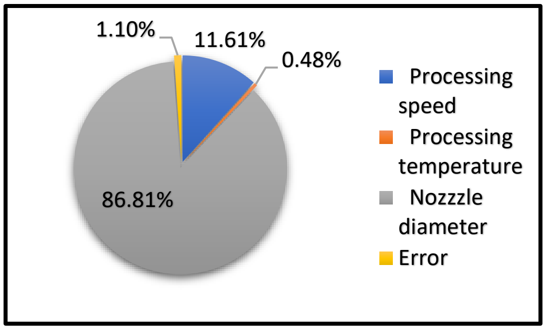

Figure 5: Significance of process parameters for Ultimate Tensile Strength

4.1.4 Prediction by Taguchi Method

For the optimal condition of process parameters, as determined in section 4.1 of this report: Nozzle Diameter (D) at level 3 (0.8 mm), Cutting Speed (S) at level 3 (90 mm/s), Processing Temperature at level 3 (230 °C), the value of the optimised Ultimate Tensile Strength can be predicted based on equation 4 (Krishnaiah et al., 2012):

$$\text{Ultimate Tensile Strength (UTS)}_{\text{predict}} = (\bar{D}_3 + \bar{S}_3 + \bar{T}_3) - 2\bar{Y} \qquad \textbf{(11)}$$

Hence, using the parameter levels stated in Table 3:

$$\bar{Y} = \frac{54.17+60.42+60.83+59.58+58.75+54.17+61.67+56.25+61.67}{9}$$

$$\bar{Y} = 58.61 \qquad \textbf{(12)}$$

$$\bar{S}_3 = \frac{61.67+56.25+61.67}{3}$$

$$\bar{S}_3 = 59.85 \qquad \textbf{(13)}$$

$$\bar{T}_3 = \frac{60.83+54.17+61.67}{3}$$

$$\bar{T}_3 = 58.89 \qquad \textbf{(14)}$$

$$\bar{D}_3 = \frac{60.83 + 58.75 + 61.67}{3}$$

$$\bar{D}_3 = 60.42 \qquad \textbf{(15)}$$

Therefore, the Calculated Optimized UTS value using the Taguchi Model is as given:

UTS = 59.86 + 58.89 + 60.42 – (2 x 58.61)

UTS = 62.00 N/mm^2

ISSN: 2408-7920

African Journal of Applied Research
Vol. 9, No. 2 (2023), pp. 104-123
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Table 3: Ultimate Tensile Experimental Results and Corresponding S/N Ratio

Experiment No.	Processing speed mm/s	Processing temperature ℃	Nozzle diameter (∅) mm	Average ultimate tensile load (F) KN	Average ultimate tensile strength (σ) N/mm^2	S/N Ratio Ultimate Tensile Strength
1	70	215	0.40	1.30	54.17	34.6752
2	70	220	0.60	1.45	60.42	35.6236
3	70	230	0.80	1.46	60.83	35.6824
4	80	215	0.60	1.43	59.58	35.5020
5	80	220	0.80	1.41	58.75	35.3802
6	80	230	0.40	1.30	54.17	34.6752
7	90	215	0.80	1.48	61.67	35.8015
8	90	220	0.40	1.35	56.25	35.0025
9	90	230	0.60	1.48	61.67	35.8015

Table 4: ANOVA for Ultimate Tensile Strength

Source	DF	SS	MS	F	P	% Contribution
Processing speed (mm/s)	2	8.4648	4.2324	10.53	0.087	11.61
Processing temperature (°C)	2	0.3472	0.1736	0.43	0.698	0.48
Nozzle diameter (mm)	2	63.2732	31.6366	78.72	0.013	86.81
Error	2	0.8038	0.4019			1.10
Total	8	72.8890				100.00

4.1.5 Ultimate Tensile Strength Prediction by Multi-Linear Regression Analysis

Minitab 18 software was used to develop the Multiple Linear Regression Predictive Model for the Ultimate Tensile Strength (UTS) in this work. The predictors are Processing Speed (S), Processing Temperature (T), and Nozzle Diameter (N). The Regression Equation for ultimate tensile strength (UTS) for this work using the coefficients obtained in Table 5, is therefore fitted as:

$$\mathbf{UTS} = 38.13 + 0.07 \text{ Processing Speed (S)} + 0.03 \text{ Processing Temperature (T)} + 13.88 \text{ Nozzle diameter (D)} \qquad \mathbf{(17)}$$

The significance of each coefficient in the UTS Regression Equation 17 above, was analyzed using ANOVA and tested by the p-value statistics and by, the method of model comparison. From Table

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African Journal of Applied Research
Vol. 9, No. 2 (2023), pp. 104-123
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4, the regression statistics indicate that the coefficient for Nozzle Diameter (D) is statistically significant. That is, $p < 0.05$ at a 95% confidence level. This therefore rejects the null hypothesis, since at least one of the parameters out of the three (processing speed, processing temperature and nozzle diameter) is significant. Hence, the stated Multi-linear Regression Model (equation 17) is valid, and there is some significant linear relationship between the input variables and the output results as well. More so, the residual spread plots for the Ultimate Tensile Strengths values obtained in this work (UTS), as seen from Figures 6 (a, b), lie along a straight line, and that suggests that the residuals are distributed normally. Again, the graphs reveal an unsystematic and usual pattern of residuals, which indicates that the variables affect the response in an orderly way, and also demonstrates the adequacy of the Multi-linear Regression Model developed in this work (equation 17). Furthermore, it can be seen from Figure 6b specifically that, experiment 3 with a Processing Speed of 70 mm/s, Processing Temperature of 230 ℃, and Nozzle Diameter of 0.8 mm, has the shortest distance to the theoretical line, which implies, it is the experiment with the least mistake.

Additionally, to compare the established multi-linear equation model with the ANOVA model established in sections (4.1.4 and 4.1.5) of this report, an optimized UTS value was calculated by substituting the optimal condition of process parameters, Nozzle Diameter (D) at level 3(0.8); Processing Speed (S) at level 3 (90); and Processing Temperature (T) at level 3 (230) into the multi-linear regression equation as stated: UTS = 38.13 + 13.88 Nozzle Diameter (D) + 0.07 Processing Speed (S) + 0.03 Processing Temperature (T):

$$= 38.13 + 13.88*0.8 + 0.07*90 + 0.03*230$$
$$= 38.13 + 6.3 + 6.9 + 11.10$$
$$= \underline{62.43\ N/mm^2} \quad \textbf{(18)}$$

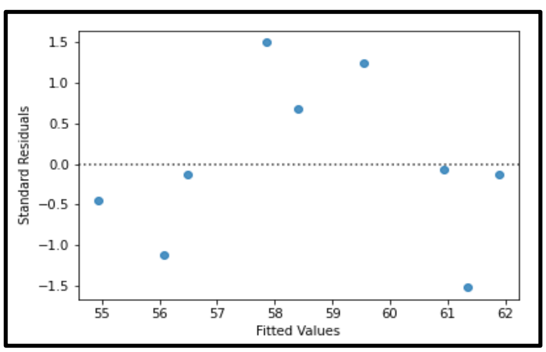

Figure 6a: Plot of standardized residuals vs. fitted value

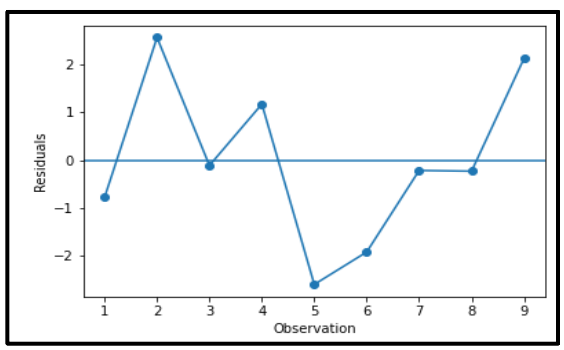

Figure 6b: Plot of Residuals vs. Observation

ISSN: 2408-7920

Table 5: Regression Table for Ultimate Tensile Strength (UTS)

Predictor	Coefficient	Standard Error coefficient	T stat	P-value
Constant	38.125	26.742	1.426	0.213
Processing speed (S)	0.070	0.088	0.787	0.467
Processing Temperature (T)	0.030	0.116	0.257	0.807
Nozzle Diameter (D)	13.883	4.418	3.143	0.026

4.1.6. Confirmation of Tensile Strength Experiment Result

To validate the results obtained during the tensile strength experiments, it is necessary to perform confirmation experiments for the tensile strength response characteristics at optimal levels of the process variables, that is, Nozzle diameter (D) at level 3 (0.8 mm); Processing speed (S) at level 3 (90 mm/s); and Processing temperature at level 3 (230 ℃). The average value of the ultimate tensile strength characteristics from the confirmation tests was compared with the predicted values, as obtained in the previous sections of this paper. This average value is calculated in Table 6.

Table 6: Result of confirmation tensile test experiment

Experiment No.	Ultimate Tensile Strength (N/mm^2)
1	62.10
2	61.89
3	61.85
Average	61.95

4.1.7 Summary and Comparison of Optimal Predicted Values for the two Models Developed in this work and the average value of the confirmation tensile test results

Figure 7 shows the graph of Ultimate Tensile Strength (UTS) of the optimal combination of process parameters by the two predictive Models developed in this work, and the highest ultimate tensile test results (table 3). It can be seen clearly from Figure 7 that, the highest predicted value of UTS in this work (62.43 N/mm^2), obtained from the Multi-linear Regression Model, differs from the lowest predicted value by the Taguchi Method, by not so significant percentage value of 0.7%.

Also, the average Ultimate strength (UTS) value from the confirmation experimental results (61.95 N/mm^2) as pictured in Table 6, differs by less than just 0.1% of the prediction by Taguchi Model (62.00 N/mm^2).

Again, the approximate Optimised Ultimate Tensile Strength value of 62 N/mm^2 predicted by all two Predictive Models established in this work, which is approximately the same as the average Ultimate Tensile Strength confirmation experimental results, tends to cross-validate the two models and demonstrates their significance. The two models (that is, the Taguchi model and multi-

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linear Regression models) established in this work, therefore, can be used to make meaningful, accurate, and relevant predictions of the Ultimate Tensile Strength of 3D printed PLA parts.

Clearly, from the results obtained from this work, the optimized tensile strength is about 62 N/mm^2, and this value is significantly influenced by the nozzle diameter with a contribution of about 86.81% of the three selected parameters and their levels used for this work. The nozzle diameters used for this work are 0.4 mm, 0.6 mm and 0.8 mm; and the results as presented in Table 3, clearly indicate that the highest tensile strength values are achieved at the highest selected nozzle diameter of 0.8 mm. That is, as the nozzle diameter increases, the tensile strength increases. Indeed, these findings from the work confirm the earlier works done by other authors. For example, according to Tezel and Kovan (2022), it is recommended to use a larger nozzle diameter and lower layer thickness to produce parts with superior properties. The study concluded that an increase in nozzle diameter leads to increased part strength, while layer thickness significantly affects surface quality. Increased nozzle diameter and part density contribute to reduced production time. It is recommended to use a larger nozzle diameter and lower layer thickness for parts with superior properties.

Also, Triyono et al. (2020) investigated the impact of nozzle hole diameter on the porosity and tensile strength of 3D printed parts using PLA material. The authors conducted their experiments using fused deposition modelling (FDM) 3D printing, with varying nozzle hole diameters of 0.3, 0.4, 0.5, and 0.6 mm. They maintained consistent bed temperature (60°C), extruder temperature (200°C), and printing speed (80 mm/s) across all experiments. The layer thickness was set at a ratio of 20% to the nozzle hole diameter, and a 100% line-type infill pattern was used. Their study also clearly concluded that increasing the nozzle hole diameter of 3D printing processes tends to increase the product density and tensile strength.

Again, Czyzewski et al. (2022), examined the effects of extruder nozzle diameter on the improvement of functional properties of 3D-printed PLA products. In their experiment, the RepRap device for additive manufacturing was used, with the use of nozzles with diameters of 0.2 mm, 0.4 mm, 0.8 mm and 1.2 mm. The test samples were produced with a layer height of 0.2 mm, full filling (100%) and with constant remaining printing parameters. They reveal findings that, when it comes to strength properties, the samples produced with the use of nozzles with diameters of 0.4 mm and 0.8 mm were characterized by a higher tensile strength. However, the lowest values of mechanical properties were observed in the case of samples produced with the use of the 0.2 mm nozzle. They also brought to the fore that, the use of an extruder nozzle diameter of 0.8 mm allows one to obtain a macrostructure with a high degree of interconnection of layers and paths and favourable mechanical properties. So, therefore, their test results can be used in the construction of functional elements that are produced by fused deposition modelling (FDM) and fused filament fabrication (FFF) methods in prototype, unit and small-lot production.

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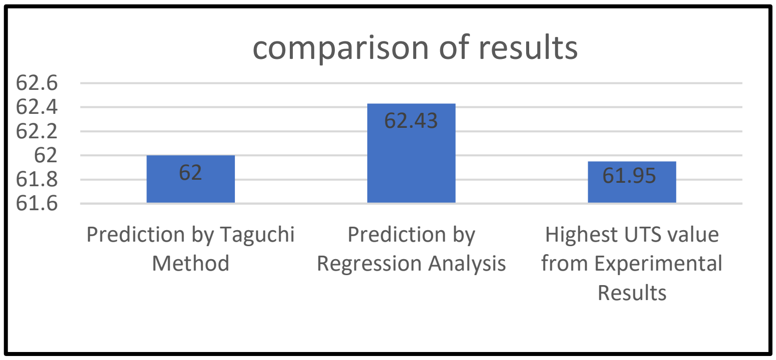

Figure 7: Comparison of results for Ultimate Tensile Strength

5.0 CONCLUSION

Efficient and accurate prediction of the mechanical properties of 3D printed parts is of great significance for improving the productivity of the process and reducing downtime. The present project work was carried out to essentially analyze and optimize 3D printing process parameters such as processing speed, processing temperature and nozzle diameter on the ultimate tensile strength of 3D printed PLA. The process parameters considered in the experiments are optimized to attain the maximum Ultimate tensile strength of the 3D-printed PLA parts. Taguchi's mean estimation method and multi-linear regression model are used to predict the ultimate tensile strength of the 3D-printed PLA in this work. The following conclusion has been drawn from the study. Ultimate tensile strength is mainly affected by Nozzle diameter (86.81%), and Processing speed (11.6%). The least significant parameter for Ultimate tensile strength is processing temperature (0.48%). The best combination of process parameters for the 3D printing within the selected range in this work is as follows: Increased Nozzle diameter at level 3 (0.8 mm), followed by Increased processing speed at level 3 (90 mm/s), and relatively increased Processing temperature at level 3 (230 ℃). This, therefore, constitutes the determined optimal levels of the three selected 3D printing parameters used in this work.

More so, the Ultimate tensile strength of the PLA filament used for this work according to the manufacturer and captured in Table 1 of this paper is around 49.5 N/mm^2. However, after 3D printing the black filament, using the selected parameters at their current selected levels, and performing the tensile test experiments on the samples, the ultimate tensile strength recorded was around 61.67 N/mm^2 (Table 3). This value shows a significant improvement in the original ultimate tensile strength of the PLA filament used for this work. This, among other things, suggests that with an informed and critical selection of process parameters, and implementing the same concurrently to 3D print PLA filaments, higher mechanical strength characteristics, including higher tensile strength properties are attainable. Indeed, observations and visits to most 3D printing industries, particularly in Ghana and elsewhere, reveal that 3D printing filaments are printed, using the same nozzle diameter without taking cognizance of the effects of the nozzle diameter on the mechanical, and thermal strengths of their 3D printed products. Nonetheless, this research reveals

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that the nozzle diameter has the most profound effect on the tensile strength of the 3D-printed parts. It is, therefore, incumbent on 3D printing industries to select appropriate nozzle sizes to 3D print filaments to achieve desirable mechanical, thermal and surface finish properties.

Practical Implications

The optimisation method frequently results in enhanced efficiency in material utilization, hence diminishing both material waste and associated expenses. This is by sustainability objectives and serves to reduce the ecological footprint. Grossly, 3D printing, as an additive manufacturing process, enables expedited prototypes and iteration of design intents to be achieved. The acceleration of the product development cycle and the subsequent reduction in time-to-market are crucial factors in competitive sectors.

The enhancement of tensile strength in 3D-printed PLA items can be achieved through the optimisation of process parameters. This results in enhanced product performance and increased reliability, rendering PLA a feasible material for a broader spectrum of applications.

Social Implications

The utilization of efficient PLA printing techniques results in a reduction of material wastage and expenditure when compared to conventional manufacturing methods. This is by the objectives of sustainability and serves to reduce the ecological footprint of production, making a positive contribution towards the establishment of a more environmentally conscious society.

The application of optimised PLA printing has the potential to efficiently manufacture essential relief products, including components for shelters and medical supplies, in places affected by disasters. The aforementioned talent possesses the potential to preserve human lives and mitigate the experience of distress in times of emergencies.

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6.0 REFERENCES

ASTM International (2014), "Standard Test Method for Tensile Properties of Plastics: *U.S. Department of Defense*, Designation: D638-14".

Atefeh R.K., Saber R., Aliha, M.R.M, & Berto F. (2021). Optimization of properties for 3D printed PLA material using Taguchi, ANOVA and Multi-objective Methodology. *ScienceDirect, Elsevier*, 34(2021)71 - 77.

Bermudez, M. (2021). A theoretical and contextual background of 3D printing and design. *Novel Research in Sciences*, 7(1), 000654.2021.

Brischetto, S., & Torre, R. (2020). Tensile and compressive behaviour in the experimental tests for PLA specimens produced via fused deposition modelling technique. *Journal of Composite Science*, 4, 140, 40301140, 1-25.

Boon, W., & Van, W.B. (2018). Influence of 3D printing on transport: a theory and experts Judgement-based conceptual model. *Transport Reviews*, 38(5), 556-575.

Chamil, A., Pimpisut, S., & Anura, F. (2020). "Optimization of Fused Deposition Modeling Parameters for Improved PLA and ABS 3D Printed Structures". *International Journal of Lightweight Materials and Manufacture*, 3(2020), 284-297.

Czyzewski, P., Marciniak, D., Nowinka, B., Borowiak, M., & Bielinsk, M. (2022). Influence of extruder's Nozzle diameter on the improvement of functional properties of 3D printed PLA products, *Polymers*, 14(2), 14020356.

Durakovic, B. (2017). Design of Experiments application, concepts, examples: state of the art. *Periodicals of Engineering and Natural Sciences*, 5, 2303 - 4521, 421-439.

Gibson, I., Rosen, D.W., & Stucker, B. (2010), "Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing", *Springer*, New York, USA.

Gomez, G., Jerez-Mesa, R., Travieso-Rodriguez, J.A., & Liuma-Fuentes, J. (2018). Fatigue performance of fused filament fabrication PLA specimens. *Materials and desig*n, 140, 278-285.

Imran, S., & Pushpendra, S.B. (2020). Reliability analysis of a 3D printing process. *ScienceDirect, Elsevier*, 173(2020), 1877-0509, 191-200.

Krishnaiah, K., & Shahabudeen, P. (2012). Applied Design of Experiments and Taguchi Methods. *Asoke K. Ghosh, PHI Learning Private Limited*, New Delhi-110001, pp. 24-250

Kumbhar, N. N., & Mulay, A. V. (2016, December). Finishing of fused deposition modelling (FDM) printed parts by CO2 laser. In *Proceedings of 6th International & 27th All India Manufacturing Technology, Design and Research Conference* (pp. 63-67).

Lay, M., Thajudin, N.L.N., Hamid, Z.A.A., Rusli, A., Abdullah, M.K., & Shuib, R.K. (2019). Comparison of physical and Mechanical properties of PLA, ABS, and Nylon 6 fabricated using fused deposition modelling and injection moulding. *Compos. Part B Engineering*, 176, 107341.

Maisarah, M., Mohamad, Z.M.O., & Mahfodzah, M.P. (2019). Optimization of 3D printing parameters for improving the mechanical strength of ABS printed parts. *International Journal of Mechanical Engineering and Technology*, 10, 0976-6340, 255-260.

Mohammed, R.N., Garesh B.K., & Madhan P. (2019). Application of Taguchi's experimental design and range analysis in optimisation of FDM printing parameters for PET-G, PLA and HIPS. *International Journal of Scientific and Technology Research*, 8(09), 2277 - 8616, 891-902.

Mohammad, D. Z. (2020). Study and characterization of Mechanical properties of wood-PLA composite (Timber fill) material parts built through fused filament fabrication. *Phd thesis, Universitat Politecnica De Catalunya, Barcelonatech*.

ISSN: 2408-7920

Arca Academic Publisher

Oppon, C., Hackney, P. M., Shyha, I., & Birkett, M. (2015). Effect of Varying Mixing Ratios and Pre-Heat Temperature on the Mechanical Properties of Polyurethane (PU) Foam. *Procedia Engineering*, *132*, 701-708.

Pascucci, F., Perna, A., Runfola, A. & Gregori, G.L. (2018). The hidden side of 3D printing in management. *Symphoya, Emerging Issues in Management*. 2, 1593-0319, 91-107.

Ramya, A., & Vanapalli, S. L. (2016). 3D printing technologies in various applications. *International Journal of Mechanical Engineering and Technology*, *7*(3), 396-409.

Raviteja, B.V., Teja, A., Sarath, R.D., Sardeep, V., & Chandini, P. (2020). Optimization of cutting parameters in CNC turning machine using Taguchi method and ANOVA technique. *Journal of Engineering Technologies and Innovative Research*, 7, 2349-5162, 1277-1285.

Sumalatha, M., & Malleswera, R. J.N. (2021). Optimization of process parameters in 3D printing-fused deposition modelling using the Taguchi Method. *IOP Conference Series: Material Science and Engineering*, 1112(2021), 012009, 1-14.

Tezel T, & Kovan V. 2022. Determination of optimum production parameters for 3D printers based on nozzle diameter. Rapid Prototyping J, 28(1): 185-194.

Triyono J, Sukanto H, Saputra RM, Smaradhana DF. 2020. The effect of nozzle hole diameter of 3D printing on porosity and tensile strength parts using polylactic acid material. Open Eng, 10(1): 762-768.

Ventola, C.I. (2014). Medical Applications for 3D: Current and Projected Uses, *P T: Peer Rev.J. Formul. Manag*., 39(10), 704-711.

Wille, R. (1990). Landing Gear Weight Optimization Using Taguchi Analysis, *Paper presented at the 49th Annual International Conference of the Society of Allied Weight Engineers Inc*, Chandler, AR.