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Optimization of Process Parameters for FDM Printed Tensile Test Specimens to Reduce Energy Consumption and CO_2 Emission for Sustainable Manufacturing

Kolusu Venkatesh [1]* , L. Siva Rama Krishna [2], A. Seshu Kumar [3]

Abstract

Three-Dimensional Printing (3D Printing) is one of the advanced manufacturing technologies which is being tremendously used in many fields because of its innovative applications. The concept of making a three-dimensional product by adding the material layer upon layer through Computer Aided Design (CAD) file data as input source is known as 3D Printing. Fused Deposition Modelling (FDM) is one of the leading technologies from all the available 3D Printing technologies, because of its easy operation, high accuracy with less running and maintenance costs. FDM uses different types of plastic materials in the form of filaments as input material for producing a three-dimensional product. Sustainable Manufacturing (SM) is the universal acronym for representing the practice of effectively using the resources by fulfilling the needs of present generations without compromising the needs of future generations. It focuses on environment, economy and society. Green Manufacturing (GM) approaches like reduce, reuse and recycle are used to attain sustainability. Evaluations through trails on ASTM D638 Type-IV tensile test 3D printed specimens by altering the input process parameters on FDM with Acrylonitrile Butadiene Styrene (ABS) as material had been worked out in the present study. By employing Taguchi optimization approaches, Design of Experiments (DOE) have been performed to explore how various input process factors impacts the use of energy consumption, emissions of CO_2, and mechanical attributes. Percentage contribution of process factors on responses has been find out through Analysis of Variance. The study on reducing the energy consumption and emission of CO_2 has been highlighted for attaining sustainability through green manufacturing approach.

Keywords: FDM, energy consumption, CO_2 emission, sustainable manufacturing, taguchi optimization techniques

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INTRODUCTION

Additive manufacturing (AM) technologies, such as fused deposition modelling (FDM), have emerged as a promising approach for the production of a wide range of components, from prototypes to functional parts [1]. These methods have many benefits, such as shorter lead times, less material waste, and the capacity to produce complicated geometries [2]. However, the sustainability of these processes must be carefully evaluated, especially for applications that require high mechanical performance, such as structural components or tensile test specimens [3]. FDM is a widely deployed additive manufacturing approach in numerous industries, notably healthcare, automotive, and aerospace. However, the increasing use of FDM raises concerns about its environmental sustainability [4]. Filaments composed of polymeric materials are directed into the nozzle through FDM, where they undergo heating, melting, and semi-solid extrusion. That ejected semi-solid-state material from the nozzle solidifies and forms a fast connection with the previously printed layer, until the 3D model is finished, this will be done repeatedly [5]. When printing a three-dimensional object by layering one layer on top of the other, the nozzle travels in the X and Y dimensions while the platform travels in the Z axis. To build the entire three-dimensional item, the build platform travels one layer thickness downward in the Z direction after printing one layer [6].

LITERATUR REVIEW

Considering ASTM-standard polylactic acid tensile and flexural test samples, Khalid and Peng examined the performance of FDM process variables and they came to the conclusion that layer height and building orientation have the most effects on production time, energy consumption, and material consumption [7]. Camposeco-Negrete optimized the FDM process parameters for the material Acrylonitrile Styrene Acrylate (ASA) by printing ASTM D638 standard tensile test specimens with different process parameters as variables and energy consumption and processing time as responses. It was discovered that these factors are influenced by the printing plane [8]. Bio-inspired infill structures at various infill densities have been implemented by Dev and Srivastava to print ABS bending and compression samples using ASTM D790 and ASTM D695 with FDM. It was identified that naturally shaped infill patterns with an infill density of 80% had favourable outcomes that has minimal material consumption and excellent mechanical properties [9]. Tanoto et al. tested the FDM printed ABS plastic ASTM D638 standard tensile test specimens in three distinct orientations for the duration of printing, dimensional precision, and mechanical properties. The results showed that printing plane orientation affected both time consumption and mechanical strength [10]. According to the research of Espach and Guptato, topology optimization for FDM printed parts can achieve sustainability by lowering material and electrical energy usage in a shorter amount of time by enhancing mechanical qualities [11]. Al-Ghamdi had examined the feed rate, layer thickness, infill density, and shell thickness of the FDM process for ABS material in order to guarantee low energy consumption, light weight, and short printing times. It was found that while layer thickness, infill density, and shell thickness increased, less energy, time, and feed rate were consumed [12]. This paper aims at the environmental impacts of Fused Deposition Modelling (FDM) and discusses strategies for sustainable manufacturing in FDM [13]. We explore the effects of FDM on energy consumption, CO_2 emission and examine existing solutions for reducing its ecological footprint [14].

MATERIALS AND METHODOLOGY

Tensile test specimens as per ASTM D638 Type- IV standard has been chosen and modeled in Creo by using sketch and extrude commands. Schematic diagram of specimen has been displayed in fig-1 as well as its measurements that are shown in the following Table 1. The Computer Aided Design (CAD) format was subsequently transformed towards an STL model to be utilized by FDM as input information.

Table 1. Tensile test specimens dimensional parameters with measurements.

Parameter	All Measurements in mm
Gauge width	6
Over all width	19
Radius of fillet	14
Outer Radius	24
Thickness	4
Gauge Length	33
Total Length	115

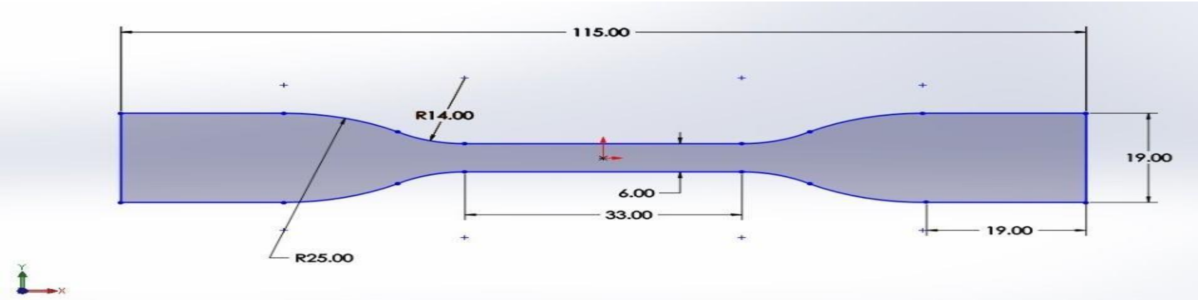

Figure 1. Sketch of ASTM D638 Type-IV tensile Test specimen modelled in Creo.

After conducting an extreme literature survey, the following four process parameters have been identified for investigating their effect on energy consumption and CO_2 emission for printing tensile test specimens on FDM. These four process parameters at three levels with three different values have been chosen as shown in table-2 and Taguchi optimization techniques have been implemented through design of experiments by L9 orthogonal array.

ABS as filament material possessing with high strength, impact resistance and high melting temperatures around 210 to 250 °C has been used for printing test specimens on Ultimaker S5 Pro FDM printer.

During the printing process energy consumption and CO_2 emission are measured using MECO Power guard meter by fitting it to the FDM Printer as shown in Figure 2. Continuous readings for every 5 mins were noted for energy consumption and CO_2 emission. Average of all the readings recorded were noted until the completion of specimen printing time.

Figure 2. Measuring the readings for energy consumption & CO_2 emission of FDM during specimen printing with MECO power guard meter.

Table 2. Process Parameters of FDM for Printing ABS Tensile Test Specimens with three values

S N.	Factors	Levels		
		low	**medium**	**high**
1.	Infill Density (%)	20	50	80
2.	Wall Line Count	2	4	8
3.	Position on Platform	Start	Center	End
4.	Infill Pattern	Honeycomb	Concentric	Gyroid

By considering L9 orthogonal array all together 18 specimens have been printed by making two repetitions of each run for considering the average value of the test specimens during experimentation as displayed in fig-3. Tensile tests have been performed on UTM and surface roughness have been measured by Talysurf.

Tensile test specimens after printing are displayed in Figure-4. Fractured specimens after completion of tensile test on UTM are shown in Figure-5.

RESULTS AND DISCUSSIONS

All the input process parameters vs output results have been listed out in the below table-3. The L6 sample exhibits the highest tensile strength of the various samples whilst consuming a minimal quantity of energy and emitting the least quantity of CO_2. On the other hand, specimen, which is possessing less tensile strength, is L4. When coming to the sustainability factor it is L9 specimen, which is consuming less energy, emitting less CO_2 and L5 specimen, which is consuming more energy, and emitting more CO_2. To find the impact of process parameters, main effects plots for means graphs were plotted and shown in fig-6 and fig- 7 for both energy consumption and CO_2 emission by using Taguchi, design of experiments [15]. Regression equations have been generated along with analysis of variance for both.

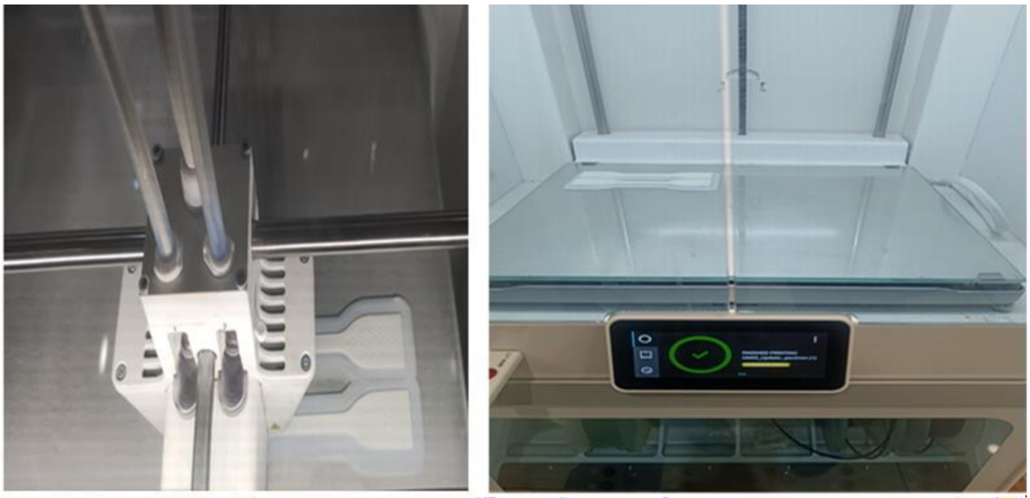

Figure 3. Printing of tensile test specimens on build platform at START position by FDM.

Figure 4. 3D Printed ABS tensile specimens

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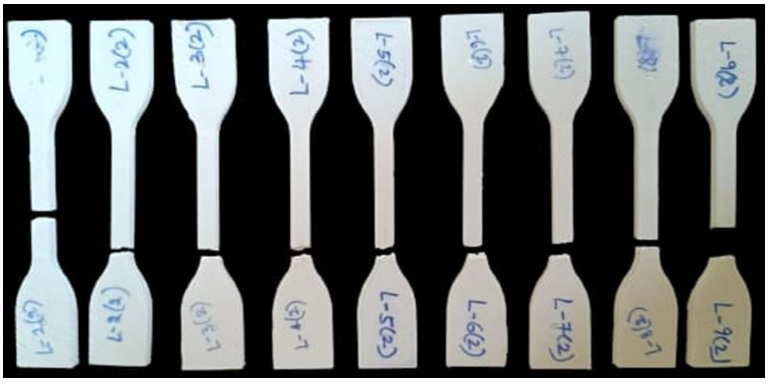

Figure 5. Set of fractured tensile test samples.

Table 3. Input process parameters and output responses of ABS Specimens.

Run	Input Process Parameters				Output Responses			
	Infill density (%)	***Wall line count***	***Position on platform***	***Infill pattern***	***Energy consumption (KWH)***	***CO_2 emitted (Kg)***	***YTS (MPa)***	***Ra (µm)***
L1	20	2	Centre	Honeycomb	0.86	0.47	42.55	2.11
L2	20	4	Start	Concentric	1.03	0.57	41.31	2.21
L3	20	8	End	Gyroid	1.95	1.08	50.03	2.47
L4	50	2	Start	Gyroid	1.35	0.75	29.90	2.60
L5	50	4	End	Honeycomb	2.59	1.44	37.92	2.64
L6	50	8	Centre	Concentric	0.68	0.38	52.15	2.33
L7	80	2	End	Concentric	1.60	0.88	51.01	3.04
L8	80	4	Centre	Gyroid	2.27	1.26	48.78	2.86
L9	80	8	Start	Honeycomb	0.54	0.30	33.99	3.76

Means Graphs

Mean effects graphs were plotted by considering lower the better for energy consumption and CO_2 emission and shown in Figure-6 & 7. Energy consumption was mainly influenced by position on the platform at start position followed by wall line count, infill pattern and infill density.

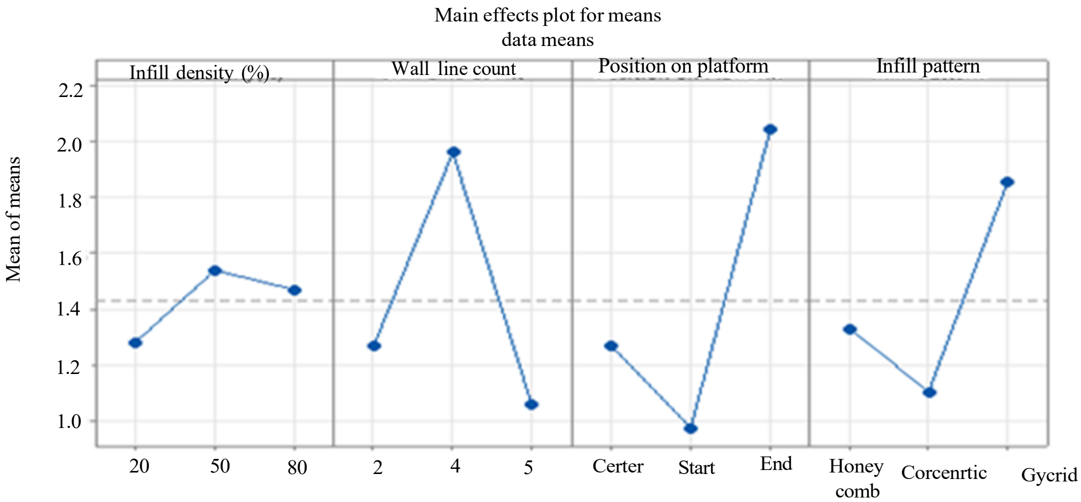

Figure 6. Main effects plots for means- energy consumption of ABS printed tensile test specimens.

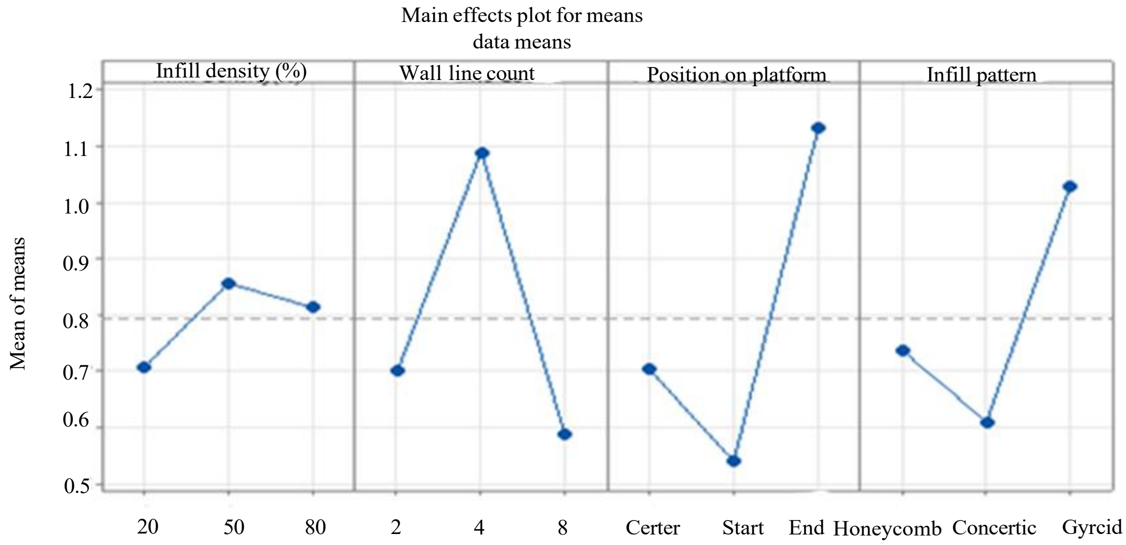

Figure 7. Main effects plots for means- CO_2 emission of ABS printed tensile test specimens.

CO_2 emission was mainly influenced by position on the plat form at start position followed by wall line count, infill pattern and infill density. Interestingly both the reposes have same influence by the variables.

Regression Equations

Below are the two regression equations obtained for energy consumption and CO_2 emission by considering the effect of all input process parameters over output variables.

Energy Consumption (KWH)	=	0.8600+ 0.0 Infill Density_20 + 0.2600 Infill Density_50 + 0.1900 Infill Density_80 + 0.0 Wall Line Count_2 + 0.6933 Wall Line Count_4 - 0.2133 Wall Line Count_8 + 0.0 Position on Platform_Center - 0.2967 Position on Platform_Starting + 0.7767 Position on Platform_Ending + 0.0 Infill Pattern_Honeycomb - 0.2267 Infill Pattern_Concentric + 0.5267 Infill Pattern_Gyroid .... Equ. (1)
CO2 Emission (Kgs)	=	0.4700+ 0.0 Infill Density_20 + 0.1500 Infill Density_50 + 0.1067 Infill Density_80 + 0.0 Wall Line Count_2 + 0.3900 Wall Line Count_4 - 0.1133 Wall Line Count_8 + 0.0 Position on Platform_Center - 0.1633 Position on Platform_Starting + 0.4300 Position on Platform_Ending + 0.0 Infill Pattern_Honeycomb - 0.1267 Infill Pattern_Concentric + 0.2933 Infill Pattern_Gyroid… .... Equ. (2)

ANOVA

To figure out the P-Value and the percentage contribution of every variable to the response's energy consumption and CO_2 emissions, analysis of variance has been conducted for every one of the input variables and output responses, which are displayed in following tables 4 and 5. Confidence interval of 95% was applied but unfortunately, the P- values are greater than 0.05, due to unavoidable machine and man errors [16]. However, the Position on the Platform at the start position has highest percentage of contribution followed by Infill Pattern, Wall Line Count and Infill Density for energy consumption [17].

Table 4. ANOVA of Energy Consumption for ABS printed tensile test specimens

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Regression	6	3.01494	3.01494	0.50249	0.85	0.629	71.85%
Infill Density (%)	1	0.05415	0.05415	0.05415	0.09	0.791	1.29%
Wall Line Count	1	0.22126	0.22126	0.22126	0.37	0.603	5.27%
Position on Platform	2	1.84327	1.84327	0.92163	1.56	0.391	43.92%
Infill Pattern	2	0.89627	0.89627	0.44813	0.76	0.569	21.36%
Error	2	1.18146	1.18146	0.59073			28.15%
Total	8	4.19640					100.00%

In case of CO_2 emission, the major percentage of contribution on the output responses was Position on the Platform followed by Infill Pattern, Wall Line Count and Infill Density.

Table 5. ANOVA of CO_2 Emission for ABS printed tensile test specimens

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Regression	6	0.92455	0.92455	0.15409	0.83	0.637	71.33%
Infill Density (%)	1	0.01707	0.01707	0.01707	0.09	0.790	1.32%
Wall Line Count	1	0.06537	0.06537	0.06537	0.35	0.613	5.04%
Position on Platform	2	0.56362	0.56362	0.28181	1.52	0.397	43.48%
Infill Pattern	2	0.27849	0.27849	0.13924	0.75	0.572	21.49%
Error	2	0.37161	0.37161	0.18580			28.67%
Total	8	1.29616					100.00%

SEM

Scanning Electron Microscopy analysis has been done to clearly examine the fracture portion of the dog bone specimens in order to find the reasons behind the effect of input process variables on the responses. It is an evident that low strength specimens possess more voids and porosity as shown in fig-8. High strength specimens possess more yield strength sue to more ductility the layers of the specimens at fractured portions gets elongated as shown in the Figure 9.

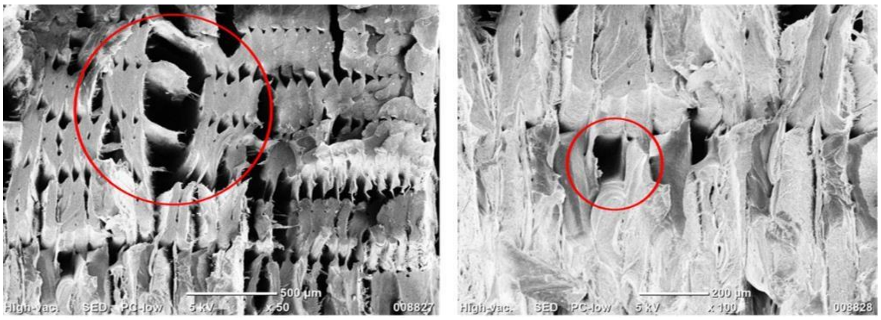

Figure 8. SEM Images of ABS printed tensile test specimens with low strength.

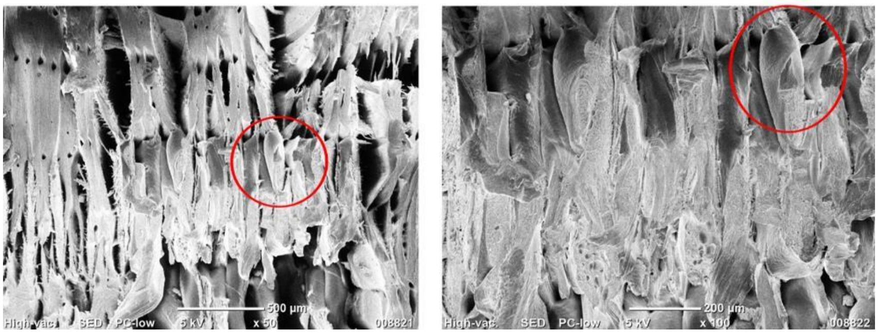

Figure 9. SEM Images of ABS printed tensile test specimens with high strength.

CONCLUSIONS

ASTM D638 Type-IV tensile test specimens were successfully printed on FDM by varying the input process parameters through Taguchi design of experiments by L9 orthogonal array in order to find out the optimum parameters to reduce energy consumption and CO_2 emission and increase mechanical properties. Infill patterns adopted in this study are considered through natural point of view like honeycomb, concentric and gyroid to encourage sustainable manufacturing. Optimum process parameters obtained are start position on platform, with 50% infill density, wall line count 8 and Honeycomb as infill pattern have more impact on the responses with less energy consumption, CO_2 emission, high tensile strength and low surface roughness. The highest yield tensile strength obtained is 52.15 MPa because of wall line count 8 which impacts the elongation of the specimen with a greater number of lines and increases the yield tensile strength. Surface roughness Ra value obtained is 2.11 µm which is very low with honeycomb infill pattern as surface texture. Less energy consumption and CO_2 emission values obtained are 0.54 KWH and 0.30 Kgs due 50% infill density and at start position on the platform with less nozzle travel distance, printing time and less material consumption. After all conformability experiment has been carried out by considering the above four optimum process parameters from each set and compared with the predicted values. The specimen was reprinted with these parameters on FDM and tested. The experimental values are very close to the predicted values within 5% deviation. Over all the considered process parameters at three levels have a positive sign on the responses studied in this research work.

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