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Analysis of dimensional performance for a 3D open-source printer based on fused deposition modeling technique

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Abstract

In this paper an analytical dimensional performance evaluation and comparison is illustrated, done on benchmarks manufactured using two different 3D FDM printers: an industrial system, and an open-source one (a modified Fab@Home Model 1 printer).
Using a factorial analysis design of experiment (DOE), optimum process parameters were found to improve dimensional accuracy on rectangular test specimens, minimizing changes in length, width and height. Fab@Home printer demonstrated to be a good platform, simple, flexible and inexpensive.

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Keywords: Additive manufacturing; Dimensional performance; Fab@Home Model 1, Design of experiment (DOE), Industrial 3D system, Open-source 3D system, Dimensional accuracy.

1. Introduction

The technological development of additive manufacturing and 3-D printing has been substantial, fueling rapid growth in commercial rapid prototyping (RP) as it has proven useful for both design and small batch production [1-6]. The great spread of these technologies has driven the manufacturers and the hobbyists in machine and process improvements. One of the most commonly used technologies is fused deposition modeling (FDM). The main advantages of this technology for industrial machines include: a good variety of materials available, easy material change, low maintenance costs, quick production of thin parts, a tolerance equal to ±0.1 mm overall, no need for supervision, no toxic materials, very compact size and low temperature operation [7]. Annual unit sales of RP systems using FDM technique worldwide grew by an estimated 13.9% [8]. The technological evolution of the 3-D printers, widespread internet access and inexpensive computing has made a new mean of open design capable of accelerating self-directed sustainable development [9]. There are many types of small scale 3-D printers, the RepRap, the Fab@home and Ultimaker are open-source projects, which were started at universities and have a large open source community supporting their development [10]. Parts accuracy built with RP technologies has leaded key issues in research fields. The optimization of process parameters is a major challenge for dimensional accuracy, surface roughness, parts strength, and build time parts improvement. For this reason, existing additive manufacturing machines are currently modified in order to improve their accuracy and capabilities. Industrial machines still have many contradictions to be considered including high costs, material restrictions and the difficulty in studying process parameters [11]. Open-source machines allow a thorough study of several process parameters involved in part fabrication and the selection of the correct process parameters such as deposition velocity, layer thickness, deposition rate and speed movement [12]. Fab@Home, uses a three axis system driven by stepper motors and uses

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extruded layers of working material to build up the 3-D shape [13].

This work is focused on the creation of building model system from “cold” to the “hot” extrusion head for Model 1 printer. The parts quality and strength built with silicon was poor leading the authors to upgrade the extruder system with “hot” technique allowing in this way the use of ABS resins and PLA as model materials. The process parameters were investigated and the upgraded system then was calibrated in order to the hot extrusion technique. Based on these parameters found by the factorial analysis design of experiment (DOE) the standard specimen dimensional accuracy was improved to ensure the design parameters and contrasting them with the industrial system.

2. Materials and methods

2.1. Industrial and open-sources machines

An industrial Stratasys FDM 3000 3D printer (Stratasys Inc., USA) was selected to fabricate the rectangular specimens. The extrusion head has two nozzles, the first one extrudes the construction material and the second one extrudes material to support inclined surface against the building direction of the part/specimen [16]. The head then moves around in the x-y plane and deposits material according to the part geometry. The platform holding the part then moves vertically downwards in the z-plane to begin depositing a new layer on top of the previous one. The printer is controlled and parts are built by the Stratasys Insight 4.2 software.

An open-source Fab@Home Model 1 3D printer was used. Fab@Home is a simple, low cost, flexible and manageable machine, with a Philips LPC-2148 ARM7DMI microcontroller, and two stepper motors control cards, a Xylotex XS-3525/8S-4 and a PDMX-150. This printer was modified, adding a FDM extruder, consisting in a thermoplastic extruder mounted on an aluminium support and driven by the computer-controlled platform in a Cartesian space. The material is supplied to the extruder through a feeding system, composed by two gears and driven by a stepper motor NEMA 17. The printer was calibrated for this new fabrication technology, and used to fabricate the same rectangular specimens, as with the industrial system (Fig. 1).

The material is an ABS 3mm of diameter; it enters in the extruder in which it is fused at 240 °C.

The pressure of the feeding system causes the extrusion, changing in the filament diameter from 3 mm to 0.5 mm.

The filament is ejected through the nozzle, and finally deposited in layers onto a simple platform, covered by a cardboard moistened with dimethylketone (acetone) to allow first layer material adhesion.

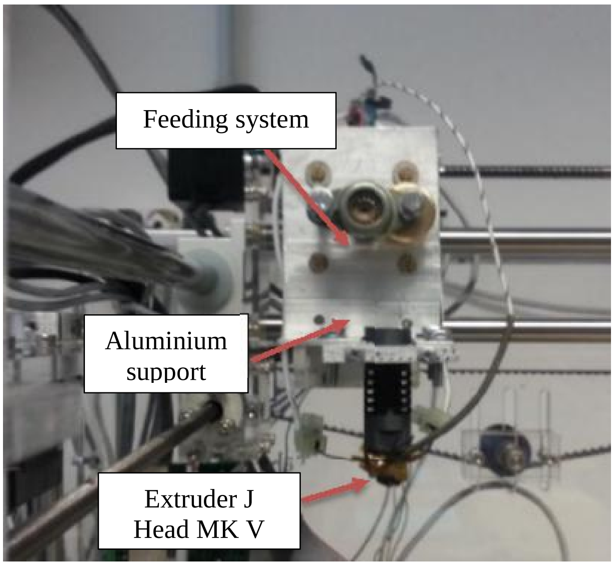

Fig. 1. The upgraded FDM system for Model 1

The software used for this work is Fab@Home_v0.23 based on Fab@Home V3 ELF firmware. The 3D models are designed in a solid modeling software in a STL format and then transferred to the Fab@home software which operate the slicing, calculates the tool paths, and then provides the command and control of the machine in order to fabricate the 3D object.

2.2. Specimen manufacturing

A 2^3 DOE full factorial experimental plan was performed, using Minitab 16.0 (Minitab, USA) software, for the fabrication with both systems, having 3 replications, for a total of 24 experiments. The experimental activity was carried out over two phases, focusing on independent variables process parameters for both FDM printers (Fig. 2). The first phase consists in manufacturing the specimens with both printers. For FDM 3000 Stratasys, the variables considered for specimen fabrication are tip size, raster width and slice height. For the upgraded Model 1 printer the variables considered for specimen fabrication are slice height, raster width and path speed. The second phase was the dimensional measurement of the specimens manufactured with both printers, for the performance analysis.

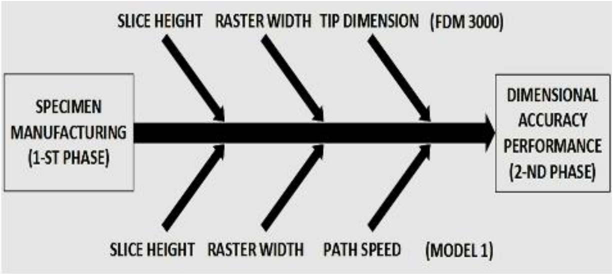

Fig. 2. Workflow diagram for specimen manufacturing and analysis

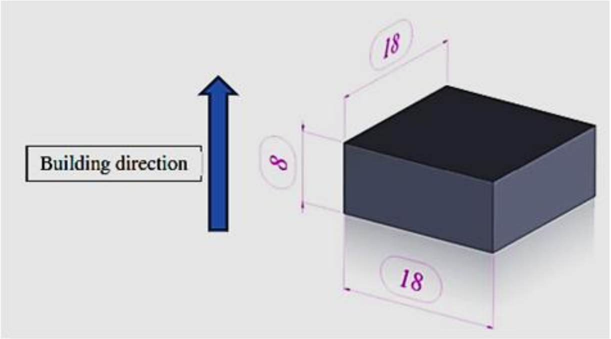

Fig. 3. Rectangular specimen design

Table 1. FDM 3000 factor levels for specimen fabrication

Factors	Low	High
Raster width (mm)	0.304	0.729
Slice height (mm)	0.178	0.254
Tip dimension (mm)	0.254	0.305

Table 2. Model 1 factor levels for specimen fabrication

Factors	Low	High
Raster width (mm)	0.45	0.50
Slice height (mm)	0.45	0.50
Path speed (mm/s)	7	10

A very simple rectangular shape of the specimens (Fig. 3) was used to facilitate their dimensional measurements: L1 = 18mm; L2 = 18mm and H = 8mm.

For FDM 3000, the values of the input process variables are shown in Table 1, and for Fab@Home Model 1 in Table 2.

Several process parameters for Model 1, such as the tip diameter and the deposition rate, were maintained constant throughout the experimentation.

For both methods the response variables are: length (L1), width (L2) and height (H).

Preliminarily, several process parameters were calculated and optimized for the Fab@Home printer, by doing some experimentations.

2.3. Materials

The rectangular specimens are produced on the industrial system using a filament of ABS-P400 material with outer diameter of 1.75 mm and a density of 1000 kg/m^3 [14]. For the open-source it was used a filament of ABS material with outer diameter of 3.00 mm and a density of 1060~1200 kg/m^3 [15]. ABS material is widely used by FDM technique for industrial and other application parts manufacturing due its characteristics and being non-toxic.

2.4. Dimensional measurements

All specimens were measured using a digital microscope “Dino-Lite pro AM413-T”, having an accuracy of ± 0.01 mm after calibration. To have accurate precision during the dimensional measurements the microscope was set to 20 times enlargement. All the specimens were weighed with an electronic balance.

3. Results and discussion

3.1. Dimensional analysis

In Fig. 4 are shown two of the samples obtained by each system.

All the 24 specimens were measured in order to see and compare the parts quality manufactured by both systems. This analysis was performed to check the consistency and reliability of the upgraded Model 1 machine, compared to the industrial machine.

The models were left in the environmental temperature in the laboratory and they were measured after three days from their manufacturing.

In Table 3 and Table 4 are represented the measured average dimensions (on the three replications) for the 8 types of specimens fabricated with both systems.

Fig. 4. Manufactured specimens: a) Model 1 b) FDM 3000

Table 3. Dimensions of specimens fabricated with FDM 3000

Part groups	Slice height	Raster width	Tip	L1 (mm)	L2 (mm)	H (mm)
1	0.178	0.304	0.254	17.90	17.92	8.15
2	0.254	0.304	0.254	17.99	17.97	8.25
3	0.178	0.729	0.254	18.33	18.05	8.07
4	0.254	0.729	0.254	17.90	18.61	8.10
5	0.178	0.304	0.305	17.87	17.92	8.05
6	0.254	0.304	0.305	17.96	17.87	8.09
7	0.178	0.729	0.305	17.91	17.91	8.27
8	0.254	0.729	0.305	17.89	17.84	8.19
Av. value				17.97	18.01	8.15

Table 4. Dimensions of specimens fabricated with Model 1

Part groups	Slice height	Raster width	Path speed	L1 (mm)	L2 (mm)	H (mm)
1	0.45	0.45	7	17.64	17.47	8.26
2	0.50	0.45	7	17.69	17.77	8.24
3	0.45	0.50	7	17.81	17.85	8.28
4	0.50	0.50	7	17.88	18.95	8.37
5	0.45	0.45	10	17.91	17.88	8.34
6	0.50	0.45	10	17.98	17.95	8.14
7	0.45	0.50	10	17.88	18.04	8.21
8	0.50	0.50	10	17.85	18.09	8.17
Av. value				17.78	17.87	8.25

The manufactured specimens exhibited a percentage average error of -0.2% on L1, +0.1% on L2 and +1.9% on H for the industrial system, and -0.9% on L1, -0.7% on L2 and +3.2% on H for the open-source system.

A higher error in H dimension occurred for the specimens fabricated with the open-source system, due to the first layer gluing problem in the building platform.

By analysing the data distribution and the standardized residual effects for L1, L2 and H dimensions, it is noticed that the data have a Gaussian distribution, due to the of small samples measured values range.

In the main effects plots, based on the ANOVA analysis perfomed from Minitab 16 software, the influencing factors on L1 dimension are highlighted, for the parts dimensional analysis and predictive factor set values (Fig. 5 and 6).

For FDM 3000 the main influencing factor on length is tip. The deviation caused by tip from the ideal dimension happens due to the deposited diameter of the material filament. Slice height gives a minimal deviation from the ideal value caused from the material interaction with air humidity after production and from FDM model cleaning bath. Part raster width also has the same effect on length.

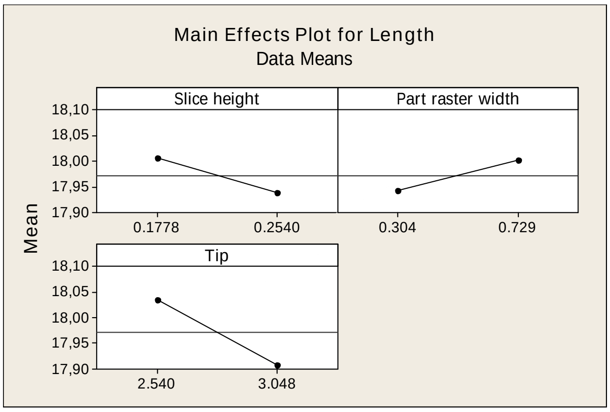

Fig. 5. Factor effects plot L1 (Length -mm) FDM 3000

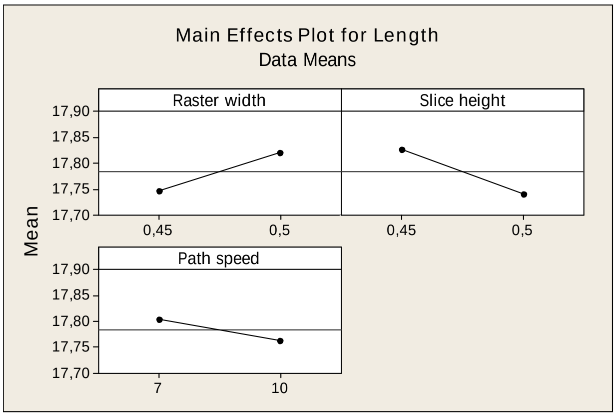

Fig. 6. Factor effects plot L1 (Length -mm) Model 1

For Model 1, the deposited material is subjected to the shrinkage. The deviation from the ideal dimension of L1 caused by the volumetric shrinkage is quite visible. The most influencing factors on L1 are raster width and slice height, caused by the deposited material filament changes from the theoretical cylindrical shape.

The same analysis is done for the change in width and height. The slice height as a small influence on width instead the part raster width and the tip for FDM 3000. The importance of the tip, which contributes to change the texture of the last slice, increases. Slice height and path speed influence for width is greater than the raster width on Model 1. Even with the recalculated factors values, the shrinkage phenomenon is quiet visible on width for Model 1, causing a larger deviation from the ideal dimensions. This happens due to the roughly temperature difference of the deposited material (242 °C) and the deposition platform, which has the environmental temperature (25 °C).

On both machines the deviation from the ideal value of the height is visible. This is caused by the material deposition on layers due to the filament deposited shape change, as it is considered an ideal cylindrical shape.

Slice height and part raster width have a greater influence on height, and the tip influence is smaller for FDM 3000. During the deposition of parts with high values of slice height, some distortion of the filaments grid were created; this could be related to the increase of the volume extruded by the nozzle. For Model 1, the influence of raster width and path speed is greater on height than of slice height influence reduction. The deviation from the ideal value could be caused by the problems encountered for the correct first layer material deposition on the platform, due to the material adhesion problems. The material shrinkage of the first layer, caused by this poorly material deposition, tends to increase the specimens height for the other layers.

By representing in a histogram the deviations between the ideal dimension and the real ones respect to the average of the three repetitions, the following graphs are obtained in the Fig. 7 and 8: L1: -0.028 mm; L2: 0.014 mm and H: 0.149 mm (FDM 3000) and L1: -0.156 mm; L2: -0.125 mm and H: 0.253 mm (Model 1).

For Model 1, the shortening of the lateral dimensions could be caused by the material shrinkage.

On the contrary, for the height the expansion is greater than the ideal dimensions for all specimens caused by imperfect first layer adhesion.

Based on these analyses, it is quite visible an improvement of the Fab@home Model 1 printing quality with the new FDM extruder.

4. Conclusions

The upgrade of the Fab@Home Model 1 with the FDM extruder gave an acceptable parts quality for the fabrication with the material used in this machine. In this direction, the present work emphasizes that the improvement of part quality can be found operating a proper control of the process parameters, not only for an industrial printer, but also for a low – cost one.

This methodology can help to explain the complex building mechanism, but also represents in detail the effect of process parameters on output responses, especially for the part quality.

Improvement of the dimension accuracy can be obtained reducing the path speed, but this increases the building model time.

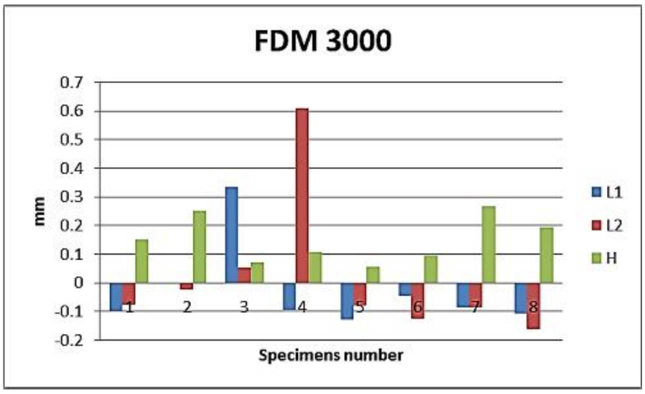

Fig. 7. Difference between real and ideal specimen dimensions

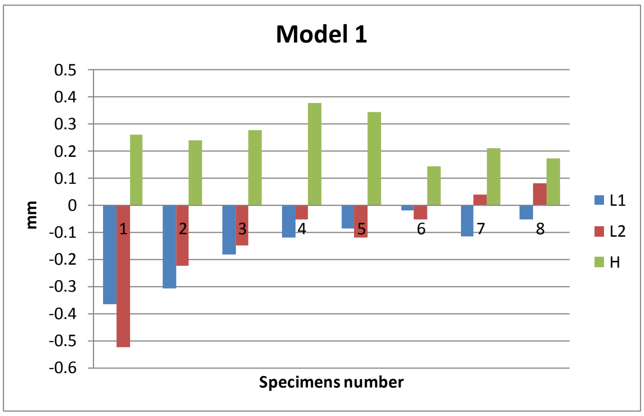

Fig. 8. Difference between real and ideal specimen dimensions

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