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INFLUENCE OF FUSED DEPOSITION MODELING (FDM) PARAMETERS ON SURFACE FINISH OF PLASTIC PARTS

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ABSTRACT
In the present paper, influence of FDM (fused deposition modeling) parameters on surface finish of printed parts is presented. Cylindrical specimens were printed in PLA (Polylactic Acid). Five variables were considered, namely layer height, infill, printing angle, nozzle diameter and plastic temperature. A fractional factorial design was defined with central points. Roughness of printed parts was measured with a contact roughness meter and different roughness parameters were determined. Main factors influencing surface roughness are printing angle and layer height, while the rest of the variables had much lower influence on surface finish. In the future, geometry and mechanical strength of the specimens will be studied and analyzed, and multiobjective optimization will be carried out.
Keywords: surface finish; fused deposition modeling (FDM), printing angle, layer height.

1. INTRODUCTION
Additive manufacturing provides a quick and flexible way to manufacture parts. Specifically, main advantages of Fused Deposition Modeling (FDM) (also known as Fused Filament Fabrication or FFF) are that it is an easy and versatile technology, that price of plastic filament is relatively cheap, and that many different plastic materials can be printed. However, this technology has some disadvantages too. Since the piece is constructed by placing each new layer on the previous one, the front layer must have a surface similar to that of the new layer to be placed. This implies, for example, that in cases of cantilevers or bridges, the gravity would deform the extruded filaments at areas where there was no previously deposited material, so that the piece would not have the desired geometry. Thus, it is not possible to print neither wide bridges nor highly inclined walls without the use of printing supports [1]. In addition, surface finish is relatively poor because surfaces are formed by steps. Other authors have studied surface finish obtained in FDM printing processes. Singh et al. improved surface finish of FDM parts through chemical exposure to acetone [2]. Peng and Yan performed dual-objective analysis in order to optimize both energy consumption and surface roughness in FDM processes. Layer height was the most influential variable, leading to higher roughness and higher energy consumption [3]. Valerga et al. found that color of the filament influences surface roughness [4]. In general, lowest roughness was found for transparent filament, followed by gray, green and pink.
In the present paper, design of experiments (DOE) was used in order to obtain a linear model for average roughness Ra in FDM processes. Five different process variables were considered: layer height, infill percentage, extrusion temperature, inclination angle, and nozzle diameter.

2. MATERIALS AND METHODS
2.1. Materials
Nowadays, FDM technology allows printing different plastic materials. Plastic is supplied as a filament. Thermoplastic materials must be heated to a temperature at which they melt and can be extruded and deposited on a printing bed, layer by layer, in order to obtain required shapes. In the

present paper, polylactic acid (PLA) was used in white color. It is a biodegradable material composed mainly of starch from sugar cane or corn. Properties of commercial PLA are listed in Table 1.

Table1. Properties of commercial PLA [6].

Property	Values
Tensile strength (MPa)	34-51
Elastic modulus (GPa)	1.7-2.8
Density (g/cm3)	1.0-1.4

Cylindrical specimens of 10 mm diameter and 20 mm height were printed (Figure 1), using a Sigma double extruder printing machine from BCN3D.

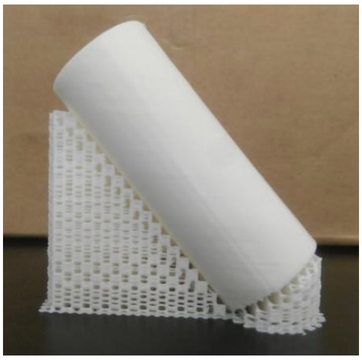

Figure 1. Printed cylindrical specimens

In order to get the g-code that is necessary for printing, Cura software was employed.

2.2 Methods

Five different printing parameters were selected (Table 2). A two-level fractional factorial design with five factors, 2^5-1, was used, corresponding to 16 runs. 3 central points were added in order to test the curvature of the model. Thus, total number of runs was 19.

Table2. Levels for variables in DOE.

Variable	Low level	High level
Nozzle diameter (mm)	0.4	0.6
Layer height (mm)	0.05	0.25
Infill (%)	30	70
Filament extrusion temperature (ºC)	190	210
Inclination angle (º)	0	90

Nozzle is the final part of the printing head, where the material is extruded. Selected values for nozzle diameter were the usual ones for the Sigma machine.
Layer height corresponds to resolution in the vertical axis. Values were selected according to previous studies, taking into account that maximum recommended layer height is 80 % of nozzle diameter employed [7].
Infill percentage is related to density of the part. The higher the infill, the higher the density of the part will be. In the present paper, grid structure was used. Limit values for infill were selected according to previous studies.
Extrusion temperature of the wire corresponds to temperature to which the material is heated before it is deposited. Temperature needs to be high enough to assure adhesion between layers. As temperature increases, material becomes more liquid, and it will be more likely to drip from the nozzle. If strands

are formed, a defect called stringing will appear. In addition, excessive temperature would require higher speed and worse surface finish would be obtained. Levels for extrusion temperature were selected according to PLA manufacturer recommendations.
In order to print inclined parts, inclined cylinders must be drawn and then exported to Cura software (0.1.5-beta2 version), which will add supports if necessary. Inclination angle is angle between vertical direction and longitudinal direction of the part. Low value for inclination angle was 0º (conventional printing) and high value corresponds to maximum inclination angle of 90º.
Roughness was measured by means of a Taylor Hobson Form Series 2 roughness meter. Roughness was measured along a generatrix of the cylinders, specifically the highest generatrix of the cylinder (contained in a vertical plane) for inclined samples. Roughness parameter Ra was taken into account for assessing surface finish of printed parts.

3. RESULTS

Table 3 contains roughness Ra results for the experiments performed.

Table 3. Average roughness Ra (μm).

Experiment	Nozzle dimeter (mm)	Lauer height (mm)	Infill (%)	Temperature (ºC)	Inclination angle (º)	Ra(μm)
1	0.6	0.25	30	190	90	0.54
2	0.6	0.05	30	210	90	0.75
3	0.6	0.25	30	210	0	17.98
4	0.6	0.05	70	190	90	0.62
5	0.6	0.25	70	210	90	0.56
6	0.6	0.05	70	210	0	3.94
7	0.6	0.05	30	190	0	3.60
8	0.6	0.25	70	190	0	18.23
9	0.5	0.15	50	200	45	21.15
10	0.5	0.15	50	200	45	20.70
11	0.5	0.15	50	200	45	20.72
12	0.4	0.25	70	190	90	0.78
13	0.4	0.05	70	190	0	5.06
14	0.4	0.25	30	210	90	0.76
15	0.4	0.05	30	190	90	0.77
16	0.4	0.25	30	190	0	17.76
17	0.4	0.05	30	210	0	4.58
18	0.4	0.05	70	210	90	0.59
19	0.4	0.25	70	210	0	19.04

Ra values range between 0.6 μm and 21.5 μm, with many values below 1 μm. High Ra values correspond to experiments 3, 8, 9, 10, 11, 16 and 19, with high or medium layer height and low or medium inclination angle. Central points showed high roughness, suggesting that better fit would be obtained with a quadratic than with a linear model. Low roughness values correspond to experiments 1. 2, 4, 5, 12, 14, 15, and 18, printed with high inclination angle. Since roughness is measured along the highest generatrix of the cylinder, when inclination angle is 90º roughness is measured along the highest layer of the part. Thus, roughness value will be close to zero. This suggested that the model for roughness would present curvature. This fact was confirmed with an ANOVA analysis. In the future, axial points will be added to have a central composite design and a second order model will be found for average roughness Ra.

The simplified model for Ra in codified units is presented in Equation 1.

$$Ra = 5.972 + 3.485 \cdot LH - 5.300 \cdot IA - 3.494 \cdot LH \cdot IA + 14.867 \cdot \text{Central Point} \quad (1)$$

Figure 2 shows the Pareto Chart for average roughness Ra.

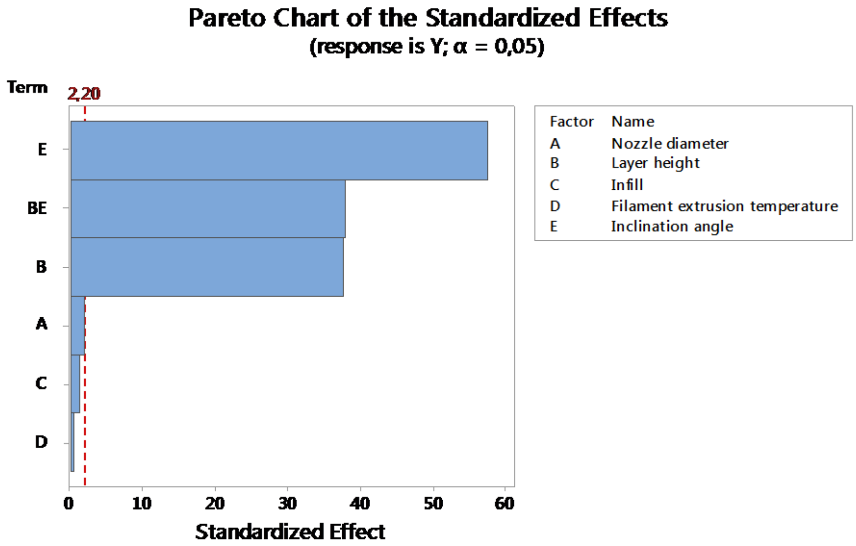

Figure 2. Pareto chart for Ra

Most significant term of the simplified model for Ra is inclination angle, followed by the interaction between inclination angle and layer height, and by layer height. When inclination angle is 0º, roughness is measured in the perpendicular direction to layers. However, as printing angle increases, layer direction changes and this influences roughness. As for layer height, the higher the layer height the wider and higher the roughness peaks become, thus increasing roughness values.

4. CONCLUSIONS

In the present work, influence of five process variables on surface finish was assessed in FDM printing processes, by means of design of experiments (DOE). A linear model was obtained for average roughness Ra. It was observed that main factors affecting average roughness Ra are inclination angle and layer height. Since curvature was detected, a second order model will be found for Ra in the future. In addition, cylindricity and mechanical strength of samples will be studied.

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