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Influence of Process Parameters on Mechanical Properties and Printing Time of FDM PLA Printed Parts Using Design of Experiment

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ABSTRACT
Fused deposition modeling (FDM) is one of the most popular additive manufacturing technologies for various engineering applications. FDM is an additive manufacturing technique for rapid prototyping which can build complex parts in time with minimal human intervention. The quality of FDM processed parts mainly depends on careful selection of process variables. Thus, identification of the FDM process parameters that significantly affect the quality of FDM processed parts is important. This requires a large number of experiments to be determined. This paper presents a study on the influence of three FDM process parameters (layer thickness, infill density, and printing orientation) on the mechanical properties (tensile strength, bending strength and compression strength) of the FDM manufactured parts using the Taguchi method.Five of infill density percentage, layer thicknesses and printing orientation are (20%, 50%, and 80%) , (0.1, 0.2 and 0.3) and (0, 45, 90 degree) respectively have been considered to study their effects on tensile strength, bending strength, compression strength and printing time of test specimens made of polylactic acid (PLA). Experimental results indicate that the mechanical properties of the 3D-printed PLA samples increased with the increasing of infill density and layer thickness while the results indicate that the strength of the process parameter is high at 45 and less at 0 and 90 for all samples when testing the mechanical properties.On other hand lowering the infill percentage value significantly decrease the time of printing the sample.
Keywords-Fused Deposition Modeling (FDM), PLA, process parameters, Infill Density, Tensile Strength, Bending strength, Compression strength, and Printing time

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I. INTRODUCTION

Product cost, quality, and time to market are the three effectiveness criteria for the design process. The development of the technology of rapid prototyping (RP) which uses 3D printing technology makes the design or the product development process become faster. [1]

The process builds objects by adding material in a layer by layer fashion to create a three-dimensional (3D) part, offering the benefit to produce any complex parts with shorter cycle time and lower cost compared to the traditional manufacturing process. The additive manufacturing technology is widely used in engineering for customized products, functional models, pre-surgical models and conceptual models. This technology finds its applications in many fields of engineering and industry, such as aircraft, dental restorations, medical implants and automotive products. With increased competition in the world economy, designers and production engineers face the challenge of producing products more quickly than ever to meet customer requirements and achieve a competitive edge [2].

3D printing is an emerging technology that can be used to construct complex structures inexpensively for modeling, prototyping, or production through deposition or solidification. Fused deposition modeling (FDM) is a standard method for 3D printing using thermoplastic feedstock. As shown in Fig. (1), in this process, the material is melted into a liquid state in a liquefier head and then selectively deposited through a nozzle that traces the parts cross sectional geometry to produce 3D parts directly from a CAD model in a layer by layer manner &[3].

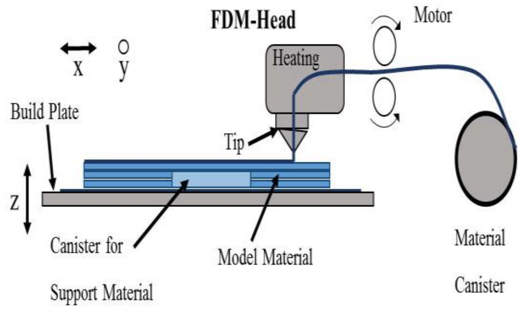

Figure (1) Principle of FDM process [4].

In the FDM process, first a 3D CAD model is created. This model is then exported to slicing software like the FDM Quick Slice software using stereo lithography (STL) format that tessellates the part into numerous basic triangular components. Although the part loses some resolution while exporting, STL format is advantageous because it simplifies the geometry. The software then uses this data to formulate a process plan for the FDM machine's hardware (Fig. 1) [5, 6].

The materials used in these processes include photo-curable resin, polyamide, wax, acrylonitrile-butadiene-styrene (ABS), polycarbonate, metal/ceramic/polymer powders, adhesive coated sheets, etc.[7].

This paper presents a comprehensive review of FDM process parameter involving infill density, layer thickness and part orientation[8].

II. DESIGN OF EXPERIMENT

The Taguchi method is a widely accepted technique that provides efficient methodology for design optimization. It has been extensively used for product design and process optimization worldwide. This is due to the advantages of the design of experiment using Taguchi's technique, which includes simplification of experimental plan and feasibility of study of interaction between various process parameters. This is especially vital for rapid prototyping where cost to produce prototypes is still high. Taguchi proposes experimental plan in terms of orthogonal array that gives different combinations of parameters and their levels for each experiment. In this study, three important process parameters such as infill density, layer thickness and part orientation have been considered to study their effects on response characteristics such as tensile strength, bending strength and manufacturing time as shown in Fig.(2).

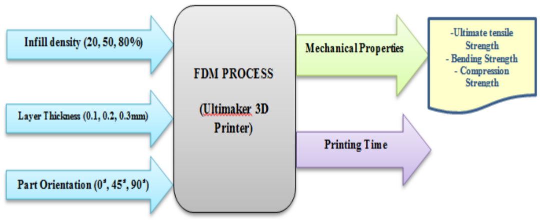

Fig. (2) Experimental Process

In this work the material tested were polylactic acid (PLA) which was used to produce samples. All the five samples were fabricated using the 3D machine as shown in the Table (1).

Table (1) FDM Parameters and Their Levels

No. Test	Parameters	Levels		
		1	2	3
1	Infill Density (%)	20	50	80
2	Layer Thickness (mm)	0.1	0.2	0.3
3	Part Orientation (degree)	0	45	90

Table (2) L9 Orthogonal array

no. test	Infill density (%)	Layer thickness (mm)	Part orientation (degree)
1	20	0.1	0
2	20	0.2	45
3	20	0.3	90
4	50	0.1	45
5	50	0.2	90
6	50	0.3	0
7	80	0.1	90
8	80	0.2	0
9	80	0.3	45

III. EXPERIMENTAL WORK

3.1 FDM process parameters

The dimensions of the specimens were determined in accordance with ASTM D638 for tensile test and ASTM D790 for bending test. Specimens drawing was created using UG Nx software. The UG Nx files were saved in STL format which then was imported into 3D Printing software, namely Cura software is processed the model specimen printing process according to the parameters input.

After creating the specimen model the software generates an appropriate G code to input themachine. The model prepared in the software is saved as a STL file and inputted to the FDM machine as a G code. The machine reads the G code and prints the specimen according to the instruction provided. The dimensions of samples for are shown in Figure (3) .The specimens are printed by using Ultimaker 2+.

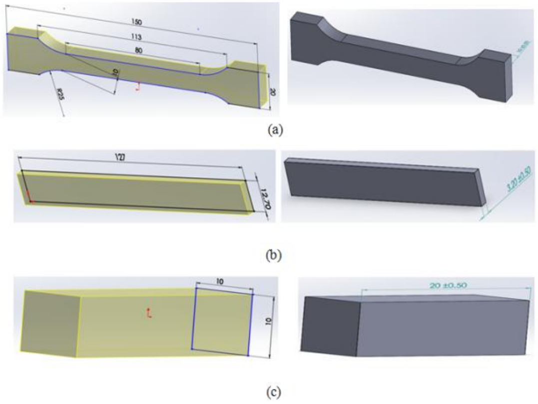

Figure (3) Schematic tensile, bending and compression specimens

As the printing condition for tensile specimens vary with major FDM parameters, the economic factors like printing time gets affected due to the change in FDM process parameters.

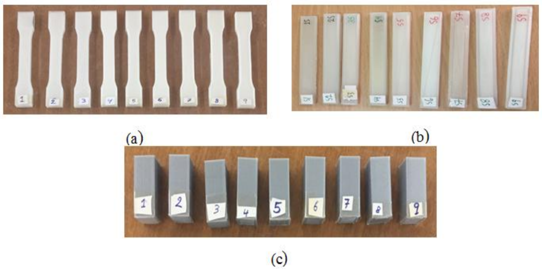

Fig. (4) Photographs of manufactured test specimens (a) tensile strength, (b) bending strength, (c) compression strength

3.2 TENSILE TEST

Tensile strength is defined as a stress, which is measured as force per unit area. The tensile test is performed according to (ASTM D638) by using tensile machine (universal testing machine) at a cross head speed (strain rate) of (5mm/min) and load was applied equal to (5 KN) until break the specimen occurs.

The basic idea of a tensile test is to place a sample of a material between two fixtures called "grips" which clamp the material. The material has known dimensions, like length and cross-sectional area then begins to apply weight to the material gripped at one end while the other end is fixed. Keeping increase of the weight (often called the load or force) while at the same time measuring the change in length of the sample.

3.3. BENDING TEST

In this test a specimen with round, rectangular or flat cross-section is placed on two parallel supporting pins. The bending test is performed according to ASTM D790. All data measured from three point bending test machine by using the same tensile machine at across head speed (strain rate) of (5 mm/min) and load was applied equal (5 kN) until break the specimen occur.

3.4. COMPRESSION TEST

The compression test is performed according to (ASTM D695) by using the same tensile machine at across head (strain rate) of (5mm/min) and applied load was (25 kN) until the break of the specimen occur.

3.5. PRINTING TIME

Time intensive process which depends on the complexity of the object printed. The more complex, the more time it takes to remove all of the supports. Printing orientation has a significant impact on print time. Using

4. RESULTS AND DISCUSSION

Table (3) shows the experimental results for various combinations of process parameters. It is observed that higher ultimate tensile strength, bending strength and compression strength were recorded for the experiment number 9.

Table (3) Experimental results as per L9 orthogonal array

No. test	Infill density (%)	layer thickness (mm)	part orientation (degree)	Ultimate tensile strength (MPa)	Printing time for tensile (min)	Bending strength (MPa)	Printing time for bending (min)	Comp. strength (MPa)	Printing time for comp. (min)
1	20	0.1	0	43.209	75	58.824	42	19.5	25
2	20	0.2	45	49.135	40	63.438	23	25.5	13
3	20	0.3	90	53.893	29	72.721	17	32.75	9
4	50	0.1	45	59.785	85	79.438	40	44.16	30
5	50	0.2	90	63.086	45	82.723	23	45.05	15
6	50	0.3	0	68.37	32	86.178	17	48.52	10
7	80	0.1	90	80.962	94	99.351	42	61.82	35
8	80	0.2	0	84.295	50	101.021	24	64.17	18
9	80	0.3	45	89.358	35	108.421	17	72.5	12

4.1. ULTIMATE TENSILE STRENGTH

According to the values of S/N ratios better values for tensile strength is obtained by larger values of S/N ratio, the main effects of S/N ratio shown in the figure, S/N ratio increases with increasing infill density, layer thickness, and part orientation. On the basis of analysis of S/N ratio the optimized process parameters for achieving larger tensile strength are 80% infill density, 0.3mm layer thickness, 90 degree part orientation.

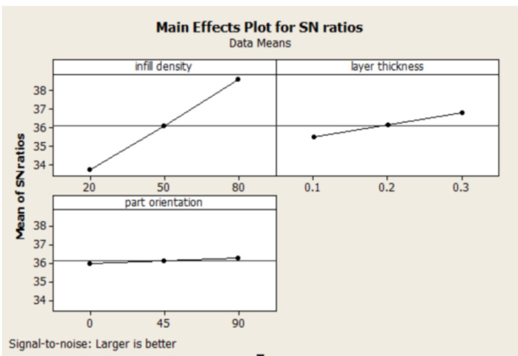

Fig (5) S/N ratio for Ultimate tensile strength

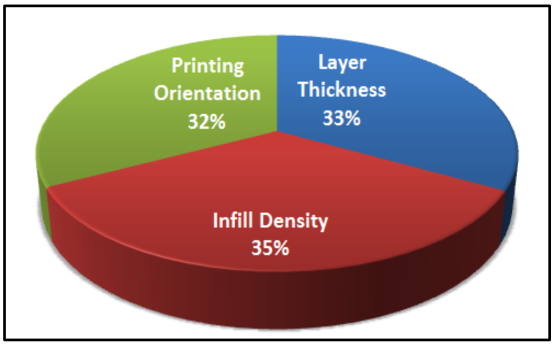

Fig. (6) Percentage contributions of process parameters on Tensile strength.

4.2 BENDING STRENGTH

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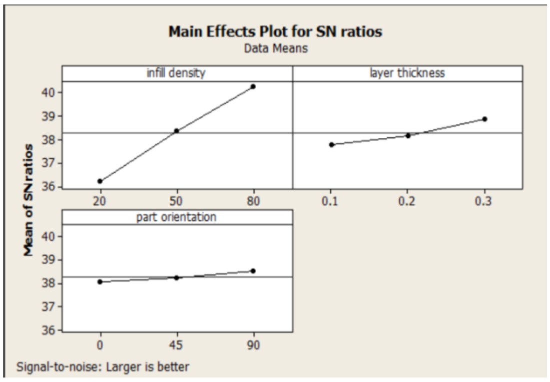

Fig (7) S/N ratio for bending strength

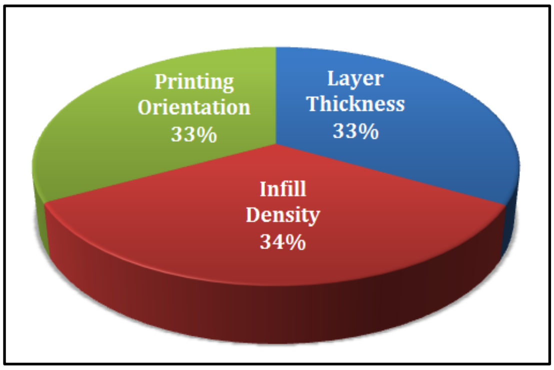

Fig. (8) Percentage contributions of process parameters on Bending strength

3.3. Compression strength

With height layer thinner increases the print quality, leading to a smoother surface. On the other hand, by using thicker layers you can decrease the print time substantially.

Layer height is an important design parameter that impacts the printing time, cost, visual appearance and physical properties of a printed part.

As the layer thickness increases, less number of layers will be required and distortion effect is minimized and hence, strength increases.

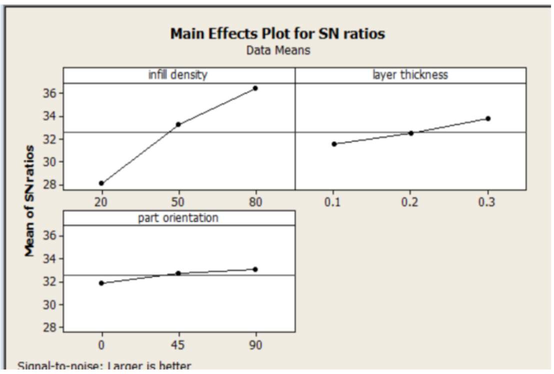

Fig (9) S/N ratio for compression strength

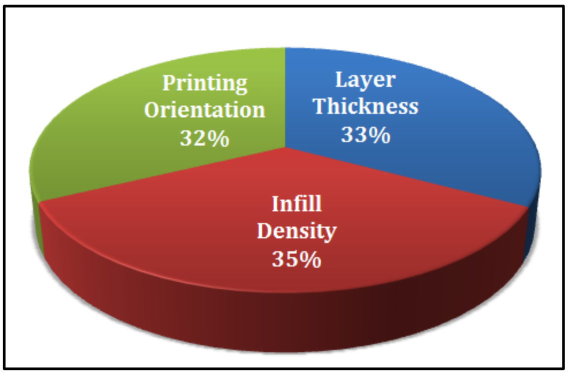

Fig. (10) Percentage contributions of process parameters on compression strength

3.2. PRINTING TIME

Increasing infill % means a higher amount of material is used (= higher cost) as shown in Fig. (11). When the infill percentage is high, the size of the rectangular is small and the nozzle has to travel a longer distance to print the same element. Thus the printing time will be longer than about 80%.

Fig.(11) illustrated the main effects for printing time. Based on the values of S/N ratios minimum time for printing is obtained by smaller values of S/N ratio. From the main effects of S/N ratio shown in the Fig.(11), S/N ratio increases with increasing layer thickness, similarly S/N ratio decreases with increase in infill density. On the basis of analysis of S/N ratio the optimized process parameters for achieving minimum printing time using Gray Relation Analysis (GRA) are 80% infill density, 0.3mm layer thickness, 90 degree part orientation

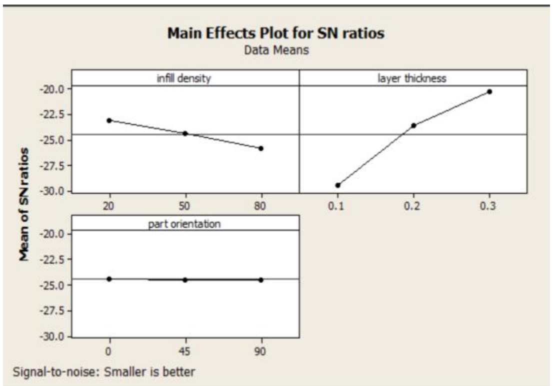

Fig (11) S/N ratio for printing time

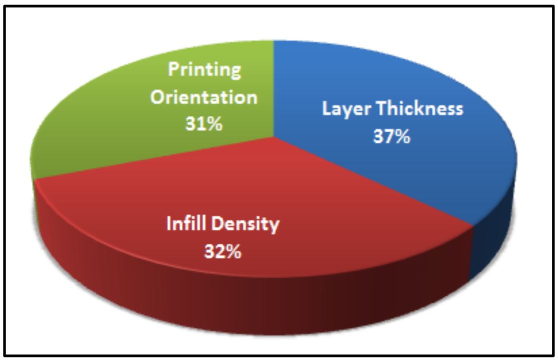

Fig. (12) Percentage contributions of process parameters on compression strength

IV. CONCLUSION

PLA material was used to fabricate nine samples with variations infill density, layer thickness and part orientation. when samples fabricated by the FDM process using 3D printing machine, the mechanical properties tested when The experiment was carried out to investigate the effects of infill density, layer thickness and part orientation on the mechanical properties (tensile, bending and compression strength) of the FDM. The experimental investigation included samples of the tensile, bending and compression test.

According to the results obtained, the parameters (infill density, layer thickness and part orientation) that use are approximate. However, the most influential parameter is the infill density, which is illustrated according to the percentages which is shown in the previous figures for all the mechanical properties (tensile, bending and compression strength). While can be noted from the results obtained for the best printing time, the values are also approximate and the most influential variable on printing time is layer thickness.

The relationship between mechanical properties (tensile, bending and compression tests) and process parameter infill density, layer thickness and part orientation is a positive relationship, the mechanical properties increases with increases of infill density and layer thickness. The results explain that to reduce printing time should decrease the infill density and layer thickness. Low infill density percentages are recommended when looking for fast printing, but not mechanical properties.

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