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Analysis of influence factors on part quality in micro-SLA technology

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Abstract

Stereolithography (SLA) is one of the most widely known technologies in the scope of additive manufacturing. It consists in printing layer by layer a photo-polymerizable liquid resin using ultraviolet light. This technology is used for creating models, prototypes and production parts. This paper studies the influence of different parameters in the Micro-SLA (for small scale production) process. The analyzed factors are the resin type, layer height, part orientation and cleaning operations. Our study includes the use of two different resins, widely used in dental and jewelry applications, and the effect of changing the orientation of geometrical primitives in the micro-SLA printing quality.

Keywords: Micro-SLA, Additive manufacturing, 3D printing, dimensional quality, superficial quality

1. Introduction

The Stereolithography (SLA) process consists in printing layer by layer a photo-polymerizable liquid resin using ultraviolet light. Printed parts are subjected to a post-curing process to give them greater consistency. Later on, a manual process is necessary to remove the supports required for printing. This technology is used for creating models or prototypes and, lately, production parts. The Micro-SLA is a variant of SLA printing for small scale production, mainly focused in medical, dental and jewelry sectors. Quality of parts printed with this technology depends on four

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main factors: resin type, layer height, orientation of the part to be printed and cleaning operations. With regard to precision, manufacturers offer only information of layer resolution, assuming it is independent of the type of resin.

This paper analyzes the micro-SLA printing quality using different types of resin and part orientation. To choose a good orientation leads to an improvement of surface finish and accuracy, as well as reduction of required support structures [1].

Several researchers have designed specific test parts in order to verify the dimensional and surface quality of printed parts with additive technologies. As already discussed, it is necessary to include features along all axes to check the resolution of the machine [2]. Test parts already designed include round, rectangular and spherical holes, cantilevers, ramps, angles, cylinders, prisms and spheres, structures with free forms and thin thicknesses [2,3]. However, although printing accuracy along X and Y axis using test parts of features has been studied, accuracy along Z axis has not been well studied yet [3]. On a micro scale, Thompson [4] designs three test parts with features with many shapes and sizes made with DLP technology, but we have not found works using Micro-SLA that analyze the printing quality of different geometric features with different orientations according the printing axis.

Therefore, there is an untested field in SLA technology, in particular on the small scale version. It is interesting to analyze the quality of the printed parts with this technology, both at dimensional level and surface quality; so that, a new test part has been designed to allow a complete study. This test part includes geometries such as planes, spheres, cylinders and holes in different orientations relative to the printing axis. Existing test parts, besides having a larger size than necessary for this type of technology, do not consider different orientations of features. Once the test part was designed, a methodology was established to analyze the print quality provided by a commercial machine widely used in the mentioned sectors. The 3D printer used was a Project 1200 (3DSystems), with a printing area of 43 x 27 x 150 mm, layer resolution of 30 micrometers, and native resolution (XY) of 56 µm (585 dpi).

2. Design of the test part

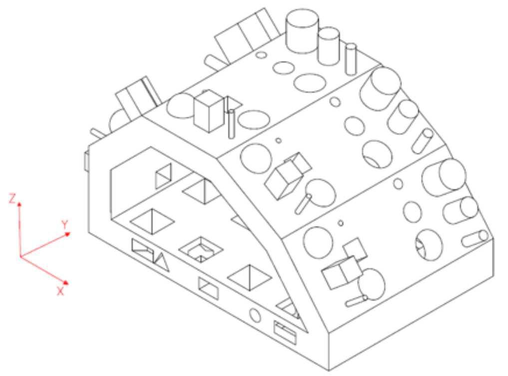
The recommendations expressed by Moylan have been taken into account for the test part design [3]. Among them, the test part must be greater enough to check the printer performance, containing both outgoing and incoming geometries; these geometries must have small, medium and large dimensions, manufacturing time should not be very long and consume of material low. Also, test part should be easy to measure.

In addition to these considerations, the machine used to print the test part has been taken into account, keeping the maximum dimensions inside the available printing platform (43 x 27 x 150 mm). An accessibility analysis performed for measuring the geometries made it necessary to redesign the test part several times, obtaining at the end the design shown in Fig. 1.

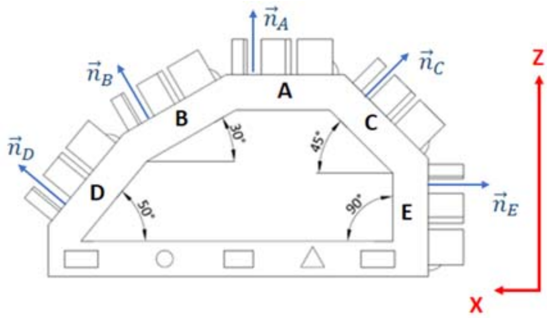
In consequence, the test part has dimensions of 32x25x20mm. Planes A, B, C, D and E have angles of 0°, 30°, 45°, 50° and 90° with the printing axis (Z axis), respectively. In each plane the following geometrical features have been included:

- 4 cylinders of 3 mm height and 3 mm diameter (CL-O_3), 2 mm (, CL-O_2), 1 mm (CL-O_1) and 0.5mm (CL-O_0.5), respectively.
- 4 holes with the same dimensions (CL-I_3, CL-I_2, CL-I_1 y CL-I_0.5).
- 1 square prism with 2 mm side (SPR-O_2).
- 1 square pocket of 2mm side (SPR-I_2).
- 1 semi-spherical hole (SP-I_2) and 1 semi-spherical protrusion of 3 mm diameter (SP-O_2).

The test part was lightened at the bottom to decrease cost and printing time. As Fig. 1c) shows, the elements were arranged in the outer part to facilitate the measurement of their height. A free space was left in the center of each plane to facilitate the access of the roughness probe tip.

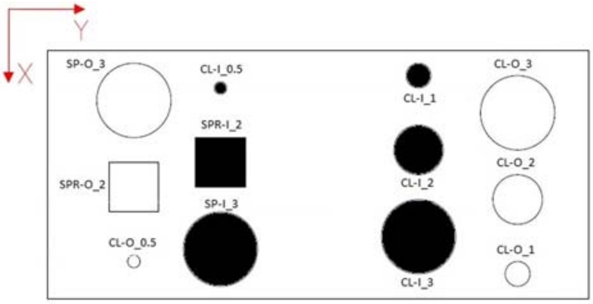


a) Isometric view



Surface	A	B	C	D	E
Orientation (Z axis)	0º	30º	45º	50º	90º

b) Planes orientations with respect to the printing bed and with respect to the Z axis



id	ELEMENT	DIMENSIONS
SP-O_3 / SP-I_3	Outer / Inner Sphere	3mm diameter
SPR-O_2 / SPR-I_2	Outer /Inner Square Prism	2mm x 2mm
CL-O_0.5 / CL-I_0.5	Outer /Inner Cylinder	0.5mm diameter
CL-O_1 / CL-I_1	Outer /Inner Cylinder	1mm diameter
CL-O_2 / CL-I_2	Outer /Inner Cylinder	2mm diameter
CL-O_3 / CL-I_3	Outer /Inner Cylinder	3mm diameter

c) Distribution of elements on each plane

Fig. 1. Designed test part.

3. Methodology and instrumentation

This section shows the methodology and equipment used, once the test part has been design. The machine allows to work with several materials of the 3D Systems Visijet FTX family, that include cast, clear, gold, green, silver and gray resins. In this work, two different resins widely known in aforementioned sectors were used: Green resin (for casting) and Gold resin (for prototypes), with densities of 1.04 g/cm3 and 1.16 g/cm3, respectively.

3.1. Methodology followed.

The printing parameters are optimized by the manufacturer to work adequately with each resin. 3DSPrint software was used to orient the test part on the printing platform and to add the necessary support structures. Fig. 2 shows the followed methodology.

Printed parts require an exhaustive cleaning process that is performed according to the manufacturer's recommendations [5]. For this purpose, an Ultrasonic Cleaner, MLINK, Model 820HTD, is used. In this cleaner, the part is inserted in a recipient with isopropyl alcohol and then the cleaning process finishes with compressed air. Next, the part is introduced into the post-curing chamber for 20-30 minutes, so that the resin properties improve significantly. Once the curing process is completed, the supports are removed and the part is separated from the printing platform.

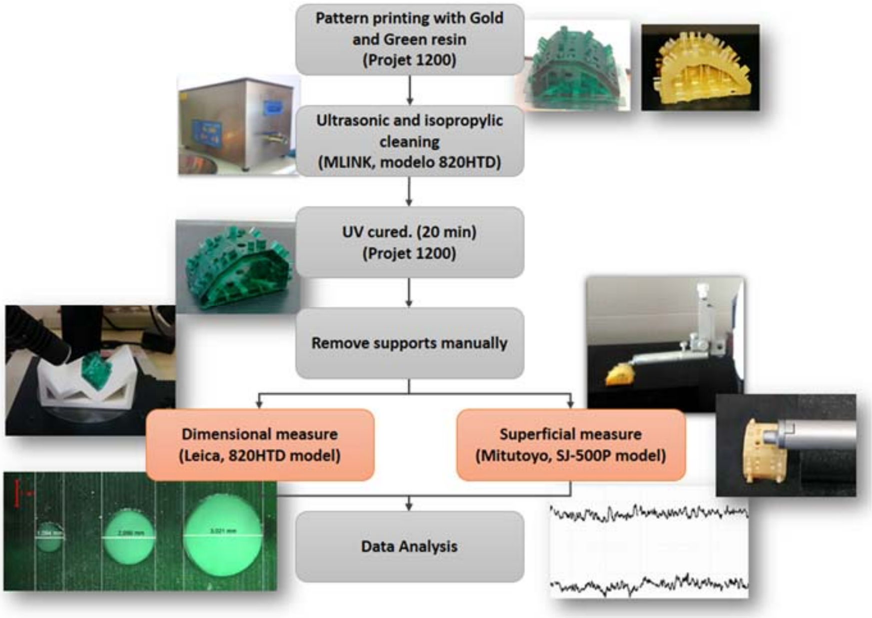


Fig. 2. Methodology and instrumentation.

3.2. Dimensional and roughness measurements

For dimensional measurements, a Leica microscope, model Z16 APO, connected to a digital camera Leica EC3 of 3.1 Megapixels was used. It is also equipped with a Leica LED light source model KL 1500 LED plus. In order to carry out the measurements, a specific fixture was also designed and manufactured to allow the test part to be placed with an orientation normal to the microscope objective. To check the dimensional accuracy of the features, several measurements were taken depending on the geometry to measure:

- For cylinders and hemispheres, two measurements were taken in orthogonal directions and the average diameter was calculated.
- For square pockets and prisms, two measurements were taken in every side and the average value was calculated for each side.
- For measuring the height of each element, two measurements were also taken and the average height was calculated.

For measuring the surface roughness, a Mitutoyo rugosimeter-profilometer, model SJ-500P, was used. The probe was a 12AAC731 with 2µm tip radius and 60° tip angle. The values of Ra, corresponding to the average of the absolute values of deviations of the profile with respect to the midline, were obtained on each flat surface of the test part. For the calculus, 8 measurements were performed in each orientation, 4 measurements along the X axis and 4 measurements along the Y axis.

4. Dimensional analysis results

Although the dimensional analysis was performed for all the designed geometries, only results obtained for the case of "Cylinder" elements are shown in this section. Similar results with the same trend were found for the rest of studied geometries.

4.1. Cylindrical holes (CL-I_0.5, CL-I_1, CL-I_2 and CL-I_3)

The cylindrical holes printed with gold and green resins were analyzed. Fig. 3 shows that when using 0° orientation, holes are printed with quality, regardless of their dimension. When slope of supporting plane increases with respect to Z axis, smaller dimension holes (0.5mm) are not printed with the gold resin, but when increasing the size they start to be printed but with low quality. This behavior is also observed on the green resin, but in this case the holes close at a higher inclination with respect to Z axis than with the gold resin. Orientations at 50° and 90° showed the worst results, as expected for both resins.

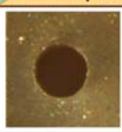
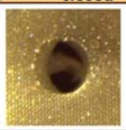
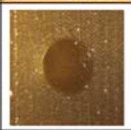
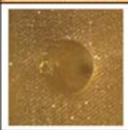
HOLES VISIBILITY	Green resin / Gold resin				
	SURFACES ORIENTATION – Z AXIS				
DIAMETER HOLES (mm)	0º	30º	45º	50º	90º
0.5	Open / Open	Open / Closed	Partially closed / Closed	Closed / Closed	Closed / Closed
1	Open / Open	Open / Partially closed	Partially closed / Closed	Partially closed / Closed	Partially closed / Closed
2	Open / Open	Open / Partially closed	Partially closed / Partially closed	Partially closed / Partially closed	Partially closed / Partially closed
3	Open / Open	Open / Partially closed	Open / Partially closed	Partially closed / Partially closed	Partially closed / Partially closed
Example (CL-I_1 and gold resin)					

Fig.3. Holes visibility-orientation.

For the green resin, Fig. 4 shows the results obtained when measuring the holes at 0° and 30° with respect to Z axis. In other orientations the results cannot be exposed due to the absence of complete cylindrical holes. As shown in the same figure, the values obtained for diameters are higher than the nominal value of each cylinder, regardless of the orientation. In relative terms (percentage), the largest error corresponds to the smallest diameter hole and the smallest error corresponds to the largest diameter hole, in the two orientations studied.

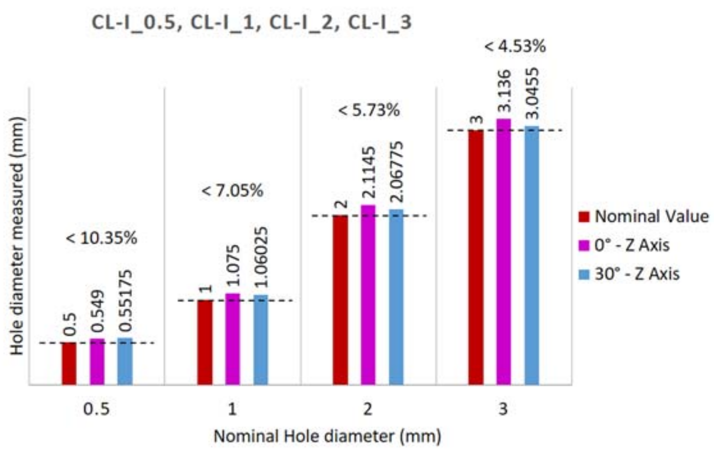


Fig. 4. Holes diameter-orientation in green resin.

4.2 Cantilever Cylinders (CL-O_0.5, CL-O_1, CL-O_2 and CL-O_3)

In the case of cantilevered cylinders, it was possible to measure all diameters except the 0.5 mm ones, which, although printed in all the planes, they could not be all preserved during the cleaning process due to the very small size. Diameters were measured at the top of each cylinder, due to the lack of cylindricity especially in the most unfavorable orientations and with the smaller diameter holes. Fig. 5 shows pictures of the quality obtained for cylinders of 3 mm and 1 mm diameter in relation with the printing orientation. It can be seen a worse quality with the gold resin but, in any case. The only orientation that allows to print with acceptable quality is the one that has the normal parallel to the printing axis (Plane A).

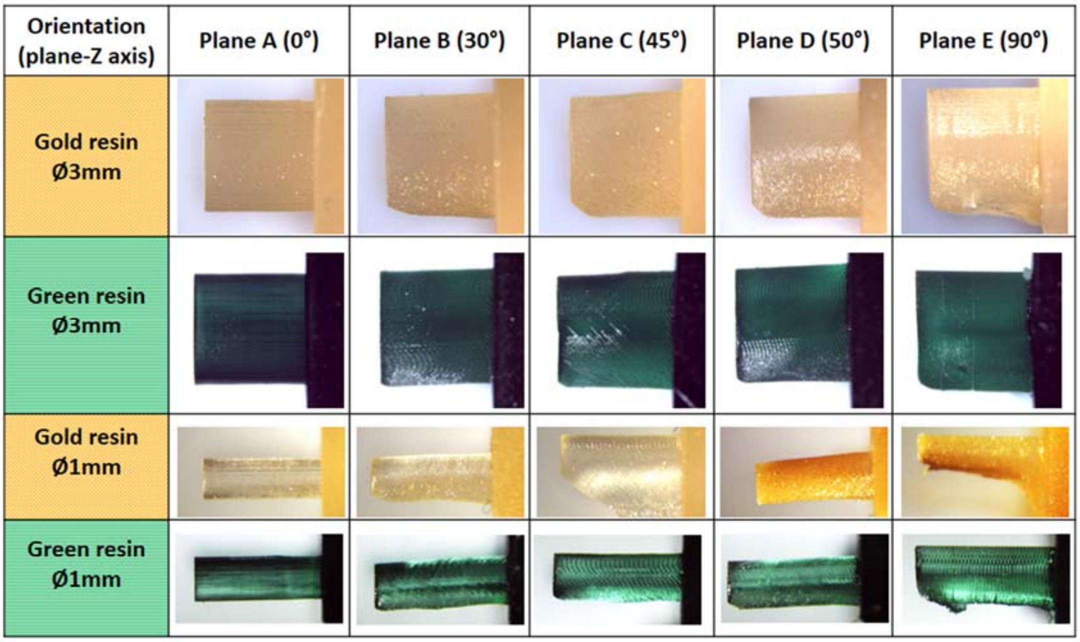


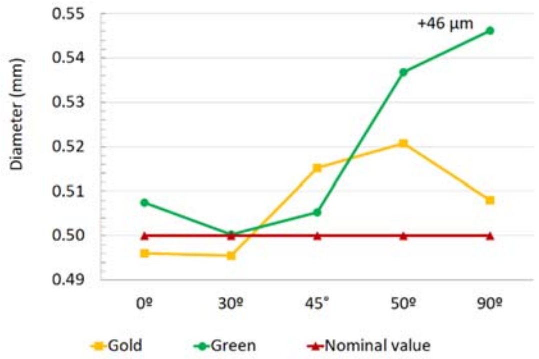
Fig. 5. Cylinder deformation-orientation.

Fig. 6 shows the cylinder diameters according to the different orientations. Printed cylinders follow the same trend in all dimensions greater than 0.5 mm: a reduction in the diameter below the nominal is observed for 45° orientation and this value increases again for 50° and 90° orientations. As expected, for cylinders with 0.5 mm diameter, the highest setting is achieved at 0° and 30° and the lowest at 90°.

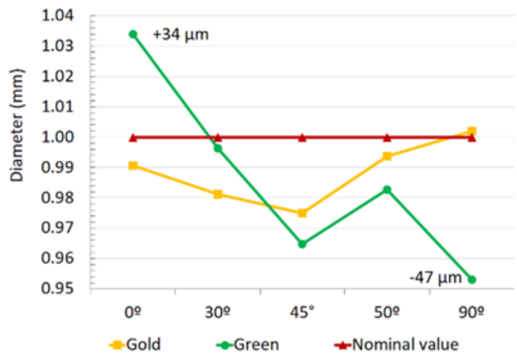
Higher variability was found in the measurement of the cylinders of smaller diameter. The largest deviation was 46 µm above the nominal value, just in the 90° orientation, being negligible (around 10 µm) in the most favorable orientations (0° to 30°). In relative values, quality improves when increasing the cylinder diameter. In general, dimensional quality increases when printing with gold resin.

The height of cylinders is shown only for cylinders of 3 mm diameter, showing the same behavior than the rest of cylinders. Fig. 7 shows the height of cylinders printed with both resins for the 5 orientations compared with the nominal value.

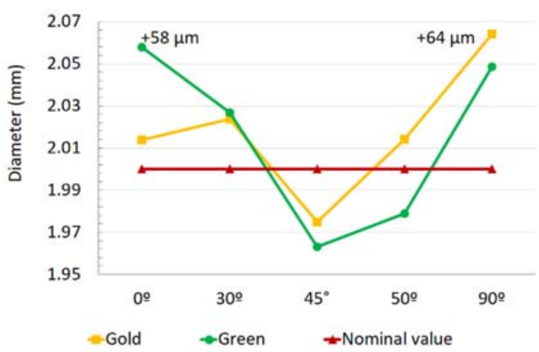
The cylinder heights are always higher than the nominal value. Deviations are 50 µm, in the most favorable orientation (0°), and 135 µm in the most unfavorable (90°) orientation. The maximum deviations are found for both resins in the orientations from 45° to 90°. Test parts printed with gold resin show better approximation at all orientations except at 90°.



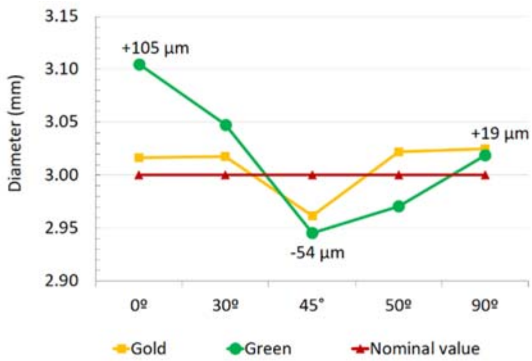
a) *Diameter of 0.5 mm*



b) *Diameter of 1 mm*



c) *Diameter of 2 mm*



d) *Diameter of 3 mm*

Fig. 6. Diameter-orientation.

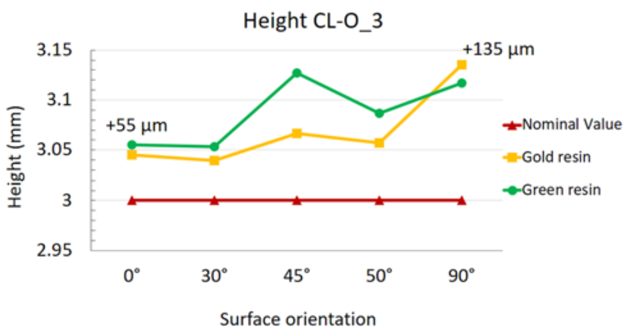
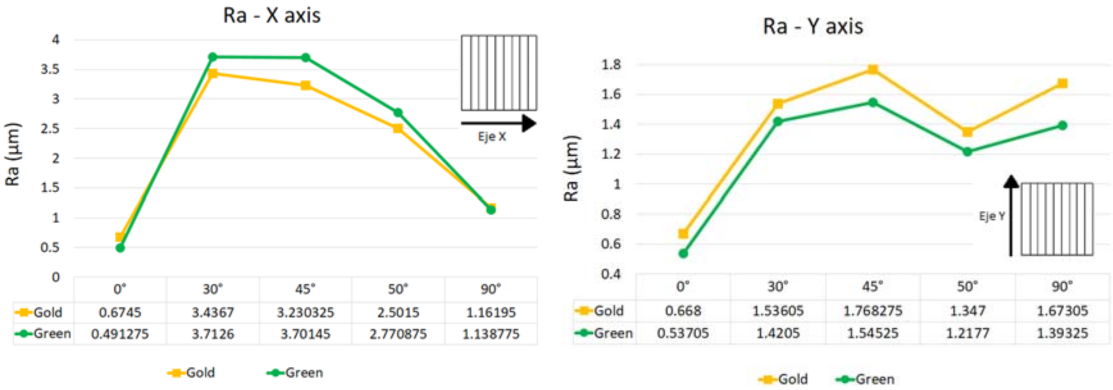


Fig.7. Height of cylinder of 3 mm diameter.

5. Superficial analysis results

Roughness was measured in the five planes A, B, C, D and E using the Ra parameter. Fig. 8a shows the Ra values obtained along the X axis. The value of Ra is similar for the two types of resin used and for all the orientations of the plane. In general, the value of Ra is lower in the Gold resin than in the Green resin, may be due to the higher viscosity of this resin. As expected, the lowest Ra value is found on the surface at 0°. On the surface at 90° the roughness is not very high, so it is verified that the printer places every layer on the top of the previous one with great precision. When inclination of the plane increases with respect to the printing axis, roughness also increases. This is due to the steps that appear between two adjacent layers: the higher plane inclination with respect to the printing bed the larger steps.



***a)** Roughness along the X-axis* ***b)** Roughness along the Y-axis*

Fig. 8. Ra values in X direction for each plane orientation.

As expected, roughness along the Y axis is much lower than the one obtained along the X axis (Fig. 8b). This is due to the test part orientation on the platform. Also, it is similar in all orientations. This is because the measurement is performed in the direction of the layers, whereas in the X axis the direction is perpendicular to the layers. X axis corresponds to the direction across the layers and the Y axis corresponds to the direction along layers.

As in the X-axis, the two types of resin follow the same trend, being the Ra value lower on the surface at 0°. In addition, roughness is very similar to that obtained in the X axis in the same orientation because the layer is projected completely at once. In the other four orientations roughness is higher but there are not great differences between them.

6. Conclusions

- The machine prints accurately with green resin the holes in surfaces with orientations between 0°and 30° and diameters between 0.5 mm and 3 mm. Holes located in planes with higher inclination cannot be printed with quality in this dimensional range.
- The cantilevered cylinders show a lack of cylindricity for all orientations, and above all in inclinations greater than 30°. Therefore, high quality cylinders must be printed in orientations around 0°. In addition, when considering the height the quality is very low for cylindrical geometries in the range of 45° and 90°.
- Since the printer has a precision of 30 µm, equivalent to the layer height, it is considered that dimensionally this printer prints with precision, being more effective in larger dimensions. Also, although not much difference was detected, better results were obtained with the Gold resin.

The results obtained for the cylinders can be extrapolated to the rest of geometries analyzed in this work. Therefore, in order to improve printing process is micro-SLA, it would be advisable to analyze the printing parameters. This would allow to evaluate their influence on the printing quality of different geometries and at different orientations. At the moment, these commercial printers do not allow the operator to intervene in these parameters; the system is completely closed and printing parameters are predefined for each resin.

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