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EFFECT OF BUILD PARAMETERS ON PROCESS PERFORMANCES AND MECHANICAL PROPERTIES OF PRINTED PRODUCT IN FUSED DEPOSITION MODELLING METHOD

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Abstract: Fused deposition modelling performances are dominated by selection of process parameters. Multi objective optimisation is essential in ensuring excellent product mechanical properties, surface quality and resource efficiency. This paper presents a preliminary work based on Taguchi orthogonal array design of experiment, considering build orientation, printing angle and layer thickness as the input factors. The build orientation has a significant influence on tensile strength while the layer thickness on energy consumption and printing time. Adverse effects on the responses can be observed during the attempts. However, two factors optimisations were still achievable. Optimal settings should be suited based on final application and economical constraints. This study has established a groundwork of further studies in optimisation of quality of the method.

Key words: Additive manufacturing, fused deposition modelling, polylactide filament, build orientation, printing angle, layer thickness.

1. INTRODUCTION

3D printing is an emerging technology for creating myriad objects with numerous design flexibilities by sequential layering (Kabir et al. 2020). Among available 3D printing technologies, Fused Deposition Modelling (FDM) is rapidly used for product design, prototyping and manufacturing processes because of its simple-to-use, low-cost and environmentally friendly features (Weng et al. 2016).
The main materials needed for the FDM 3D printer are polylactide (PLA) or acrylonitrile butadiene styrene (ABS). An example of product made using these materials using the FDM method is prototype for aerospace and automotive parts. In FDM, thermoplastic filaments are fed into the heated extrusion print head for both model and support, enabling 3D printing dispensing of the resulting polymer melts on a platform which is vertically moved step-by-step once each layer is completed (Cicala et al. 2018). The structure is then fabricated layer by layer. However, the printing parameters involved for each object must be carefully considered by the user to produce good quality products. Example of the parameters are infill density, printing speed, layer thickness, bed temperature, nozzle temperature and raster angle.
The mechanical properties of FDM printed product depend on several process parameters The selection of parameters can have a major impact on the quality and performance of FDM printed parts (Chacón et al. 2017). The impact can be significant on environmental related performances such as material usage and process energy demand. With such an unpredictable impact, recognising the economic and environmental development concerns of this sector is crucial (Griffiths et al. 2016a). Selecting FDM building parameters for performance optimisation in conjunction with cost minimisation is a critical task.
Parametric analysis of FDM processes is widely covered in literature. Most of previous studies focused on mechanical qualities of products. Build orientation or direction was found to be an influential parameter affecting surface quality, tensile properties, use of materials and production cost (Chacón et al. 2017, Griffiths et al. 2016, Yao et al. 2019). Meanwhile, printing time is dominated by the layer thickness, the feed rate and the printing angle. Currently, simultaneous consideration on product performances and associated environmental impacts in terms of resource consumption and electrical energy requirement is still limited. Griffith et al (2016a) and Griffith et al (2016b) considered product

mechanical performance, material usage and energy demand but did not cover product surface condition, which is vital for most engineering applications. A comprehensive analysis is required in creating repository of information not only to optimise product quality but with an emphasis on resource efficiency during the production.

The aim of this preliminary study is to investigate effect of FDM parameters on PLA product mechanical properties, material consumption and process energy demand. Through an L4 Taguchi orthogonal array design, the preliminary experimental trials considered build orientation (on-edge and flat), printing angle (0° and 90°) and layer thickness (0.2 mm and 0.4 mm). The selection of parameters was based on the notably influence on product performance and printing time as reported in literature. Findings of this study are intended to be a useful guide for designers to choose manufacturing parameters, where consideration is towards best product performance with minimal environmental concerns.

2. METHODOLOGY

The methodology is divided into several parts starting from sample fabrication via FDM printing method, mechanical and physical test, environmental assessment via material usage and electrical energy consumption and lastly, statistical analysis using ANOVA. The flowchart of the methodology is illustrated in Figure 1.

2.1 FDM printing process

This study used Flashforge PLA filament with a diameter of 1.75 mm. All experimental trials were carried out using Ender3pro FDM machine. The machine was manufactured by Creality from China. Rated power of the machine is 270 W. The FDM machine was used to produce dog bone shape samples as per ASTM-D638 standard for tensile tests. The sample design was created using Solidworks software before Ultimaker Cura software was used for slicing. The slicing converts the design into form of meshes and printing instruction to be read by the FDM machine. Other parameters were set as default settings, as recommended in the filament manufacturer sheet.

2.2 Experimental design

The combination of parameters was determined based on L4 Taguchi orthogonal array design for three factors with two levels, as shown in Table 1. The parameters were selected based on the most influential factors affecting the sample tensile properties, surface quality, material usage and printing time.

Table 1. Experimental trials based on L4 Taguchi orthogonal array design

Sample	Build orientation	Printing angle	Layer thickness
A	On-edge	0 °	0.2 mm
B	On-edge	90 °	0.4 mm
C	Flat	0 °	0.4 mm
D	Flat	90 °	0.2 mm

2.3 Tensile test

Tensile properties of the sample were characterised using Universal Testing Machine AG-XD plus according to ASTM-D638 standard. The machine was manufactured by Shimadzu. The properties considered in this study are tensile strength and tensile modulus.

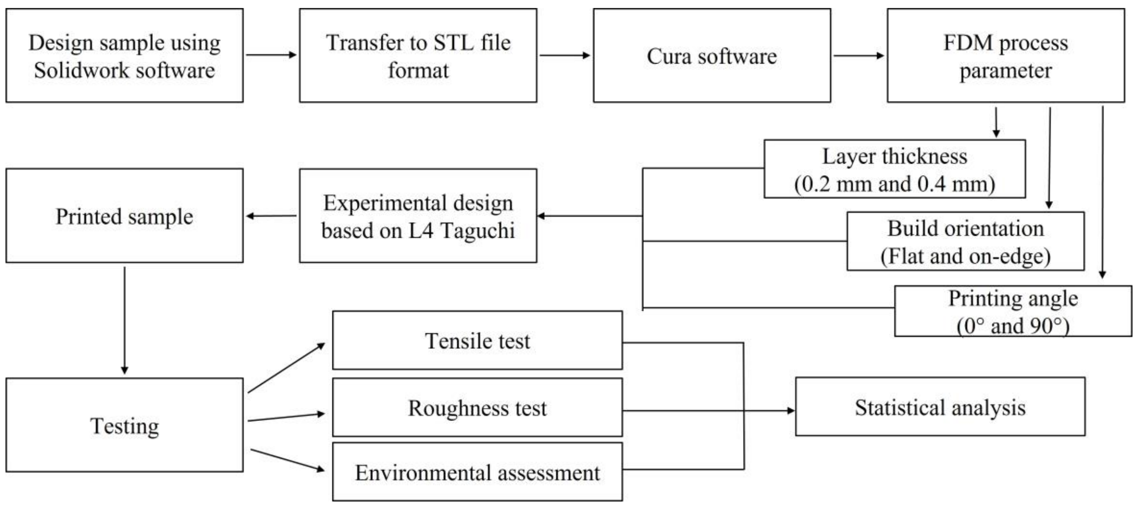

Fig. 1. Flowchart of research methodology

2.4 Surface roughness test

F-3000 surface roughness measuring instrument, manufactured by Mitutoyo was used to examine the surface condition. The machine used a needle probe by touching the surface and slowly moved along the sample surface for a measurement. The surface quality is reported in this paper as mean roughness value (Ra).

2.5 Material usage and energy consumption

Energy consumption of the machine throughout the process was estimated based on machine rated power and printing time. Total usage of PLA filament and scrap weight were displayed in Ultimaker Cura software.

2.6 Statistical analysis

Effect of the process parameters on the experimental outputs was investigated through ANOVA statistical analysis at 95% confidence level, which was executed in Minitab 19 software. The analysis also provided information on the most influential parameter for each output. Main effect plots were generated to illustrate mean response value. Two-dimensional contour plots were utilised to understand relationship between the outputs for a multi-objective optimisation.

3. RESULTS AND DICUSSIONS

Table 2 presents a summary of ANOVA analysis which indicates significance of process parameter, represented by the F-value and P-value at 95% confidence level. The P-value less than 0.05 is considered as statistically significance while high F-value indicates high variability. Rank of the parameter in terms the most influential, which acquired from mean response table analysis is also shown Table 2.

Main effect plots in showing influence of the parameters for a single output are illustrated in Figure 2. Range of output value is also included. Slope of line in the plot represent degree of the influence.

For tensile properties, printing angle has the most significant effect followed by build orientation and layer thickness. It can be inferred that selection of different printing angle changed the tensile strength and modulus by around 80% and 60% respectively. At 0°printing angle, the tension load was parallel to the deposited layers which promoted greater strength and stronger infill structure compared to perpendicular direction for 90° printing angle. The sample with the flat built orientation has wider infill and frame compared to on-edge built orientation. Better tensile properties were found for the most stable orientation because of the large area of contact between the printing bed and the structure. Low layer thickness is optimal in achieving good properties because of excellent packing density and inter-bonding strength between the printed layers. Despite that, the effect of build orientation and layer thickness was represented by average P-value of 0.287 and 0.676, which were not significant in affecting the tensile properties.

Table 2. F-value, p-value and rank with result interpretation for all parameters and output variables

Parameter		F-value, p-value and rank with result interpretation					
		Tensile strength	Tensile modulus	Surface roughness	Material usage	Scrap material	Energy consumption
Build orientation	F-value	0.720	2.32	0.00	5.00	14.41	0.00
	p-value	0.416 (NS)	0.158 (NS)	0.950 (NS)	0.049	0.004 (S)	0.981 (NS)
	Rank	2	2	3	-	1	3
Printing angle	F-value	78.2	22.81	2.05	5.00	1.22	2.07
	p-value	0.001 (S)	0.001 (S)	0.183 (NS)	0.049	0.296 (NS)	0.181 (NS)
	Rank	1	1	2	-	3	2
Layer thickness	F-value	0.44	0.05	44.71	5.00	4.31	48.38
	p-value	0.522 (NS)	0.829 (NS)	0.001 (S)	0.049	0.065 (NS)	0.001 (S)
	Rank	3	3	1	-	2	1

S: Significant, NS: Not significant

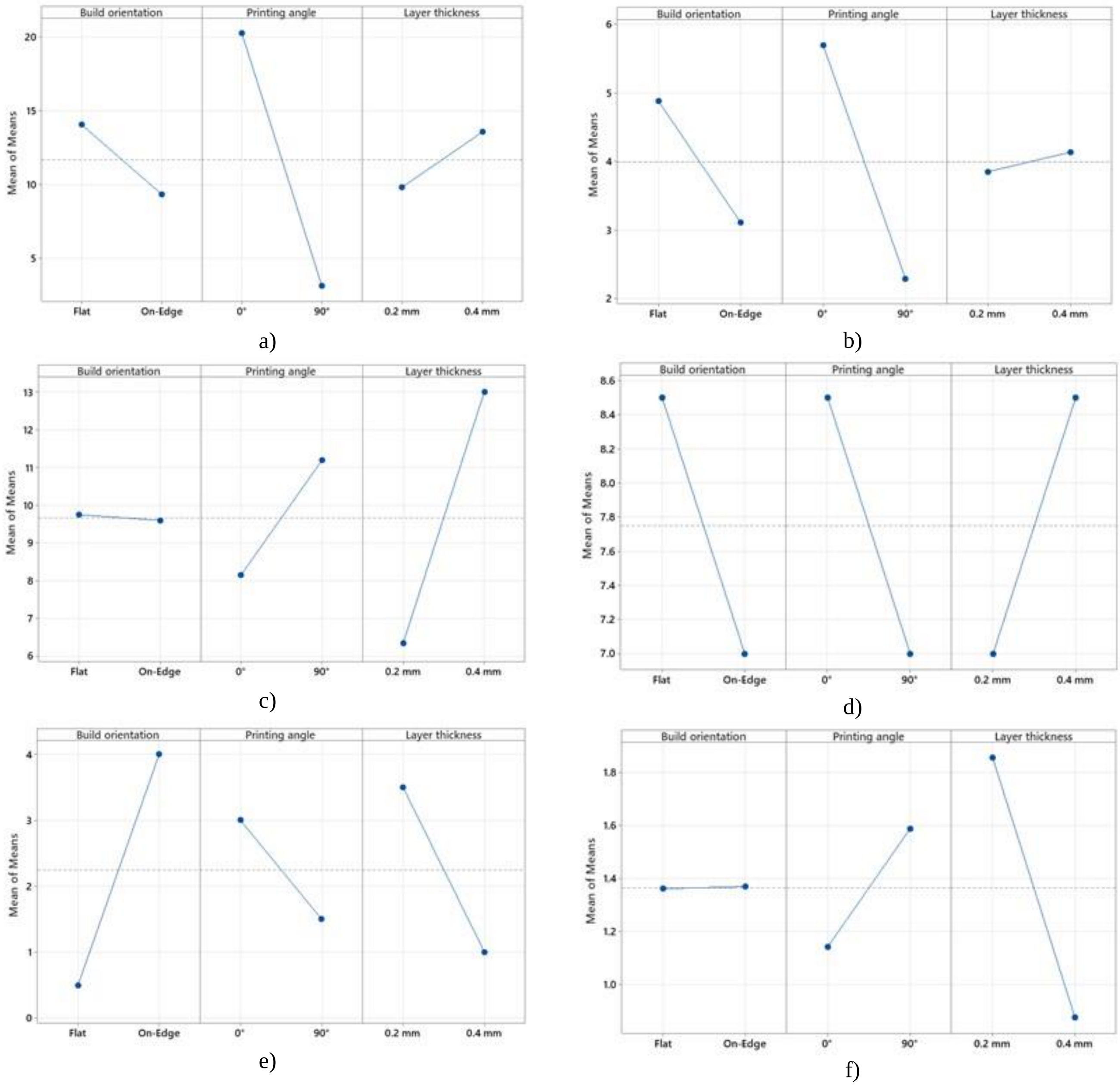

Fig. 2. Main effect plots for a) tensile strength, b) tensile modulus, c) surface roughness, d) material usage, e) scrap material, f) energy consumption

Surface roughness is analysed based on smaller the better objective. The layer thickness was identified to have predominant influence in developing staircase effect on the sample surface. A drastic reduction of surface roughness by 50% can be seen when switching from 0.4 mm to 0.2 mm layer height. The height should be kept at a minimum to reduce the effect. The effect is more distinct at higher layer thickness which may require post-processing stage to produce a smoother surface. When processing at an industrial scale, the additional requirement could increase printing cost, apart from delaying production lead time. Build orientation and printing angle were the least influential factors for the surface finish.

For electrical energy requirement, the only statistically significant parameter was the layer thickness. At lower layer height, more building time was required to completely print the sample with additional slices. By reducing layer height from 0.4 mm to 0.2 mm, there were fewer but higher steps of the layer. The energy saving was estimated to be half from the reduction as energy demand was directly related to the building time. The scrap material was based on weight of support structure and mostly depends on the orientation type. In this case, on-edge orientation consumed extra material to hold the sample vertically on its side. The support was not presented for flat orientation, where the sample was located horizontally across on the printing bed. In terms of overall material usage, each parameter has an equal ranking, hence the ranking is not shown in Table 2.

Figure 3 and Figure 4 present multi-objective optimisation analysis for selected outputs. Area of most and least desirable are denoted by number 1 and 2 respectively. There is a clear trade-off between energy consumption and surface roughness. The response at upper left quadrant is desirable for however surface roughness needs to be compromised. At a region of lowest surface roughness in the upper right quadrant, tensile strength of more than 15 MPa is achievable but with the expense of energy demand. As can be observed in lower right quadrant of Figure 4, it is possible to simultaneously consume material efficiently while maintaining the surface quality by using 0° printing angle and 0.4 mm layer height settings.

Summary of sample performances in this study is presented in Table 3. The table shows ranking of sample for each property investigated. The first ranking indicates the sample has the best performance for the given property. It can be seen that Sample C has the least overall points which mean that the sample has the best and optimum parameters followed by Sample D and Sample A. The highest point, which indicates the worst combination of parameter is Sample B.

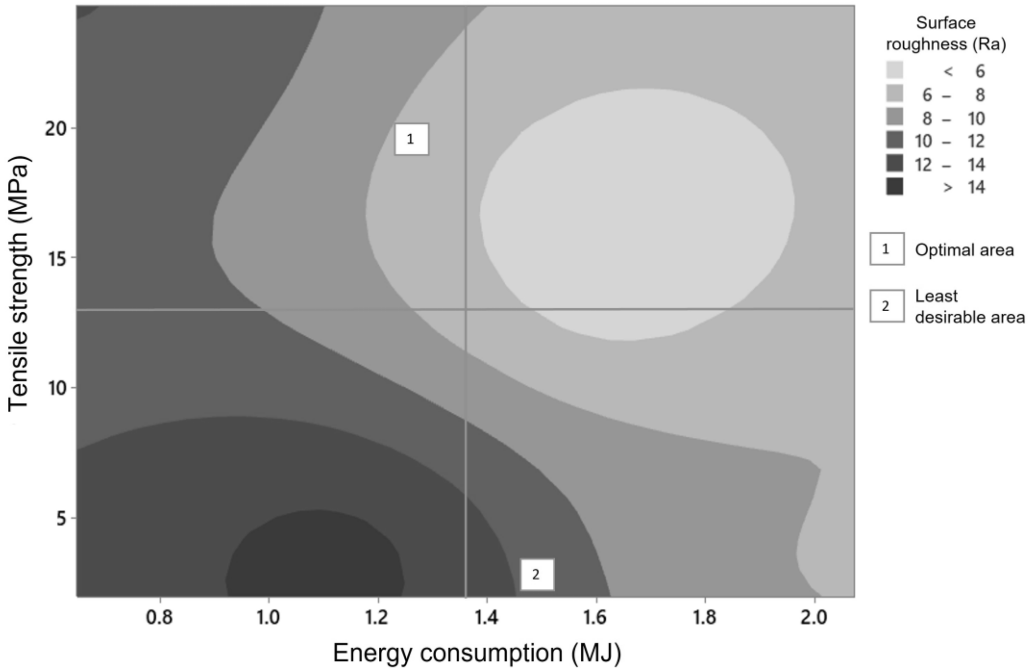

Fig. 3. Contour plot of tensile strength versus energy consumption versus surface roughness

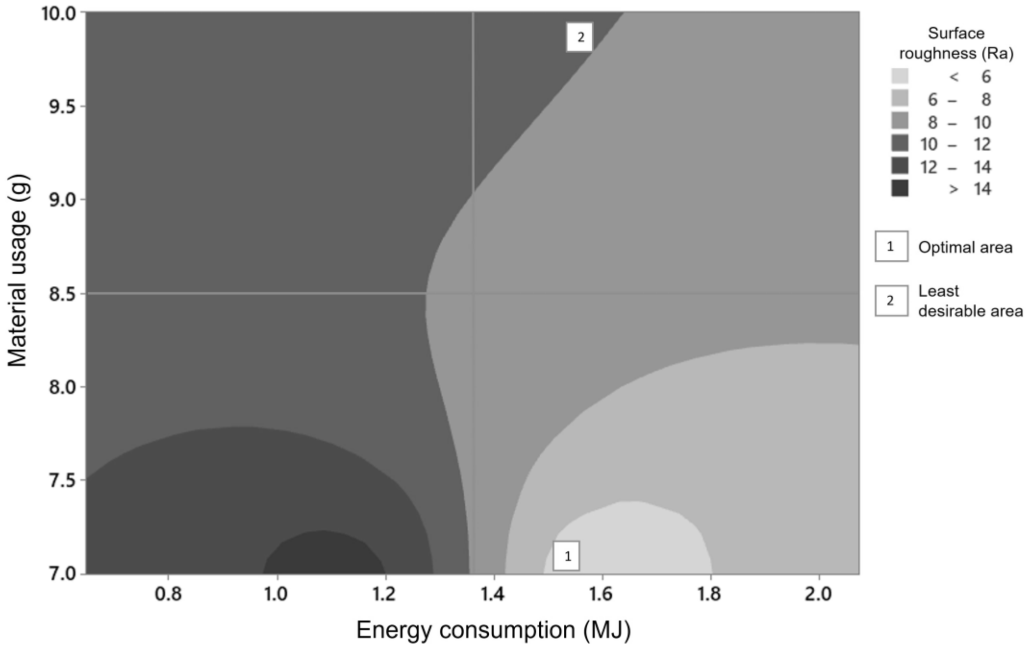

Fig. 4. Contour plot of material usage versus energy consumption versus surface roughness

Table 3. Summary of sample performances based on ranking points

Sample	Tensile strength	Tensile modulus	Surface roughness	Material usage	Scrap material	Energy consumption	Overall Points
A	2	2	1	4	4	3	16
B	4	4	4	2	3	2	19
C	1	1	3	3	1	1	10
D	3	3	2	1	2	4	15

4. CONCLUSIONS

Adverse effects in the multi objective optimisation attempts can be clearly observed. The tensile properties were influenced by the build orientation while surface roughness and overall energy demand depended greatly on the selection of the layer thickness. Two factors optimisation seems to be feasible compared to optimal settings of all factors. It is vital for users in acknowledging critical requirement of the fabricated sample and resource availability. Results of this study have provided an informed decision towards excellent product performances, quality optimisation and sustainability of the FDM technique. This preliminary work will be extended by the authors into L9 Taguchi orthogonal array approach, where other multiple factors and output response variables will be considered.

5. ACKNOWLEDGEMENT

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