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Influence of structure support printing parameters on surface finish of PLA hemispherical cups for emulation of ceramic hip prostheses

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Abstract

Hemispherical hip ceramic prostheses require certain degree of porosity on their external surface so as to fix them by means of osteointegration. This can be achieved with porous mesostructures. In contrast, internal surface needs to be smooth in order to assure appropriate sliding of femoral head. Such specific shapes can be obtained by means of 3D printing. However, in certain printing processes, structure supports are required when overhang exceeds a certain angle. In this case, once supports are removed, joints between supports and prostheses will produce irregularities which will increase roughness on the internal surface of the prostheses. In the future, bimaterial prostheses are to be printed in ceramic with plastic structure supports, which are cheaper than ceramic ones. For doing this, double head printing machines will be used. In the present work, as a first step of research, both prostheses and supports were printed in plastic material. Specifically, PLA, which is a biocompatible polymer, was used. Influence of printing variables for supports on surface finish of internal surface of hemispherical cups after removing supports was studied. Prostheses were obtained by means of Fused Deposition Modelling (FDM) technology. Full factorial design of experiments was performed, with three printing variables: Support Pillar Resolution, Horizontal Offset from Part and part, and Dense Infill Percentage. Regression analysis was carried out. Results showed that Support Pillar Resolution and Horizontal Offset from Part are main parameters factors influencing roughness parameters Ra and Rz. In order to obtain low roughness values, high Support Pillar Resolution should be selected. In case low Support Pillar Resolution was necessary, then high Horizontal Offset from Part would be recommended. In the future, research presented in the present work will help selecting proper values for printing parameters in order to obtain smooth internal surfaces of ceramic hemispherical hip prostheses. This will reduce or even avoid subsequent polishing time of the internal surface of the prostheses.

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Keywords: Fused Deposition Modelling; Horizontal Offest; Printing supports; Support Pillar Resolution; Surface roughness; 3D printing.

1. Introduction

In recent years, use of ceramic hip prostheses has increased, because of their biocompatibility. In addition, since ceramic is the hardest hip replacement material, full ceramic implants have the lowest wear rate of all implant types. This prevents the implant from loosening and spreading broken implant debris in the body [1]. In the present work, the studied part is a hip prosthesis, which is placed in the acetabulum. Acetabulum is the concave articular portion of the pelvis, where the femoral head is articulated. Orthopedic studies have shown that the position and shape of acetabulum and femoral head have a great influence on the formation of arthrosis of the hip articulation [2].

Nomenclature

FDM	fused deposition modelling
PLA	polylactic acid

Ceramic hip prostheses have typically a hemispherical cup shape that can be obtained by means of machining processes of sintered ceramic blocks. However, they require a certain degree of porosity near the external surface that will allow their fixation by means of osteointegration. In contrast, internal surface of the prostheses need to be smooth enough to favor sliding of femoral head. In order to attain porosity, prostheses need to be covered by a special layer, which increases fabrication time and costs [3]. An alternative process

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consists of printing the ceramic prostheses by means of a similar process than FDM, fusion deposition modeling, in which a ceramic ink is employed. Such process allows obtaining porous structures without excessively increasing costs. Although great advances have been achieved in recent years with FDM process for hydroxyapatite [4], 3D printing of ceramics shows currently a lower degree of development than printing of plastics.

FDM is a simple, easy and quite cheap method to obtain plastic parts. However, it has some limitations regarding geometries to be obtained, for example, it is not possible to obtain wide bridges, walls require a minimum thickness value and supports are required to print parts having a certain overhang angle [5]. As for bridges, when a part is designed, it can have a geometry that presents a roof, i.e. between two pillars there will be some space where material is not sustained. In this case, the printer will be able to print these geometries given that distance between pillars does not exceed a certain value. Otherwise, material will be deformed. Maximum distance for plastics is considered to be 5 mm. On the other hand, wall thickness cannot be lower than two times the nozzle diameter, so that the walls are not constituted by only one extruded filament.

Regarding inclination angle, FDM technique is based on successive deposition of melted material layers, which give volume to the piece. This fact implies that a lower layer is required on which the next layer is sustained. Otherwise, printed material would fall. For this reason, in FDM technique the angle α formed by vertical geometries with respect to vertical axis is critical, so that printing process is correct (Figure 1).

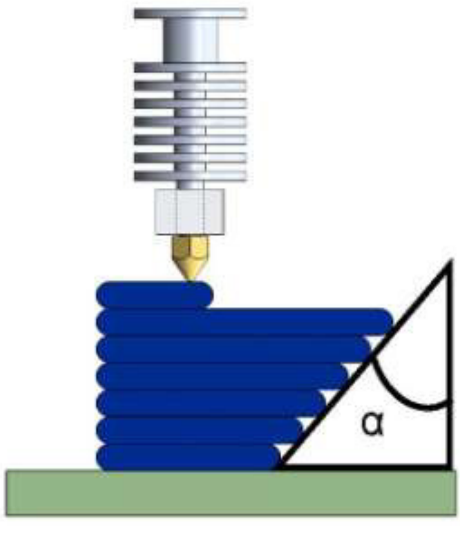

Fig. 1. Inclination angle.

It is recommended not to exceed 70º for plastic materials. When such angle is exceeded, use of printing supports is required. Several authors have studied reduction of the volume of supports, for example choosing the best orientation of 3D printed objects [6] or using tree-like supporting structures [7].

In order to print hip ceramic prostheses, printing supports are required. When supports are removed, marks are left on the internal surface of the prostheses. In the future, by means of double head printers, it will be possible to print ceramic structures with plastic supports, which are cheaper than ceramics. In the present work, as a first step of research, both prostheses and supports were emulated in PLA, polylactic acid, a biocompatible polymer with low printing temperature.

Main objective of the present work is to select proper values for printing variables that allow minimizing roughness on the internal surface of PLA hemispherical prostheses, after printing supports are removed. This will reduce further polishing time that is required to obtain a smooth surface which will be in contact with femoral head.

2. Materials and methods

Polylactic acid (PLA) was used for printing the hemispherical prostheses. A Sigma printing machine was used. Simplify 3D software was employed for obtaining the printable files from the CAD geometry.

2.1 Printing process

In the present work, hemispherical prostheses were printed with the base on the printing platform (Figure 2). This way, although an internal support is required, support is smaller than it would be if the part were printed upside down. Simplify3D was used for obtaining stl files for printing.

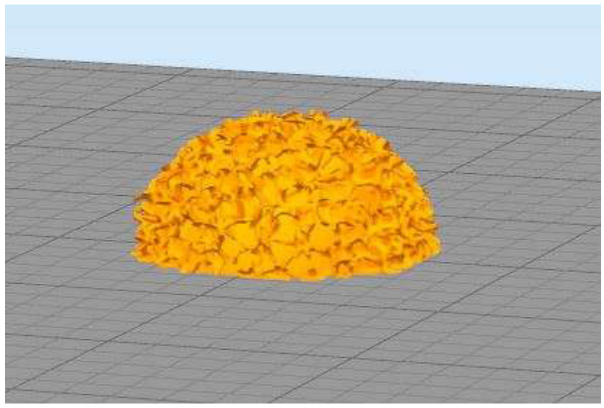

Fig. 2. Printing position of prostheses.

Hemispherical supports are required in this case, which are placed under the internal surface of the prostheses (Figure 3).

Fig. 3. Prosthesis with printing support

Figure 4 shows an example of removed support.

Fig. 4. Removed printing support.

2.2 *Design of experiments*

A full two-level factorial design was defined for performing the experiments. Variables considered were Support Pillar Resolution (Res), Dense Infill Percentage (Inf) and Horizontal Offset From Part (Off). Support Pillar Resolution is defined as width of support pillars in mm. Dense Infill Percentage is percentage of volume of solid part within the support structure. Horizontal Offset from Part is the distance from the support to the part on the xy plane. Three central points were added to the factorial design. Total amount of experiments was 11. Responses were average roughness Ra and mean roughness depth Rz.

In order to determine low and high level for three variables of the factorial design, preliminary tests were performed on cylindrical specimens. As an example, Figure 5 shows a cylinder that was printed with Support Pillar Resolution of 4 mm, Dense Infill Percentage of 70 % and Horizontal Offset from Part of 0.7 mm. The part could not be printed, because offset value was too high and the support structure did not contact the surface of the cylinder.

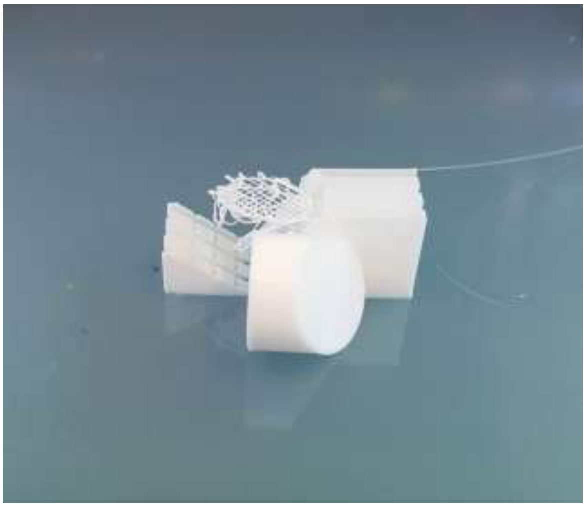

Fig. 5. Cylinder printed with Horizontal Offset from Part = 0.7 mm.

After performing preliminary tests, defective printouts were discarded. Selected levels for variables of factorial design are presented in Table 1.

Table 1. Levels used in factorial design.

Factor	Low value	High value
Res (mm)	2	8
Inf (%)	40	80
Off (mm)	0.1	0.5

2.2 *Roughness measurement*

Roughness was measured by means of a roughness meter Taylor Hobson Talysurf 2 with µltra software. Since z measurement range exceeded range for roughness tip of 1.04 mm, profile tip was used, with a range of 5.6 mm and a resolution of 84 nm.

Average roughness Ra and average maximum size Rz were considered. Since all supports contacted the internal surface of the prostheses on two points, two measurements were performed on each surface. Figure 6 shows the tool holder that was designed for the hemispherical prostheses. Blue lines correspond to roughness measurement areas.

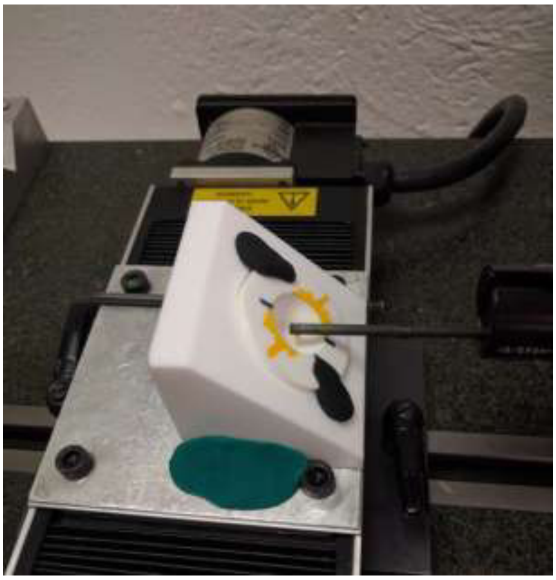

Fig. 6. Holder used for measuring roughness.

Curvature of the internal surface of the prostheses was removed from the rough profiles. Since profiles presented a high peak caused by the marks of the supports, no Gaussian filter could be applied in this case, which would have removed the peak from the profile.

3. Results

Results for Ra and Rz parameters are presented in Table 2 for the different experiments that were carried out.

Table 2. Ra and Rz values

Experiment	Res (mm)	Inf (%)	Off (mm)	Ra (μm)	Rz (μm)
1	2	40	0.1	43.58	148.50
2	8	40	0.1	3.90	16.06
3	2	80	0.1	41.31	120.17
4	8	80	0.1	6.02	23.46
5	2	40	0.5	20.08	78.23
6	8	40	0.5	21.16	68.34
7	2	80	0.5	11.83	37.24
8	8	80	0.5	4.61	16.73
9	5	60	0.3	18.03	47.02
10	5	60	0.3	24.59	86.29
11	5	60	0.3	20.96	58.43

All supports could be easily removed from the prostheses, except for experiments 1 and 3, obtained with Low Support Pillar Resolution and low Horizontal Offset from Part, for which a knife was required. Such experiments correspond to highest roughness values, above 40 μm for Ra, and above 120 μm for Rz.

Regression analysis was performed to both responses Ra and Rz. Models were simplified by means of a backward process. Simplified models for Ra and Rz are presented in Equations 1 and 2 respectively.

$$Ra = 66.43 - 7.68 \cdot Res - 94.9 \cdot Off + 14.34 \cdot Res \cdot Off \quad (1)$$

R^2 adj = 81.66 %

$$Rz = 200.00 - 23.24 \cdot Res - 274.3 \cdot Off + 41.4 \cdot Res \cdot Off \quad (2)$$

R^2 adj = 68.75 %

Pareto Charts of the Standardized Effects for Ra and Rz, showing significant terms of the models, are presented in Figures 7 and 8 respectively.

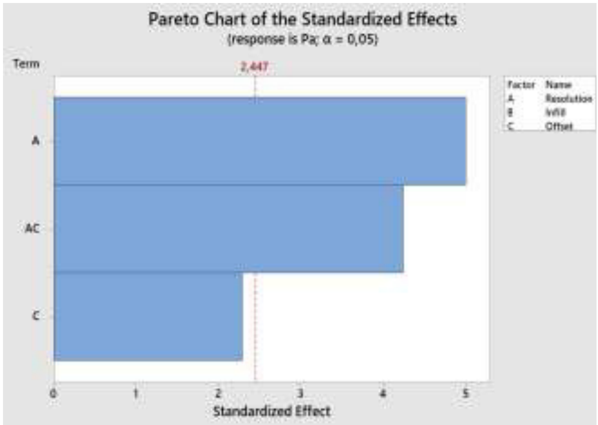

Fig. 7. Pareto chart for Ra.

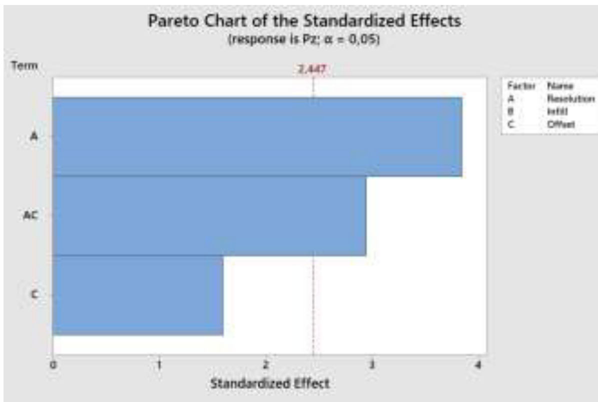

Fig. 8. Pareto chart for Rz.

For both Ra and Rz, main factor affecting roughness is Support Pillar Resolution, followed by interaction between Support Pillar Resolution and Horizontal Offset from Part and by Horizontal Offset from Part. Dense Infill Percentage was not found to be significant.

Figures 9 and 10 show contour plots for Ra and Rz respectively, for the two significant variables, Support Pillar Resolution and Horizontal Offset from Part.

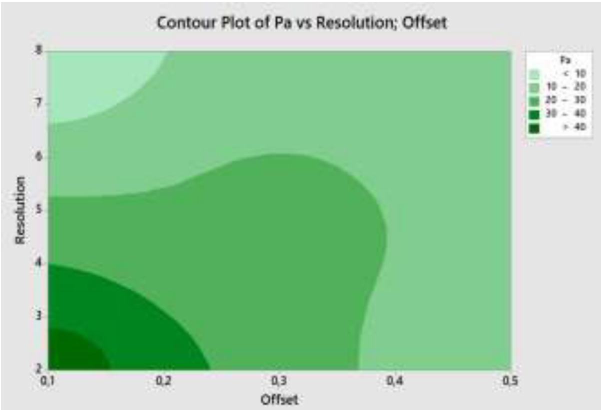

Fig. 9. Contour plot for Ra.

In Figures 9 and 10 it can be observed that, the higher Support Pillar Resolution, the lower roughness is. In case low Support Pillar Resolution was required, for example for obtaining an irregular shape, then high Horizontal Offset from Part would be recommended, in order to obtain low roughness values.

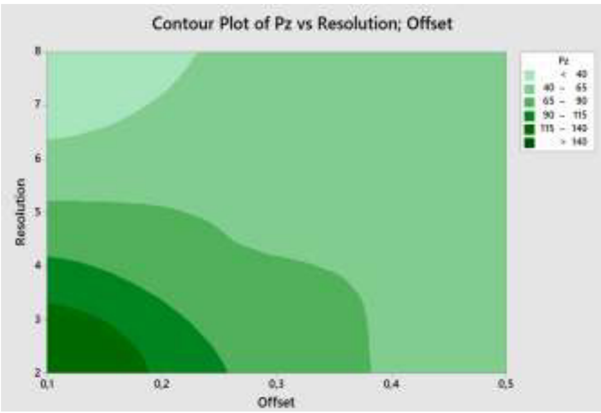

Fig. 10. Contour plot for Rz.

6. Conclusions

Roughness values obtained on internal surfaces of hemispherical PLA hip prostheses are quite high, above 40 µm for Ra in some cases. This is due to the fact that, when printing supports are removed, a protuberance remains on the surface.

It is possible to reduce height of peaks produced by supports on internal surfaces of hemispherical cup plastic hip prostheses by selecting high Support Pillar Resolution. In case low Support Pillar Resolution was required, then high Horizontal Offset from Part would be recommended.

Results obtained for PLA prostheses will be helpful for printing ceramic prostheses with PLA supports in double head printers in the future.

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