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Effect of build parameters on processing efficiency and material performance in fused deposition modelling

C.A. Griffiths[a], J. Howarth[b]*, G. de-Almeida Rowbotham[b], A. Rees[a]

[a]*College of Engineering, Swansea University, Swansea, SA2 8PP, UK*
School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M13 9PL, UK

* Corresponding author. Tel.: +44(0)161-3062352. *E-mail address:* jack.howarth@manchester.ac.uk

Abstract

Advances in additive manufacturing have resulted in significant growth of such materials, including the medical sector. It is particularly applicable to manufacture of prosthetics and implants, where design freedoms and complex geometries afforded by additive manufacturing are especially suited to such products. With this growth it is timely to consider approaches to optimization for both efficiency and performance. In this work a design of experiments approach was used to quantify the effects of build parameters on performance and efficiency outputs. This approach could prove invaluable to designers for both cost and performance optimization, applicable to both prototype and part production.

Keywords: fused deposition modelling; design of experiments; process optimisation

1. Introduction

Additive manufacturing (AM) describes a process where parts are manufactured layer by layer in an additive process [1]. Originally used in the production of complex geometry prototypes (RP), advances in the technology now make AM applicable to rapid manufacturing (RM) [2]. Although AM is unable to compete with the short cycle times and lower capital costs of more traditional processes such as injection moulding, this is compensated by the design freedoms allowed by the ability of AM processes to produce complex geometries, as well as reduced tooling costs and lead times [3].

There are various techniques classed within AM, the earliest known being stereolithography. There are also powder bed fusion processes such as selective laser sintering. The subject of this work is a material extrusion based technique called fused deposition modelling, FDM [4], which is one of the most commonly used AM techniques [5]. FDM was introduced in 1992 by American company Stratasys [6]. FDM was initially used to create conceptual models to aid product design however process and material developments have allowed FDM to diversify from RP into RM.

It is clear from the scientific literature that processing parameters in FDM affect the characteristics of manufactured products [7-13]. The most considerable challenge for FDM in RM is the selection of build parameters for optimization of performance in conjunction with cost minimization [14].

Nomenclature

AM	additive manufacturing
FDM	fused deposition modelling
PLA	polylactic acid
RM	rapid manufacturing
RP	rapid prototyping
SO	slice orientation

However the energy consumption in AM processes remains relatively unexplored. However there are some recent studies, for example Balogun et al, 2014 [13].

Medical applications of AM are expanding rapidly. Within the medical sector AM can be used in production of prosthetics and implants, models and tissue fabrication [15]. The greatest of advantage of AM in the medical sector is the design freedoms afforded in customization of products and

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equipment [15]. Other benefits include increased cost efficiency [16] and enhanced productivity [17]. The ability to produce complex geometries is especially advantageous in the manufacture of prosthetics and implants, where medical scans can be translated into the .stl files required by AM machinery [18].

As AM continues to grow within and into new sectors, it is timely to consider approaches to analyse the effects of the machine build parameters on the final properties of built parts, as well as on the effects of efficiency factors such as material usage and build times. This work presents a systematic approach to quantifying relevant build parameters to measured material outputs and efficiency factors, and demonstrates how such studies can be used in part and process optimization, depending on the product requirements.

2. Experimental Procedure

2.1 Materials and equipment

Parts were manufactured from PLA filament of diameter 1.75 mm, specifically produced for the FDM machine used in this work, a Makerbot Replicator 2. Default settings of extrusion temperature and speed were used as recommended by the manufacturer. The specimens were designed for conformity with ISO 527-2, for tensile testing of plastics.

2.2 Design of experiments

A full factorial DoE was utilized so as to collate data in a controlled way. The FDM machine inputs (parameters) and their associated variables are listed in Table 1. The SO refers to the orientation at which the object is built, and is depicted for tensile testing specimens in Figure 1. The infill level represents the density of the internal structure of the part, a 100 % infill resulting in a completely solid part. Infills under 100 % are built in regular hexagonal patterns, the size of which decrease proportionately with higher infill. A shell is a border that is printed for each layer. The machinery prints a minimum of one shell per layer. The layer height defines the thickness of each printed layer.

Table 1. Full factorial design of experiments

Experiment no.	SO	Infill (%)	No. of shells	Layer height (mm)
1	Front	60	1	0.15
2	Front	60	1	0.4
3	Front	60	4	0.15
4	Front	60	4	0.4
5	Front	100	1	0.15
6	Front	100	1	0.4
7	Front	100	4	0.15
8	Front	100	4	0.4
9	Side	60	1	0.15
10	Side	60	1	0.4
11	Side	60	4	0.15
12	Side	60	4	0.4
13	Side	100	1	0.15
14	Side	100	1	0.4
15	Side	100	4	0.15
16	Side	100	4	0.4

The measured outputs were split into two categories; efficiency outputs and performance outputs, which are listed in Table 2.

Table 2. Measured outputs of FDM parts

Efficiency	Performance
Build time	Tensile strength
Energy consumption	Young’s modulus
Part weight	
Scrap weight	

2.3 Testing and analysis

The tensile tests were performed on a Zwick Roell Z010 tensometer, and data gathered with TestExpert II 3.6 software. The tensometer was fitted with a 10 kN load cell, of accuracy 0.08 %. For each experiment (Table 1), 10 specimens were produced, 160 in total. The outputs (Table 2) were analyzed using Minitab 16. Main effects plots were used to assess the relative effects of each parameter, and Pareto plots used to quantify which parameters (and combinations of parameters) significantly affected the outputs at 95 % confidence level. Contour plots were generated for multi-objective analysis.

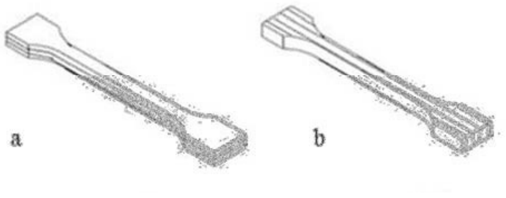

Fig. 1. (a) front SO; (b) side SO.

3. Results and Discussion

3.1 Single objective optimization

The Design of experiments approach, through quantification of significant parameters and the relationship between their variables and measured output, allows for recommendations of build parameters for said outputs. Recommended build parameters for each output (listed in Table 2) as a result of the analysis of the full factorial design are listed in Table 3.

For both tensile strength and Young's modulus, it was expected that the maximum infill would result in better properties, as a solid part is stronger and stiffer than a honeycomb structure of the same material. The layer height and SO were insignificant as the layers were oriented parallel to the loading axis (Figure 1). However a side SO was recommended for Young's modulus optimization as it was significant in combination infill level and number of shells. This result would require further study for verification, as SO's parallel to the loading axis would not be expected to influence stiffness.

The only significant parameter affecting build time and energy consumption was the layer height. The maximum layer height was recommended for optimization, and this was due to the machine achieving the required specimen thickness faster with the higher layer height.

For part weight, reduction is achieved through lower infill and number of shells. A higher infill would result in a heavier part, and a an increasing number of shells would increase weight as there would be proportionately less of the honeycomb pattern present, which is of lower density than the solid shells. Scrap weight however, depends only on SO. A side SO reduces the contact area between the build plate and the part, and hence the size of the raft (which is scrap). The other parameters are insignificant to scrap weight as they influence only the part.

Table 3. Recommended build parameters for optimization of individual outputs

Output	SO	Infill (%)	No. of shells	Layer height (mm)	Experiment no.(s)
Tensile strength	N/A	100	4	N/A	15,16
Young's modulus	Side	100	4	N/A	15,16
Build time	N/A	N/A	N/A	0.4	All even no.s
Energy consumption	N/A	N/A	N/A	0.4	All even no.s
Part weight	N/A	60	1	N/A	1, 2, 9, 10
Scrap weight	Side	N/A	N/A	N/A	9 to 16

These recommendations are based on analysis of the main effects and Pareto plots. Examples of the main effects plots are shown for tensile strength, energy consumption and scrap weight in Figures 2 to 4 respectively. Single objective optimization may also encompass more than one output, for example 'mechanical performance', which includes both tensile strength and Young's modulus. As Table 3 shows that the recommended parameters are the same (except in the case of side SO recommendation for Young's modulus, however this parameter is insignificant to tensile strength) for mechanical performance, they can be grouped together and described as co-operative, as optimization of one will concurrently optimize the other.

Similarly for part and scrap weight, which can be grouped into total material usage as part of cost optimization, the parameters of experiments 9 and 10 optimize both outputs. Energy consumption and build time could also be incorporated into cost optimization, and experiment 10 overlaps all three outputs.

In summary, the recommended build parameters for efficiency are those of experiment 10 (side SO, 60 % infill, 1 shell, 0.4 mm layer height), and for mechanical performance, those of experiments 15 or 16. Complications arise where optimization is required for multiple outputs that transcend both efficiency and performance requirements, examples of which are discussed in the next section.

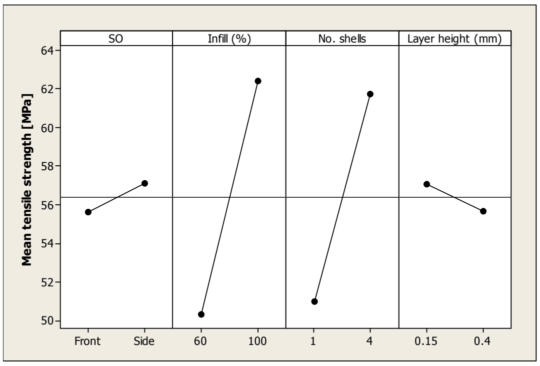

Fig. 2. Main effects plots for tensile strength.

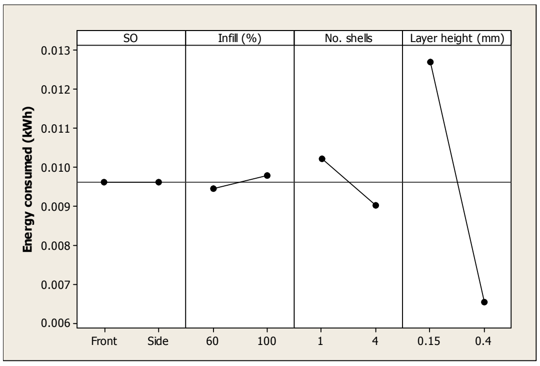

Fig. 3. Main effects plots for energy consumption.

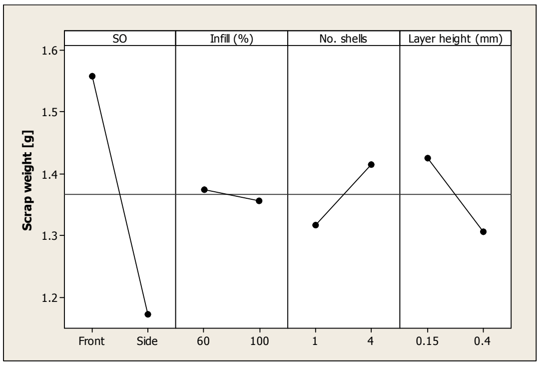

Fig. 4. Main effects plots for scrap weight.

3.2 Multi-objective optimization

The previous section discussed recommendations for build parameters based on optimization of single objectives, or groups of similar objectives of the same type. In reality, most designers are faced with multiple objectives in part production which are not necessarily co-operative, and so it useful to analyze the relationship between the build parameters and conflicting output objectives. This section discusses three examples:

- Tensile strength, build time and energy consumption
- Young’s modulus, part weight and scrap weight
- Tensile strength, Young’s modulus and part weight

In the first case, the part requirement is that of strength with a fast, energy efficient build. In the second, the part is required to be stiff whilst minimizing material usage and in the third, the part requirement is of specific strength and stiffness (strength and stiffness per unit weight). Figures 5-7 depict the Contour plots of the three cases respectively.

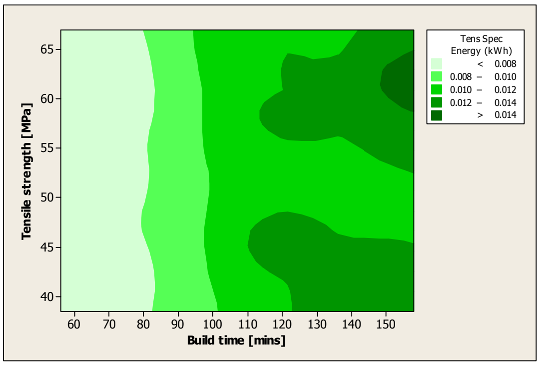

Fig. 5. Contour plot of build time vs. tensile strength vs. energy consumption.

Figure 5 shows that the 3 outputs of the first case can be optimized co-operatively. The extreme left hand corner of the plot represents the peaks of high strength and short build time, as well as low energy consumption.

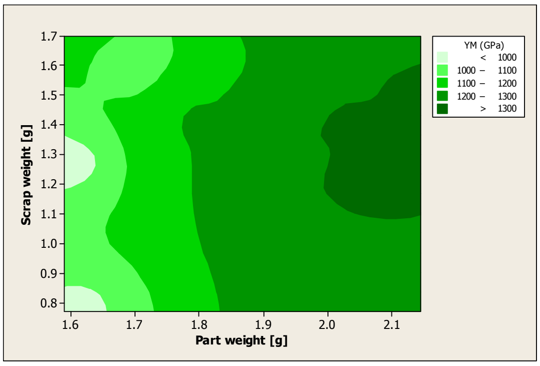

Fig. 6. Contour plot of part weight vs. scrap weight vs. Young’s modulus.

Figure 6 shows that minimization of material usage compromises the Young’s modulus. The best combination of parameters would depend on which are prioritized. In this case Young’s modulus can be prioritized where scrap weight is at an intermediate level; however the part weight is severely compromised. Figure 5 also shows a region where scrap weight is at the minimum and part weight at an intermediate level where the Young’s modulus is in the second highest of the five brackets. Optimal conditions encompassing these three outputs depend on their relative importance to each other. This highlights the need for quantifying such relative importance in multi-objective optimization, which will be the subject of further work.

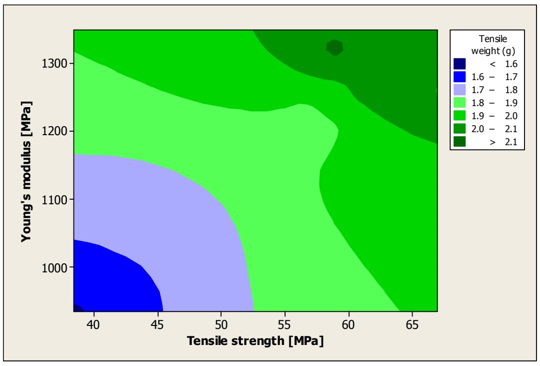

Fig. 7. Contour plot of tensile strength vs. Young’s modulus vs. part weight.

Figure 7 highlights how the mechanical performance is sensitive to part weight. Higher part weights, resulting from higher infills with the highest number of shells (which produce more solid structures) yield higher mechanical properties. As with the previous case, optimization depends on the relative importance of each output. It is clear from Figure 7 that compromises on part weight cannot be made where tensile strength and/or Young’s modulus are a priority.

4. Conclusions and Further Work

This work highlights how a Design of experiments approach can be utilized to analyze the effects of different build parameters on a variety of measured outputs of FDM parts. It is an important contribution to the field of additive manufacturing whose growth into new applications and markets continues apace. Specific conclusions are as follows:

- For optimization of tensile properties, the infill level and number of shells are the only significant parameters and should be maximized
- For optimization of efficiency outputs, the maximum layer height and lowest levels of infill and number of shells should be used.
- Where scrap weight minimization is incorporated into efficiency, the SO which reduces the contact area between part and build plate should be used, in this case a side SO.
- Where multiple objectives are required in part production, contour plots give a visual representation of the inter-relationship between three outputs and can aid the decision making process.
- Specific build parameter recommendations where multiple objectives are required are dependent on the relative importance of each output in the objective

One clear recommendation of this work for biomanufacturing is that optimal build parameters for prototyping (where aesthetics and dimensional accuracy take precedence over performance) can incorporate efficiency for cost, energy and material savings prior to the production of the part where the parameters would change for optimization of performance. Recommendations for further work are as follows:

- Multi-objective analyses using objective function (loss function), investigating the difference in recommended build parameters with changing relative priorities of the defined outputs
- Case studies on real world FDM products in the prosthesis and implants sectors
- Extension of the work to incorporate additonal materials and machinery in the creation of a database

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