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MODELING OF TENSILE AND BENDING STRENGTH FOR PLA PARTS PRODUCED BY FDM

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ABSTRACT

Fused deposition modeling (FDM) is one of the commonly used additive manufacturing methods to produce quality products with low cost complex geometries with efficient manufacturing and delivery logistics. Mechanical properties can be improved by examining numerous FDM parameters and/or using new materials through this method. In this study, mathematical models have been developed for estimation of some mechanical properties of parts produced by using PLA+ plastic material by FDM method. For this purpose, standard tensile and bending test samples were produced with 3D printer at three different printing speeds and filling ratio with two different raster angles. The effects of process parameters on tensile and bending strength were analyzed experimentally and statistically. According to the experimental results, the importance order of the parameters for mechanical properties of PLA+ based samples were determined as filling ratio, raster angle and printing speed. Tensile and bending strengths were higher in samples produced at 0/90° raster angle. On the other hand, it was determined that the increase in the printing speed decreased the tensile and bending strength proportionally. Between the results obtained from the mathematical models developed with multiple regression analysis and experimental results, an average deviation of 3% for tensile strength and 2% for bending strength were found.

Keywords: FDM, Tensile strength, Bending strength, PLA, Modelling.

1. INTRODUCTION

In recent years, the use of rapid prototyping technologies for industrial applications has increased gradually. Three-dimensional (3D) printing [1], known as one of the rapid prototyping methods, is a technology that produces 3D parts directly by adding material layers instead of subtracting manufacturing. 3D printing, also known as additive manufacturing, is the process of layering materials together to form parts from 3D model data [2], and does not require any special tools, as is the case with conventional machining methods. At the same time, additive manufacturing has an excellent potential to reduce both the production time and the cost of a product and has become a widely used manufacturing method.

Many methods can be used for additive manufacturing, and the differences between the methods are generally related to how the layers are formed. Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Stereolithograhpy (SLA) and Digital Light Processing (DLP) technologies are among the most applied technologies for additive manufacturing [1,3]. Fused deposition modeling is the layering technique by joining, using thermoplastic materials (PLA, ABS, etc.) which can be formed by heat [4]. The FDM method is a complex process with many parameters affecting product quality and material properties, and the combination of these parameters is difficult to understand [5,6]. The processing parameters (layer thickness, raster angle, temperature, scanning width, air gap, fill density, printing direction, printing speed, etc.) have a significant influence on the static and dynamic mechanical properties, quality and performance of FDM printed parts [7-10]. Today, the products manufactured using FDM are primarily used for training and prototype assembly. As the process evolves, it is known to become increasingly widespread in the bioengineering, aviation and automotive industries [11].

Parts produced from thermoplastics by the FDM method have lower technical properties than materials produced by conventional injection molding because of their anisotropic behavior. So, it is important to examine the effects of process parameters on mechanical performance [11,12]. Thus, for different material categories and processing parameters/production conditions, it is an important research subject to investigate the effects of FDM on dimensional accuracy, surface quality, material behavior and mechanical properties. On the other hand, although mechanical properties have significant effects on functional parts, characterization of mechanical properties according to experimental measurements is a time consuming and costly way. In this context, various numerical or statistical modeling techniques are used in order to estimate the mechanical properties of the parts produced by FDM. In this study, the effects of printing speed, filling ratio and raster angle on mechanical properties of PLA+ samples were investigated. In addition, mathematical models were developed for estimation of mechanical properties by multiple regression analysis method based on measurement results on standard tensile and bending samples.

2. MATERIAL AND METHOD

In this study, firstly, the effects of production parameters on mechanical properties (tensile and bending strength) of samples produced from polylactic acid (PLA) material by fused deposition modeling (FDM) method were investigated. In the second stage of the study, mathematical models were developed for tensile and bending strengths of the samples produced from PLA+ material.

2.1. Material and Equipment

PLA is a bioplastic material obtained from natural and edible sources such as corn starch, sugar cane, and is more rapidly destroyed in nature than other plastics. The filament used in the study has a diameter of 1.75 mm produced by ESUN under the trade name PLA+. The mechanical properties of the filament produced in accordance with the FDM method are given in Table 1.

Table 1. PLA+ filament properties [13].

Printing temperature (°C)	Density (g/cm^3)	Distortion temperature (°C, 0.45 MPa)	Tensile strength (MPa)	Elongation (%)	Bending strength (MPa)	Impact energy (kJ/m^2)
205-225	1.24	52	60	29	87	7

Tensile and bending samples produced from PLA+ material was formed on a 3D printer with a fixed type platen. The 3D printer is an open source software-enabled device with a nozzle diameter of 0.4 mm. In this study, the samples were prepared according to ASTM D638-IV for tensile tests and ASTM D790 standards for bending tests. For this purpose, relevant sample solid models were created in Solidworks software and converted into a format suitable for 3D printer. The solid models of the samples were converted to G-code files with Repetier-Host software and made ready for production.

2.2. Production Parameters and Tests

In the production of the parts, 17 layers were used for the tensile sample and 16 layers were used for the bending sample, depending on the nozzle diameter and standard thickness of the tensile and bending specimens. The first and last three of these layers are formed as a full layer and parallel to the selected raster angle. The remaining layers were formed automatically according to the filling ratio parameter. In addition, two outer frames with 0.3 mm thick were added to all samples. In the production of the samples, the printing temperature was selected according to the material supplier's recommendation and the nozzle tip and table temperature were set to 210 °C and 40 °C, respectively. As a result of the literature researches, three different printing speeds and filling ratios and two different raster angles were determined. To produce samples, the PLA+ filament package in the vacuum protector was opened and the same material was used throughout the production process. All production parameters used in this study are given in Table 2.

Table 2. Sample production parameters

Process parameters	Value
Raster angle (*Ra*, °)	-45/+45, 0/90
Filling ratio (*Fr*, %)	50, 75, 100
Printing speed (*Ps*, mm/s)	30, 60, 90
Nozzle temperature (°C)	210
Table temperature (°C)	40
Ambient temperature (°C)	26
Number of bottom shell layers	3
Number of top shell layers	3
Number of exterior walls	2

A total of 54 samples were produced for tensile and bending tests, three of which were produced in each production condition. The detailed images of the 3D model used in the layered production of the samples produced by Delta type printer are given in Figure 1. Tensile tests were carried out by using Shimadzu brand test device with a capacity of 50 kN. MTS brand dynamic tester with a capacity of 100 kN in Iron and Steel Institute Materials Testing Laboratory was used for bending experiments. Tensile and bending tests were performed at 5 mm/s tensile and compression speeds, respectively. Three test samples were tested for each production condition and the evaluations were made by taking the arithmetic average of the tensile and bending strength values obtained.

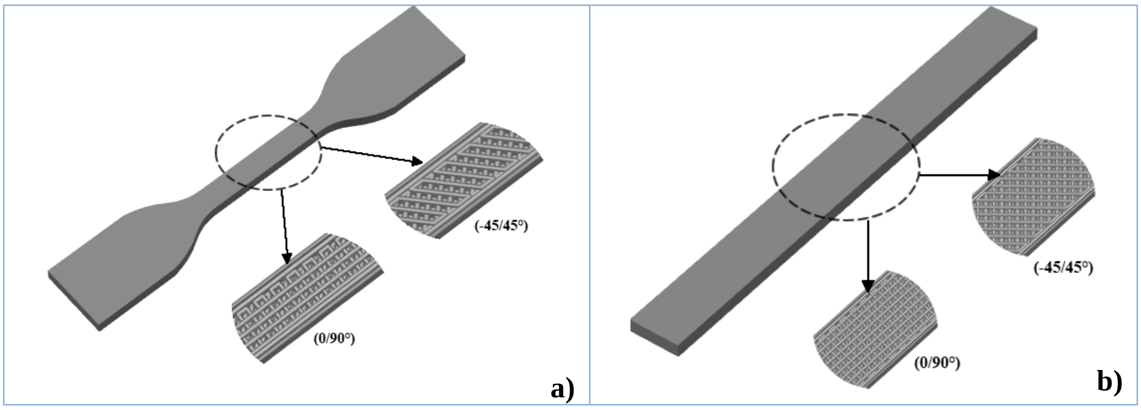

Figure 1. Sample 3D models; a) Tensile, b) Bending

2.3. Modeling of Mechanical Properties

Mechanical properties of the parts produced by FDM method generally vary according to production parameters. In this context, the most effective production parameters on the mechanical properties of the parts produced from plastic materials using 3D printing technology were determined as a result of literature research. Tensile and bending tests were carried out by using the samples produced in standard sizes according to the selected production parameters.

On the other hand, regression analysis is used extensively in order to investigate the cause-effect relationship in case of more than one processing parameters in a manufacturing process and to develop mathematical models in which the processing outputs can be predicted. Regression analysis is a statistical method that enables us to determine the relationship between independent variables (input) and dependent variables (output). For this purpose, tensile and bending strengths are considered as output while production parameters are input. Here it is possible to obtain a linear, quadratic or exponential equation representing the relationship between inputs and outputs. The dependent variable tensile and bending strength can be designed as a linear combination of independent variables (filling ratio, raster angle and printing speed). When the experimental data are considered, the least squares method is used to find the coefficients of the equation in the regression analysis. The following equation can be obtained:

$$Y_i = \beta_0 + \beta_1 P_s + \beta_2 F_r + \beta_3 R_a + \varepsilon_i \tag{1}$$

Here, *Yi* indicates the estimated tensile strength or bending strength, and for experimental observation (*i*), *Ps, Fr* and *Ra* represent the printing speed, filling ratio and raster angle, respectively. The symbols represented by β_0, equation constant, and β_1-β_3 are the regression coefficients of the parameters. Consequently, this equation is a multiple linear regression model with three independent variables. The term R^2, referred to as the coefficient of determination, is often used to indicate the effectiveness of the developed regression models. The approximation of R^2 indicates that dependent variables (processing outputs) are better predicted and that the developed model is highly compatible with independent variables (production parameters). In the present study, a linear regression equation was extracted using Minitab® 17 software and confidence level for all developed models was considered as 95% value and thus, p-value less than 0.05 was considered significant.

3. RESULTS AND DISCUSSION

3.1. Evaluation of Experimental Results

Tensile and bending strength changes of test samples produced using different printing speed, filling ratio and raster angle from PLA+ material are given as interaction graphs in Figures 2 and 3, respectively.

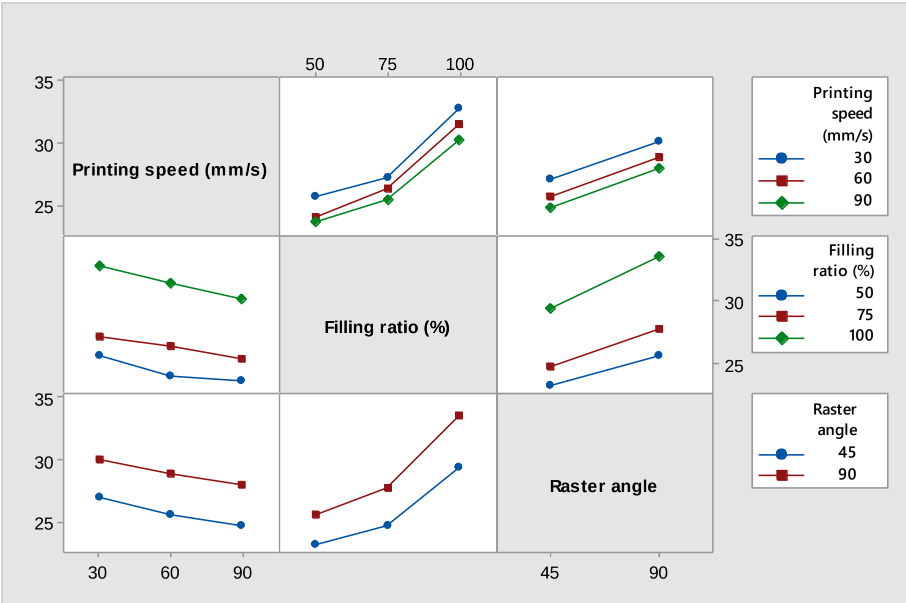

Figure 2. Tensile strength changes according to production parameters

When examining Figure 2, it is seen that the raster angle and the filling ratio have a positive effect and the printing speed have a negative effect on the tensile strength of the test samples produced by fused deposition modeling from PLA+ material. For both raster angles (-45/+45° and 0/90°), the tensile strength of the samples was significantly increased with increasing filling ratio. In addition, tensile strengths of samples produced at 0/90° raster angle were higher. This result was attributed to the tensile load capacity of the samples due to the 3D model. Although the cross-sectional area of the samples was the same, the tensile strength was increased due to the high load-carrying capacity per unit area depending on the higher filling ratio. In addition, it was reported that the raster angle caused the mechanical properties of the plastic parts produced by FDM to exhibit an anisotropic behavior [14-16]. The results of the present study were similar to the literature, and tensile strength was found to be 12% higher in the 0/90° raster angle. On the other hand, it is seen that tensile strength decreases proportionally with increasing printing speed, as stated in the literature [17]. This result was related to the decrease in layer thickness and decrease of material strength due to the increase in percentage elongation with increasing printing speed of the samples. Therefore, production with FDM should be avoided at high print speeds, as it will not source a significant reduction in printing time and cause a reduction in mechanical properties. As a result, the lowest tensile strength was obtained as 22.43 MPa in the sample produced with 50% filling ratio and -45/+45° raster angle, and the highest tensile strength was obtained as 34.60 MPa in the sample with 100% filling ratio and 0/90° raster angle.

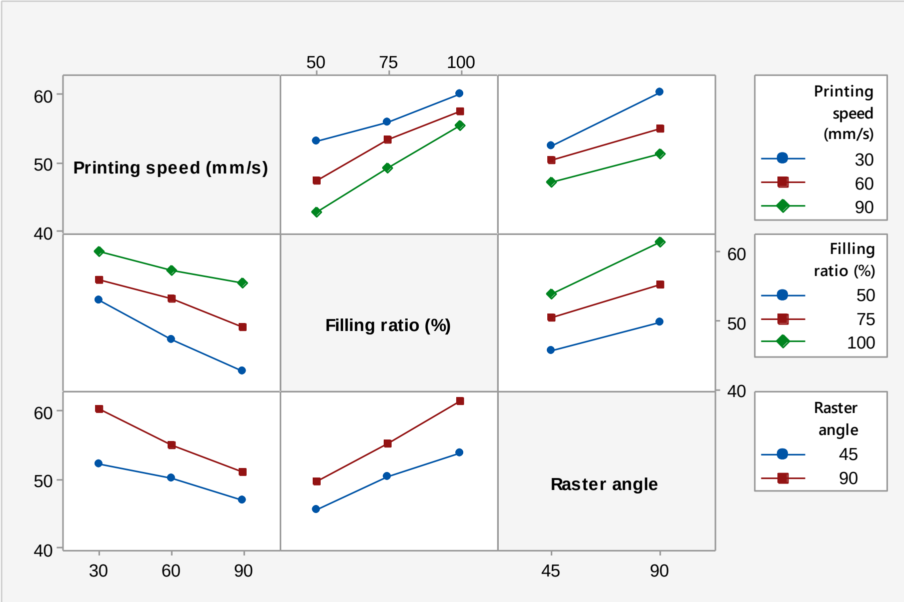

Figure 3. Bending strength changes according to production parameters.

In order to determine the degree of flexural stiffness of the samples produced by FDM method, bending strengths were measured by applying three-point bending test. As can be seen from Figure 3, it was determined that the bending strength of the samples increased for both raster angles due to the increased filling ratio. Furthermore, the strength of the samples produced by fused deposition modeling at 0/90° raster angle was higher than the samples produced with -45/+45° raster angle for all filling ratios. In a study in the literature, it was stated that strength and stiffness are increased by reducing the air gap between the fibers of the plastic part produced by FDM [15]. Also, as reported by Wu et al. [18], excessive porosity causes weak interlayer adhesion, reducing bending strength. The bending strength values obtained in the present study indicate that the amount of gap between the fibers constituting the raster pattern of the sample produced at the 0/90° raster angle is less. Accordingly, the bending strength of PLA+ samples was obtained on average 11% greater at 0/90° raster angle. On the other hand, similar to the result found in tensile strength, it is seen that the bending strength of the samples decreases depending on the increased printing speed. The lowest bending strength was found in the sample produced with a filling ratio of 50% and a raster angle of -45/+45° (41.63 MPa), while the highest bending strength was obtained at a filling ratio of 100% and a raster angle of 0/90° (65.06 MPa). This result shows the positive effect of material filling ratio on flexural stiffness in parallel with the results obtained for tensile strength as expected.

3.2. Modeling Results

As well as it is difficult to determine the actual levels of process parameters in order to produce industrial products with the best mechanical properties by FDM method, it will cause significant losses in time and cost. The main reason for this is that many FDM parameters and a high degree of interaction between the parameters affecting these properties. In this context, developing a mathematical model to estimate the mechanical properties of plastic parts based on the experimental design will facilitate finding the closest solution.

Mathematical models were developed for the estimation of tensile strength (*TS*) and bending strength (*BS*) of parts produced by fused deposition modeling from PLA+ material. First order regression models developed by using regression analysis method with the help of experimental data are given in Eq.2 and Eq.3.

$$TS=14.14-0.0359*Ps+0.1418*Fr+0.0706*Ra \qquad R^2=91.65 \qquad (2)$$

$$BS=36.47-0.1201*Ps+0.2006*Fr+0.1241*Ra \qquad R^2=92.15 \qquad (3)$$

When the mathematical models were examined, the coefficient of determinations (R^2) indicating the relationship between production parameters (dependent variables) and tensile and bending strengths (dependent variables) were found to be 91.65% and 92.15%, respectively. These values indicated that dependent variables can be predicted at high efficiency with multiple regression models. Also, when the coefficients of the independent variables of both models are observed, it was understood that the printing speed (*Ps*) negatively affects the tensile and bending strength. On the other hand, the filling ratio (*Fr*) according to model coefficients was the most important parameter for *TS* and *BS*.

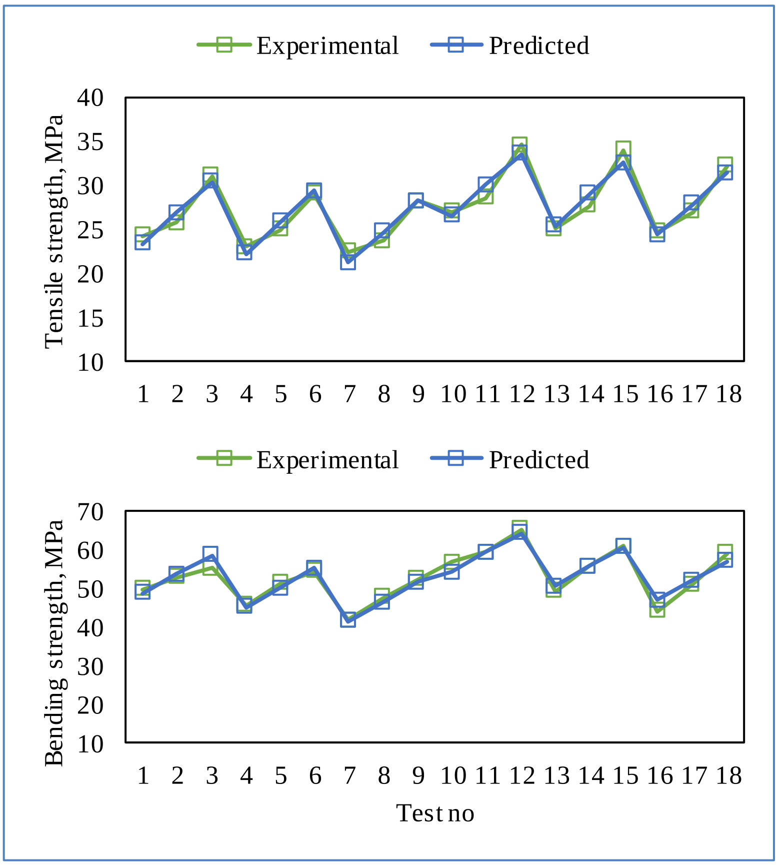

Figure 4. Comparison of experimental and modeling results

In addition, the comparison of experimental and mathematical model estimation results for tensile and bending strength according to the number of experiments is given in Figure 4. According to the Fig. 4, it was concluded that mathematical models developed by multiple regression analysis can be used as good predictive equations for the mechanical properties of parts produced from plastic-based material by fused deposition modeling.

4. CONCLUSIONS

This study focuses on the effects of printing speed, filling ratio and raster angle on mechanical properties of parts produced using FDM based 3D printer from PLA+ material. In addition, mathematical models have been developed for the prediction of mechanical properties. The results are summarized below.

- It was found that the raster angle and the filling ratio have a positive effect on the tensile strength and the printing speed has a negative effect on the tensile strength. The maximum tensile strength was obtained as 34.60 MPa in the sample produced at filling ratio of 100%, printing speed of 30 mm/s and raster angle of 0/90°.
- Bending strength increased with increasing raster angle and filling ratio but decreased with increasing printing speed. The highest bending strength was obtained as 65.06 MPa in the sample produced at fill rate of 100%, printing speed of 30 mm/s and raster angle of 0/90°.
- The smaller tensile and bending strength of the samples produced with -45/+45° raster angle shows that the mechanical properties of the plastic parts produced by the FDM method exhibit an anisotropic behavior.
- The coefficients of determination of mathematical models developed for tensile and bending strength are 91.65% and 92.15%, respectively. This result shows that these equations can be used to estimate the mechanical properties of FDM based plastic parts.

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